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Cognitive mechanisms of visual attention, working memory, emotion, and their interactions

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Cognitive mechanisms of visual attention, working memory, emotion, and their interactions

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Editorial: Cognitive mechanisms of visual attention, working memory, emotion, and their interactions

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Editorial on the Research Topic
Cognitive mechanisms of visual attention, working memory, emotion, and their interactions

We, as human beings, inhabit a visually rich world that necessitates the cooperation of various cognitive systems to function and adapt effectively within this environment. Notably, visual attention plays a crucial role in selectively focusing on specific information and further processing it, facilitating efficient information processing. Working memory (WM) enables us to temporarily store and manipulate the information captured by attention, allowing us to handle more complex tasks. Furthermore, our emotional system actively participates in both attention and WM processes, by exerting influence and bias on them. Undoubtedly, the interconnectedness of these three systems is of great importance. However, it is common for researchers to investigate these cognitive processes separately, which ultimately leads to a limited understanding of the underlying neural basis and the interactions among them. Thus, the objective of this Research Topic collection is to bring together researchers from these three areas, with a particular focus on studies exploring the underlying interactions and mechanisms between these functions and how they mutually influence each other.

Fundamentally, WM provides a framework of prior knowledge and expectations, guiding attention and aiding in the understanding of incoming stimuli. For instance, Chen Z. et al. investigated whether the memory-driven factor or the cue-driven factor from WM representation affects visual search. The authors discovered that when controlling for WM representation as an additional variable, the memory and target match condition (i.e., the positive cue) had a lesser impact and even caused some impairment in subsequent visual search compared to the memory and non-target match condition. Therefore, the authors suggest that there are distinct components of target and distractor templates in our WM system, and the positive cueing effect observed in previous studies could primarily be driven by automatic WM guidance rather than the effect from the predictive cue itself. By conducting an Electroencephalograph (EEG) study during Shepard-Metzler's mental rotation task (SMT), Anomal et al. examined the link between cortical activation and visuospatial SMT performance in adolescents.

The researchers measured WM skills and other dimensions of IQ scores using intelligence scales. The findings revealed a negative correlation between WM scores and alpha activity in the frontal cortex, particularly during the challenging task condition. This suggests the crucial role of the frontal lobe in both WM abilities and SMT performance.

Our WM has limited capacity, but we often employ various strategies to accommodate more items. For example, Ren et al. investigated whether memory performance for identical objects improves due to the strengthened associations between them. They conducted three-color recall tasks and discovered evidence of a facilitation effect of identical objects in WM. However, they also demonstrated that this facilitation effect was influenced by the location information of the objects, which requires further investigation. In addition to the self-employed strategies, WM can also be influenced by various other external factors. Through a systematic review of previous studies, Zhu et al. discovered that physical activity had a small yet significant positive impact on visual-spatial working memory (VSWM) in healthy individuals. This impact was particularly notable in children and seniors after engaging in long-term exercise. As a result, the researchers recommended specific exercise intervention programs that could be considered for these age groups. In turn, WM training has the potential to enhance other cognitive functions. Wang et al. conducted a study that provided EEG evidence supporting the beneficial effects of WM training on enhancing fluid intelligence in children. The researchers specifically identified the predictive role of response inhibition ability in this improvement, offering both theoretical understanding and practical implications for enhancing children's WM and intelligence.

In our day-to-day experiences, we frequently encounter strong memory formation associated with highly positive or negative events. However, the precise mechanism underlying the encoding and integration of emotional stimuli into attention and WM remains uncertain. In this sense, Cianfanelli et al. conducted a study investigating the role of WM subcomponents in binding negative emotional and visuo-spatial information. By utilizing a dual task paradigm to interfere with the central executive (CE) subcomponent and an immediate post-task to interfere with the episodic buffer (EB) subcomponent, the study found that interference with the EB task prevented the emotion-enhancing effect of negative pictures, while interference with the CE did not. These findings highlight the key role of the EB and the involvement of pre-attentive automatic processes in binding emotional and visuo-spatial information. Similarly, Qiu et al. conducted a study focusing on the attentional capture of negative stimuli. By utilizing EEG recordings and machine learning techniques, the study revealed that visual awareness is crucial for the spatial attentional capture of fearful faces. Additionally, the researchers found that the fear-related effect persists and can modulate neural processes involved in subsequent cued spatial targets but also requires top-down attention to the faces. Furthermore, Qu et al. conducted a study to examine the impact of dynamic and static angry facial expressions on time perception. Their findings revealed that static angry faces had an earlier impact, leading to an overestimation of time due to early emotional arousal and attentional bias. In contrast, dynamic angry faces appeared to influence time perception by eliciting response inhibition and late sustained attention.

Transitions of consciousness are closely intertwined with our attention and WM, and they can also be influenced by emotions. However, comprehending the nature of consciousness poses a significant challenge. To delve into this enigmatic phenomenon, Quettier et al. conducted a study utilizing a binocular rivalry paradigm and a joystick to map the dynamics of conscious experience in response to faces displaying different emotions or genders. The results showed that formation was slower than dissolution in general. Additionally, participants preferred happy faces in emotion rivalry and their contents were slower to form and dissolve compared to neutral faces.

Rewards often lead to pleasure and positive feelings, and different perspectives on rewards can influence our cognitive function as well. In a study conducted by Giuffrida et al., they explored how different reward perspectives can influence participants' adaptation strategies by manipulating the reward regimen in a virtual competition. The findings indicate that participants do utilize different strategies based on the value of the reward, as evidenced by variations in response speed across different conditions. Although in some cases, participants may concurrently adjust their inhibition strategies as well, there is no significant difference in the duration of the inhibition process.

Understanding the interplay between attention, WM, and emotion also provides valuable insights for the application and user-friendly design. For instance, Zhang et al. conducted a study utilizing behavioral measures and eye-tracking techniques to investigate the impact of the layout of mobile map navigation icons on users' visual search efficiency. The results demonstrated that navigation icons employing color for layout coding exhibited the highest visual search efficiency and provided a superior user experience compared to other types of layouts. The researchers also recommended developers consider implementing regular color distribution and a larger area of the same color to enhance the overall user experience. By employing EEG technique, Chen J. et al. studied how pattern, lightness, and color factors of ceramic tiles influence customers' preferences. The findings revealed that light-toned tiles captured greater attention during the initial stages of visual processing. Subsequently, the patterned and neutral-colored tiles exhibited their impact during the mid-stage processing. Moreover, Qin et al. investigated the neural mechanism involved in recognizing graphic artifacts with varying degrees of repetition within a disorganized environment. The results revealed that the arrangement of the repeating graphics had a more pronounced effect on the later stages of cognitive processing, rather than on the earlier attentional features during the initial stages. Furthermore, by recording EEG data from individuals exposed to various price variances among purchase channels, Han and Zhang established a connection between potential neural indicators (i.e., N2 and P3) and customers' identification and attention distribution when evaluating product price variances across different purchase channels. These findings offer valuable implications and suggestions for economists and marketers within the relevant industry, providing insights on how to optimize strategies and improve customer experiences.

Aligned with our initial objective, this Research Topic brings together researchers from diverse disciplines focusing on visual attention, WM, and emotions. By exploring the complex interplay and mutual influence among these cognitive processes, our Research Topic not only provides fundamental insights into the interconnected nature of these three important processes but also extends its impact to other cognitive functions. Furthermore, it sheds light on various application fields, offering potential for optimizing commercial efficiency and enhancing overall human wellbeing. We firmly believe that this Research Topic holds great promise as a gateway for future research and calls for multidisciplinary efforts to further advance this field.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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How does price variance among purchase channels affect consumers' cognitive process when shopping online?

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The rise of a flourishing online shopping market has expanded the range of purchase channels available to consumers. Meanwhile, the competition among channels has become increasingly fierce. In this study, the changes in cognitive processes caused by price variance among channels were investigated using event-related potentials. Several daily necessities with low or high price variance between a self-operated business channel and third-party seller channels were chosen as the study objects from a well-known electronic business platform. Thirty participants' electroencephalograms were collected while they faced higher or lower price variance during the experiment. The results showed that small price variances between the two channels tended to intensify component N2, while big price variances tended to diminish component P3. These results suggest that N2 may reflect consumers' identification process for price variance and inhibition of a planned response, while P3 may reflect the activation of attention caused by task difficulty due to price variance. These findings indicate that the changes in ERP components N2 and P3 may act as cognitive indices that measure customers' identification and attention distribution when considering product price variances among online purchase channels.

KEYWORDS

price variance, purchase channel, cognitive process, event-related potentials, N2, P3

Introduction

With the development of E-commerce, more and more people are turning from traditional purchase channels to online shopping. Online shopping shifts the shopping environment from a real physical environment to a virtual network environment, resulting in substantial differences in shopping characteristics from traditional businesses. The latest developments indicate that the B2C shopping website is in the process of platformization, which means that commodities will not only be sold through the B2C self-operated business channel but also be sold through third-party sellers on the B2C platform (Cao and He, 2016; Cao et al., 2019; Wang and Li, 2020). As more and more purchase channels become available to consumers, channel selection problems emerge.

Putting price variance in the context of different online purchase channels, specifically B2C online shopping platform and third-party sellers on that platform, makes the issue of the impact of price variance on consumers' cognition more interesting. The commodity prices on different channels may vary widely depending on a variety of factors, such as information costs, competitive pricing on the Internet, and marketing strategies. From the perspective of consumers, their cognition not only derive from price difference, but also different reputation of channels. For example, if you were to buy a pair of ASICS sneakers from Amazon, which channel would you choose: the Amazon self-operated channel or a third-party seller on the Amazon platform? Can one expect that the price difference between online channels will affect consumers as it does for traditional channels?

Researchers have acknowledged that commodity price is one of the critical factors driving consumer choice among sellers (Thaler, 2008; Somervuori and Ravaja, 2013; Stewart et al., 2015; Sohn, 2017) and revealed that the price difference can have a significant impact on consumers' purchase decisions (Riquelme et al., 2016; Voorveld et al., 2016). Little is known about the effect of price difference among channels on consumers' cognition. Prior research mainly discussed that consumers could make different decisions based on different channels' prices (Gino et al., 2017; Gao et al., 2019; Li et al., 2022). Because consumers can indeed perceive differences in price (Wu et al., 2015; Karmarkar et al., 2019), tend to compare the spending between channels and make different choices to get the best deal (Hamilton and Chernev, 2013; Stefano and Noriaki, 2019). For example, consumers will weigh whether it is necessary and how much time and energy would be needed to get the money that could be saved due to the price difference between channels (Fassnacht and Unterhuber, 2016). This indicates that consumers could make different decisions based on different channels' prices (Gino et al., 2017; Gao et al., 2019; Li et al., 2022). It can be observed that the commodity price and purchase channel are interrelated, and the phenomenon that price differences between channels may affect consumers' cognitive processes. That is to say, when the same commodity is sold by different entities, the differing prices among sellers may lead to different cognitive processes, which in turn lead to different purchase decisions later.

The methodology the prior research normally uses to test the effect of price differences on consumers' purchase selection is A/B testing, field experiments, interviews, questionnaires, behavior observation, data analytics within firms, and so on. However, these traditional evaluation methods are not always feasible, because people who participate in surveys are not entirely rational, and consumers may be affected by many other factors such as emotion and context when dealing with information (Solnais et al., 2013; Chneider and Woolgar, 2015; Heather et al., 2019; Bettiga et al., 2020). The traditional methods may not fully reveal the consumer response to marketing stimuli (Sharad and Tanusree, 2015). Whether the study uses a group discussion or an in-person interview, whether the data are confidential or not, consumers' self-reports are still the main resources to conduct a survey (Hsu, 2017). Some limitations accompany these methods. First, the researchers assume that the respondents can describe the whole process of recognizing problems, analyzing the problems, and making decisions. In fact, many subconscious cognitive processes are not known to the respondents, or cannot be accurately described in words (Olteanu, 2015). Second, other factors such as incentives, time constraints, and peer pressure may also drive respondents to distort their feelings (Erik et al., 2010). As a result, their real thoughts may not be easily reflected by the use of a survey alone. A new approach is needed that can provide a supplement to traditional methods. In this study, we attempt to adopt neuroimaging tools to reveal the cognitive processes that are involved when consumers deal with price differences among online channels. Exploring consumers' cognitive responses may have the potential to find neuroelectrophysiological evidence to unpack the mechanism linking pricing strategy and consumer behavior, and thus strengthen the evaluation methods based on traditional marketing data.

Scholars have gradually realized the importance of observing consumers' brain responses to stimuli as a way to understand consumer behavior. With neuroimaging tools such as functional magnetic resonance imaging (fMRI) and brain event-related potentials (ERP), researchers can directly observe consumers' cognitive processes at the brain level (Association, A. P, 2013, Zhu et al., 2022). The consumer's brain response to different marketing stimuli can be objectively and quantitatively recorded and analyzed (Clithero, 2018; Meyerding and Mehlhose, 2020; Al-Nabhani et al., 2021). Analyzing these responses not only can supplement traditional research methods, but also make it possible to observe consumer cognitive processes such as pre-judgment, behavioral monitoring, and behavioral prediction, and then provide a more solid theoretical foundation for consumer behavior research. In the current study, we attempt to use ERP to explore the cognitive differences experienced by consumers when facing high or low price variations among channels. The negative ERP waveform that is mainly distributed at the frontocentral areas and evoked during the 250–350 ms time window after stimulus presentation is usually described as N2 (Jonathan and Cyma, 2008). Scholars have suggested that N2 represents the subjects' identification process, behavioral inhibition process, which is associated with cognitive control processes (Jonathan and Cyma, 2008; Smith et al., 2009; Pandey et al., 2011). The amplitude of N2 is related to the similarity of stimulus materials, with more negative amplitudes for high similarity of stimulus materials than low ones (Nieuwenhuis et al., 2004; Azizian et al., 2006; Kasai et al., 2011; Leek et al., 2016). ERP component P3 is a positive waveform with peak latency around 300–500 ms after the onset of a stimulus (Hagen et al., 2006). P3 is generally considered to be closely related to the attention distribution and target recognition processes (Polich and Comerchero, 2003; Polich, 2007). The amplitude of P3 is generally believed to be related to task difficulty (Polich and Comerchero, 2003; Miller et al., 2011). When the difficulty of the task increases, the attention resources that the subject must devote to the task will increase, and thus the amplitude of P3 will increase, and vice versa (Polich and Corey-bloom, 2005; Hagen et al., 2006).

Based on this, we hypothesize that the interaction of price and channel could modify consumers' cognitive processes, and that the cognitive change could be reflected in the difference in ERP components N2 and P3 evoked by the high or low price variances between two channels. Specifically, small price variances between channels may tend to evoke a more intense component N2 because a small price variance between channels seems to demand more cognitive resources when subjects perform the task. Meanwhile, smaller price variances between channels may tend to evoke a bigger component P3 because a decrease in price variance between channels may increase the task difficulty and consequently lead to a more intense P3. Our research attempts to make several important contributions to existing literature. Firstly, our research extends and enriches prior research on the relationship of price variance and consumers' decision, by providing the evidence of the impact of price variance among different online channels on consumers' cognition. Secondly, our finding that the price-driven differences in the channels' impacts on consumers at the brain level can not only make up for the shortcomings of traditional research methods, and also strengthen the consumer behavior theory. Thirdly, our work contributes to marketing strategies that help online platforms and third-party sellers to formulate reasonable price competition strategies and enable them to rid itself of meaningless promotional competition.

Research method

Subjects

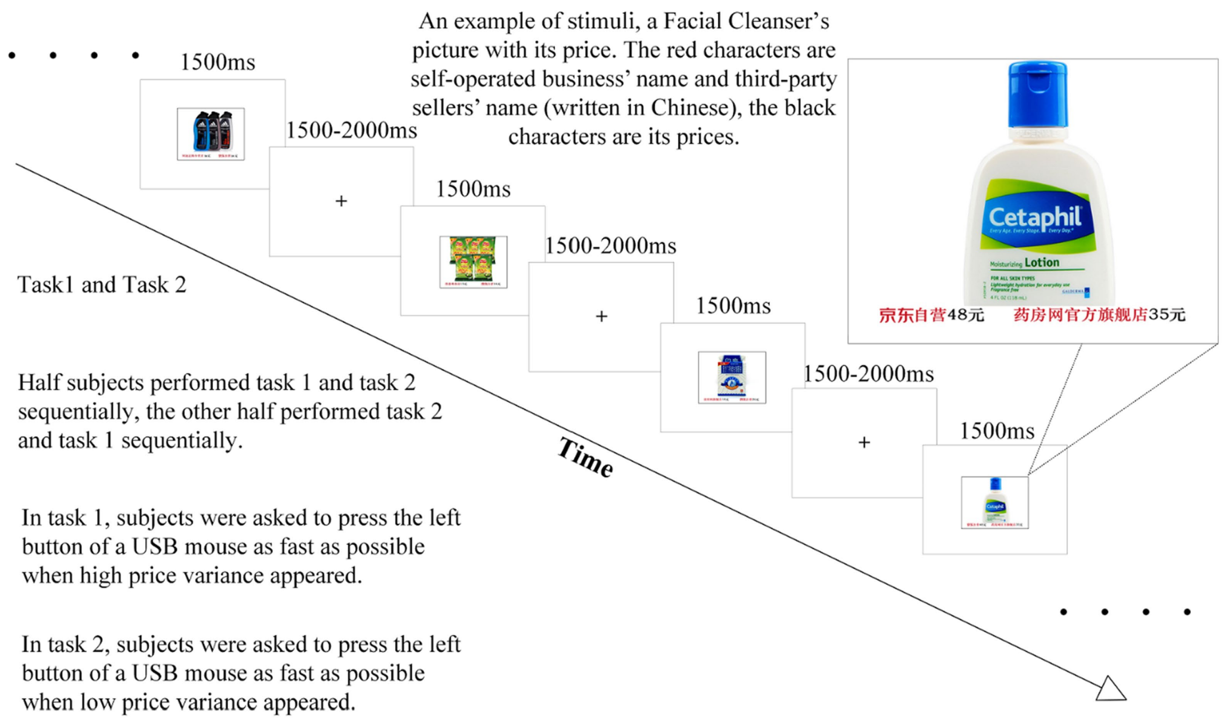
Thirty-three right-handed undergraduate students were recruited for this study. Three subjects were eliminated in the later stages due to excessive EEG artifacts, leaving 30 valid participants remaining for analysis (15 males and 15 females, mean age 24.8 ± 2.6). Normal or corrected-to-normal vision was reported by all 30 participants. None of them had neurological or mental illness, head trauma, or drug abuse, and none were taking medication within 1 month before the experiment. All participants were native Chinese speakers. Written informed consent was obtained from each subject before the experiment, in line with The Code of Ethics of the World Medical Association (Declaration of Helsinki), printed in the British Medical Journal (18 July 1964). The experimental protocol was approved by the local Ethics Committee.

Before the experiment, verbal communication with each participant was conducted to determine frequency of online shopping, spending on online shopping per month, and favorite forms of promotion. The survey showed that all participants were familiar with online shopping. All participants had purchased daily necessities from E-commerce platforms in the past 3 months, and all were aware of the differences between commodities sold or services provided by self-operated channels vs. other third-party seller channels on the platform. After the experiment, a small gift worth about five USD was given to each participant as compensation for participation.

Stimuli

Two types of online shopping channels were examined in this study: one self-operated business channel vs. other third-party seller channels on one specific platform in China. The commodities involved were all daily necessities such as shampoo, toothpaste, snacks, and washing products, which were selected as experimental materials because they are all closely related to the participants' lives. All participants were familiar with the selected commodities. According to the market trading rules, commodities sold by the self-operated business channel or the third-party seller are all genuine, excluding counterfeiting and refurbishment. The reasons for the price differences included operating costs, business strategies, services provided, etc. Due to the different online shopping channels for the same commodities, the after-sale guarantees, delivery services, and payment methods available to consumers were also different. Self-operated channels support cash on delivery, fast delivery service (usually <2 days), and unconditional return and replacement (no pickup fee). Third-party sellers do not support cash on delivery service, and the goods transportation service is relatively slow (usually 3–7 days). Moreover, the return service of third-party sellers is more restricted than that of the self-operated channel. For example, in the case of Cetaphil Cleanser mentioned later in this study, consumers who purchase it through the self-operated channels will have it delivered by the self-operated express within 24 h, while those who purchase it from third-party sellers will have to wait at least 3 days for delivery; the self-operated channels also provides no-reason returns and door-to-door return services, while third-party sellers require consumers to negotiate with the sellers before consumers can carry out the more cumbersome return procedures, such as having to send the returned goods themselves. All participants had purchased goods from self-operated and third-party sellers before the experiment, and they were all familiar with the above differences. In addition, the experimenters listed these differences in their verbal communication for the participants.

An illustration of the basic stimuli and presentation sequence is given in Figure 1. Twenty-four color photographs of daily necessities with different prices were chosen as critical stimuli. The purchase channels and prices from the self-operated business vs. third-party sellers were shown paired in the right and left bottom corners of the pictures. Following the examples of the market survey and prior studies (Jones et al., 2011, 2012), the price variances between channels on an E-commerce platform were simulated by preset high and low price variances in this study: self-operated business prices were ~25% and 5% higher than those of third-party sellers, half and half. For example, for the situation in which the self-operated



An example of stimuli, a Facial Cleanser's picture with its price. The red characters are self-operated business' name and third-party sellers' name (written in Chinese), the black characters are its prices.

Half subjects performed task 1 and task 2 sequentially, the other half performed task 2 and task 1 sequentially.

In task 1, subjects were asked to press the left button of a USB mouse as fast as possible when high price variance appeared.

In task 2, subjects were asked to press the left button of a USB mouse as fast as possible when low price variance appeared.

FIGURE 1
Schematic drawing of the paradigm.

channel's price was about 5% higher than the third-party sellers' price, we set the price of Cetaphil Cleanser as sold by the self-operated channel to 48 RMB, and set the price as sold by the Yaofang store to 46 RMB ("Yaofang store" is a third-party seller's name on the platform); while for the situation in which the self-operated channel's price was about 25% higher than the third-party sellers' price, the price of Cetaphil Cleanser sold by the self-operated channel was still 48 RMB, but the price as sold by the Yaofang store was 35 RMB. In order to eliminate unnecessary interference factors, the picture did not include spokespersons or product users. Adobe Photoshop was used to ensure that all stimulus pictures had the same brightness and root mean square (RMS) contrast and visual complexity.

Experimental design

An amended Go/No-go experimental paradigm was used in this experiment. The subjects performed two tasks in total, each of which was composed of 12 pictures in which the self-operated business prices were ~25% than those of the third-party sellers and 12 pictures in which the self-operated business prices were ~5% higher than those of the third-party sellers. In order to exclude the influences on ERPs caused by presentation to the left or right visual field (Woldorff et al., 1997), and to avoid any influences caused by the probability of presentation (Falkenstein et al., 1995), the two different channel prices were randomly presented in the picture's left or right corner to ensure that the stimulus sequence could appear in a balanced manner. Half of the subjects performed task 1 and task 2 sequentially. In task 1, following the experimental instruction, subjects were asked to press the left button of a USB mouse as quickly as possible when a high price variance appeared. Then, in task 2, subjects were asked to perform the same action when a low price variance appeared. The other half of the subjects carried out the experiment under the same experimental instructions in each task, but the order was changed to task 2 then task 1. If the accuracy were under 95% in any task, the electroencephalogram data would be discarded in the combination process later. Before the formal experiment, the subjects performed an exercise block for about 5 min to make sure they had familiarized themselves with the whole experimental process.

An example of stimuli and the time line of the experiment can be seen in Figure 1. All stimuli were presented using E-prime (version 2.0 professional) in the center of a gray background LCD screen. Each trial was presented 10 times. Each trial consisted of the presentation of a stimulus (duration of 1,500 ms) followed by a fixation cross to avoid the repeated presentations of the stimuli. The inter-trial interval was random with a duration between 1,500 and 2,000 ms. All trials were presented sequentially in a randomized order. The subjects viewed the stimuli from a distance of 100 cm at the center, with a horizontal visual angle of 10.3° and a vertical visual angle of 6.8°. An electrically shielded and sound-attenuated experimental chamber was used. The participants were seated in a comfortable chair during the experiment. Subjects were offered a rest break for 5 min between tasks.

Electroencephalogram recording and analysis

The electroencephalogram was collected using the Neuroscan EEG system (Neurosoft Labs Inc) with a band-pass of 0.01–100 Hz and a sample rate of 500 Hz. The acquisition process was continuously recorded and analyzed offline. Ag/AgCl electrodes were mounted in a cap according to the international 10/20 system and located at 34 standard positions (FP1/2, FPZ, F3/4, F7/8, FZ, FC3/4, FT7/8, FCZ, C3/4, T7/8, CZ, CP3/4, TP7/8, CPZ, P3/4, P7/8, PZ, PO3/4, POZ, O1/2, OZ). A reference electrode was placed on the left mastoid and referenced to link mastoids offline. Vertical eye movements were monitored using a vertical electrooculogram that was recorded from the right eye by supra-orbital and infra-orbital electrodes (vertical EOG). Horizontal eye movements were monitored using a horizontal electrooculogram recorded by electrodes on the outer canthi of both eyes (horizontal EOG). The impedance of each electrode was kept below 5 KΩ during the acquisition process. Offline data were processed using Curry7.0 SBA (Neurosoft Labs Inc). Large artifacts caused by muscle or eye movements were manually removed. The trials in which base-to-peak electrooculogram (EOG) amplitude exceeded 200 μV, amplifier saturation occurred, or the baseline shift exceeded 250 μV/s were automatically rejected offline (7%). After band-pass filtering at 0.05–30 Hz (24 dB/Octave), the EEG was epoched offline into 1,000 ms: from 200 ms before picture onset to 800 ms after onset (baseline = 200 ms). The epoched EEG data were later combined to yield two primary conditions: self-operated business prices 5% higher vs. 25% higher than third-party sellers.

Results

The raw waveform is presented in Figure 2. Averaged ERP were drawn by Curry7.0 SBA (Neurosoft Labs Inc). Based on a visual examination of the potential distributions and the scalp topographical mapping of potentials (Figure 3), following prior studies (Eiichi and Yukihiko, 1992; Falkenstein et al., 1999; Jonathan and Cyma, 2008), the mean amplitudes of N2 within a 240–330 ms time window at the nine electrodes F3, FZ, F4, C3, CZ, C4, P3, PZ, P4 were selected for analysis. Similarly, the mean amplitudes of P3 within a 430–630 ms time window at the nine electrodes F3, FZ, F4, C3, CZ, C4, P3, PZ, P4 were chosen for analysis, following the example of previous studies (Wiese and Schweinberger, 2011; Dinteren et al., 2014; Shang et al., 2016). A within-subjects repeated measures ANOVA was used to compare the mean amplitudes of N2 and P3, with primary conditions (self-operated business prices ~25% higher vs. self-operated business prices ~5% higher) and distribution as two within-subject factors. The basic descriptive statistics of evoked N2 and P3 potentials can be seen in Table 1. For all statistical effects involving two or more degrees of freedom in the numerator, the Greenhouse–Geisser epsilon was used to correct possible violations of the sphericity assumption when appropriate. The significance level was set at $p < 0.05$.

The results showed that price variances caused significant differences in the component N2 ([F (1, 29) = 10.818, p = 0.003]) and in distribution ([F (8, 232) = 173.840, p < 0.001]), but not in the price variance × distribution interaction ([F (8, 232) = 1.788, p = 0.166]). Combining the raw waveform and the scalp topographical mapping with variance analysis, the results demonstrated that high price variance conditions were associated with smaller N2 amplitudes than were low price variance conditions. Stimuli with low price variance elicited a more negative N2 than those with high price variance, which were distributed broadly over the scalp and maximal on the fronto-central scalp.

The price variance also caused significant differences in the component P3 ([F (1, 29) = 5.980, p = 0.021]) and in the distribution ([F (8, 232) = 10.441, p < 0.001]), but not in the price variance × distribution interaction ([F (8, 232) = 1.783, p = 0.165]). We also found that the average P3 amplitude was larger for low price variance conditions than for high price variance conditions. Stimuli with low price variance elicited a more positive P3 than did those with high price variance, and the P3 was also distributed broadly over the whole surface of the scalp except the left temporal and parietal-occipital scalp.

Discussion

The results showed that, in the time window of 240–330 ms, there were significant differences in the N2 potentials evoked by high vs. low price variance between channels. A high price variance between channels resulted in a smaller N2, which was mainly located in the fronto-central area, as seen in Figures 2, 3. It has been assumed that N2 distributed over the front-central area of the scalp reflects the process of cognitive control (Luck and Kappenman, 2012; Susana et al., 2014). The average amplitude is related to the similarity between the stimulus materials: the higher the degree of similarity, the larger the N2 (Nieuwenhuis et al., 2004; Azizian et al., 2006). We posit, based on previous studies, that the component N2 reflects participants' identification of price variance information (Salil and Pierre, 2005; Hu et al., 2013; Wiese et al., 2014). Stimulation with price variance information has been divided into two categories in this experiment, high and low. When the stimulus appeared, subjects had to distinguish task stimuli according to the experiment introduction with the smallest delay possible. We believe that the change in N2 represents the cognitive resources required when identifying the price variances. A small difference between the prices for the two channels costs more resources to identify, while participants could relatively easily identify a high price variance, in which the differences

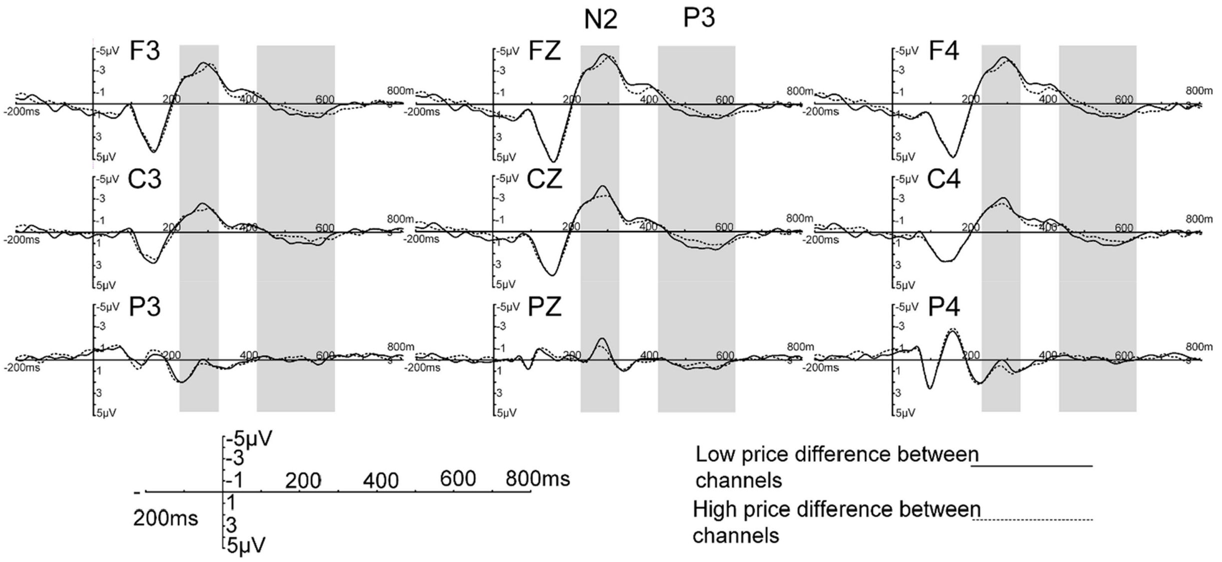


FIGURE 2
Raw ERPs waveforms at nine electrode sites.

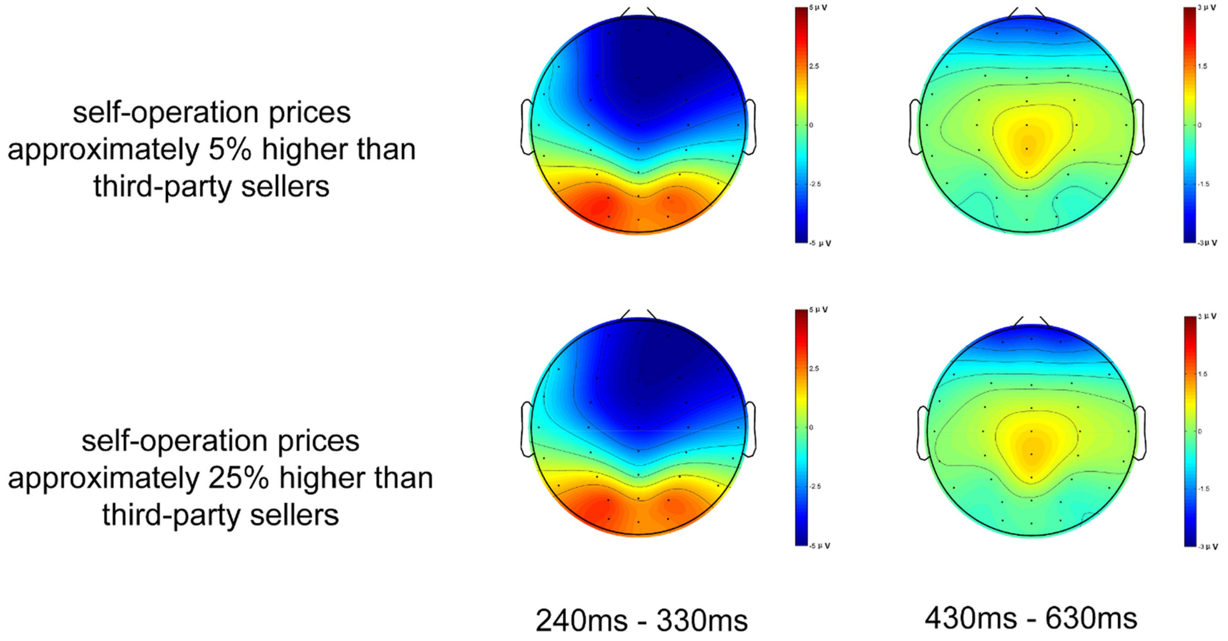


FIGURE 3
Topographic maps of N2 (240–330ms) and P3 (430–630ms).

between prices is a little significant. As N2 potentials evoked by stimuli with price variance show, the average amplitude decreased when high price variance appeared, which is consistent with prior findings (Schweinberger et al., 2002; Pawel et al., 2011). Another interpretation is that N2 may reflect the inhibition of a planned response. As some scholars have pointed out in prior research (Pfefferbaum et al., 1985; Bruin and Wijers, 2002), N2 tends to be larger in tasks for which an overt response must be withheld in the Go/No-go paradigm. The No-go stimuli shared most features with the Go stimuli and differed only in price variance. Thus, the preparation of an incorrect response that must be suppressed was triggered while participants proceeded in their task (Jonathan and

TABLE 1 The basic descriptive statistics of evoked.

Distribution		25% higher	5% higher	*t*-Value	Value of *p*
F3	N2	−3.23 ± 1.95	−3.84 ± 2.15	−3.841	0.001
	P3	−0.64 ± 0.94	−0.19 ± 1.10	2.632	0.013
Fz	N2	−4.29 ± 2.33	−4.87 ± 2.25	−2.599	0.015
	P3	−0.56 ± 0.94	−0.12 ± 1.02	2.872	0.008
F4	N2	−4.18 ± 1.79	−4.81 ± 2.16	−2.840	0.008
	P3	−0.53 ± 1.04	−0.13 ± 1.02	2.509	0.018
C3	N2	−1.89 ± 1.91	−2.35 ± 1.79	−2.910	0.007
	P3	−0.07 ± 0.88	0.26 ± 0.95	2.516	0.018
Cz	N2	−3.21 ± 1.97	−3.90 ± 1.97	−3.840	0.001
	P3	0.20 ± 0.93	0.58 ± 0.88	2.675	0.012
C4	N2	−2.57 ± 1.87	−3.11 ± 1.58	−3.141	0.004
	P3	0.00 ± 0.83	0.30 ± 0.81	2.641	0.013
P3	N2	1.51 ± 1.73	1.21 ± 1.60	−2.442	0.021
	P3	−0.25 ± 0.74	−0.05 ± 0.72	2.368	0.025
Pz	N2	0.01 ± 1.63	−0.517 ± 1.44	−3.353	0.002
	P3	0.21 ± 1.08	0.47 ± 0.96	2.586	0.015
P4	N2	1.35 ± 1.56	1.01 ± 1.39	−2.413	0.022
	P3	−0.33 ± 0.92	−0.07 ± 0.80	3.043	0.005

Cyma, 2008). The overall similarity in the small price variances resulted in larger N2 when participants were exposed to a relatively difficult trial, which means that low price variance stimuli elicited larger N2 than high price variance stimuli. This speculation is consistent with a prior study that found that difficult No-go trials elicited larger N2 than easy No-go trials (Nieuwenhuis et al., 2004).

The P3 component embodies similar functional connections; the P3 induced by low price variance was greater than that induced by high price variance between channels. The scalp distributions of P3 appeared to be central; therefore, the P3 component might be a P3a-like potential. In one interpretation, the P3, which is distributed over the central area, is thought to reflect the distribution process of attention, the amplitude of P3 component was related to the attention resource devoted (Polich and Comerchero, 2003; Hagen et al., 2006; John and Criado, 2006). We believed that subjects devoted more attention resources to distinguish the 5% condition stimulus materials. As mentioned in section 2.2 above, the differences between the two sets of stimulus materials — i.e. the self-operated channel's price being either 5% higher or 25% higher than the third-party sellers' price — would only be observed in the price of 46 RMB or 35 RMB offered by the third-party seller, while the self-operated channel price was still set to 48 RMB for both conditions. When the stimuli were presented, participants allocated fewer attention resources to identify the 25% higher price variance stimuli because 48 and 35 share fewer features than 48 and 46. In other words, the difficulty increased when participants identified the 5% condition stimulus materials, resulting in a more positive P3 component compared to the 25% higher price condition because more attention resource need to be devoted to identify the harder stimuli (Hagen et al., 2006). Another interpretation is that P3a may be subtended by neural changes in the anterior cingulate function when new stimuli replace the contents of working memory (Polich and Comerchero, 2003; Khan et al., 2020). According to this interpretation, as participants basically know the average price variance between the self-operated business channel and third-party seller channel in the real world, the stimuli that have a lower price variance could be regarded, in a sense, as a type of non-target distractor. Compared to stimuli that had high price variances between channels, stimuli with low price variances would cause participants to be more risk-avoidant when considering the possibility of errors and thus subsequently more likely to activate an anterior cingulate/medial prefrontal network during decision-making, thus leading to a greater P3 component. Other researchers have also argued that it is the P3, but not the N2, that is associated with response inhibition or with an evaluation/decision process with regard to the expected and/or given response (Bruin et al., 2001; Smith et al., 2007; Singh and Basu, 2009).

This study has some important differences from traditional studies. Prior research has mainly focused on the effects of multiple prices in traditional distribution channels and the influence of price changes on consumers' selection. In this study, the interaction of price and channel was investigated by using an experimental approach, and the consumers' cognitive processes while facing purchase channels with price variances were studied. Neuroscientific evidence was expected to be found to make up for the deficiencies in traditional research to date. Through the observation of consumers' cognitive reactions to distribution channels with price variances, neuroelectrophysiological indicators of the cognitive processes were preliminarily explored. It was found that some mature ERP indicators in cognitive neuroscience may help to explain the mechanisms of consumer behavior.

Conclusion

To summarize, the cognitive differences caused by price variance between channels were investigated using event-related potentials in this study. Some daily necessities with high and low price variance between a self-operated business channel and third-party seller channel were presented as experimental materials. The ERP data demonstrated that low price variances between channels induced an intensified N2 and P3 at the fronto-central areas and central areas, respectively. We believe that the different price variances between channels led to the differences in cognitive processes. The amplitude variation in N2 and P3 reflected differences in the identification and attention distribution processes caused by price variances. It can be concluded that EPR components N2 and P3 could serve as a cognitive index to measure consumers' identification and attention distribution to price variances between purchase channels. This study contributes to our understanding of consumers' neural activity when facing purchase channel problems with price variances. Exploration of this cognitive process can help companies to set a more reasonable price to participate in market competition and even develop a more effective marketing strategy.

Implications

Customers' price perception has a decisive influence on their channel selection decision. The impact of the interaction of price and channel on consumers' cognitive processes should be taken seriously. Whether a channel's price is able to attract consumer attention has a significant impact on the purchase decision, and can even indirectly affect product sales and profits. Different channels have different characteristics. Managers should carefully consider the nature of a channel when making its channel pricing strategy and then improve the service level in a targeted way to enhance price competitiveness. This study was not only dedicated to investigating consumers' cognitive differences caused by price variance between channels but also to providing a new method for analyzing consumers' cognitive differences caused by the interaction of price and channel. This study has shown that when consumers face the purchasing channel selection problem with price differences, their early cognitive processing stages can be observed using neuroimaging tools. Continued in-depth development of this method can not only help us understand the channel selection process for daily necessities, but is also expected to extend the research field to specialty or luxury markets so that we can acquire a more profound theoretical explanation of universal consumer behavior at the neuroscience level.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by SWUPL Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

HW and ZXF: conceptualization and validation. ZXF: methodology, software, formal analysis, writing—original draft preparation, data curation, and visualization. HW: investigation, resources, writing—review and editing, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Al-Nabhani, K., Wilson, A., and Mclean, G. (2021). Examining consumers' continuous usage of multichannel retailers' mobile applications. *Psychol. Mark.* 39, 168–195. doi: 10.1002/mar.21585

Association, A. P. (2013). *Publication Manual of the American Psychological Association*: *6th ed.*, Washington, DC, American Psychological Association.

Azizian, A., Freitas, A. L., Parvaz, M. A., and Squires, N. K. (2006). Beware misleading cues: perceptual similarity modulates the N2/P3 complex. *Psychophysiology* 43, 253–260. doi: 10.1111/j.1469-8986.2006.00409.x

Bettiga, D., Bianchi, A. M., Lamberti, L., and Noci, G. (2020). Consumers emotional responses to functional and hedonic products: a neuroscience research. *Front. Psychol.* 11, 559779. doi: 10.3389/fpsyg.2020.559779

Bruin, K. J., and Wijers, A. A. (2002). Inhibition, response mode, and stimulus probability: a comparative event-related potential study. *Clin. Neurophysiol.* 113, 1172–1182. doi: 10.1016/S1388-2457(02)00141-4

Bruin, K. J., Wijers, A. A., and Staveren, A. S. J. V. (2001). Response priming in a Go/NoGo task: do we have to explain the Go/NoGo N2 effect in terms of response activation instead of inhibition? *Clin. Neurophysiol.* 112, 1660–1671. doi: 10.1016/S1388-2457(01)00601-0

Cao, K., and He, P. (2016). The competition between B2C platform and third-party seller considering sales effort. *Kybernetes* 45, 1084–1108. doi: 10.1108/K-01-2016-0009

Cao, K., Xu, X., Bian, Y., and Sun, Y. (2019). Optimal trade-in strategy of business-to-consumer platform with dual-format retailing model. *Omega* 82, 181–192. doi: 10.1016/j.omega.2018.01.004

Chneider, T. S., and Woolgar, S. (2015). Neuromarketing in the making: enactment and reflexive entanglement in an emerging field. *BioSocieties* 10, 400–421. doi: 10.1057/biosoc.2015.37

Clithero, J. A. (2018). Response times in economics: looking through the lens of sequential sampling models. *J. Econ. Psychol.* 69, 61–86. doi: 10.1016/j.joep.2018.09.008

Dinteren, R. V., Arns, M., Jongsma, M. L. A., and Kessels, R. P. C. (2014). P300 development across the lifespan: a systematic review and meta-analysis. *PLoS One* 9:E87347. doi: 10.1371/journal.pone.0087347

Eiichi, J., and Yukihiko, K. (1992). Relation of a negative ERP component to response inhibition in a Go/No-Go task. *Electroencephalogr. Clin. Neurophysiol.* 82, 477–482.

Erik, F. C., Lisa, C., and Robert, K. (2010). Defining neuromarketing: practices and professional challenges. *Harv. Rev. Psychiatry* 18, 230–237. doi: 10.3109/10673229.2010.496623

Falkenstein, M., Hoormann, J., and Hohnsbein, J. (1999). ERP components in Go/NoGo tasks and their relation to inhibition. *Acta Psychol.* 101, 267–291. doi: 10.1016/S0001-6918(99)00008-6

Falkenstein, M., Koshlykova, N. A., Kiroj, V. N., Hoormann, J., and Hohnsbein, J. (1995). Late ERP components in visual and auditory Go/NoGo tasks. *Electroencephalogr. Clin. Neurophysiol.* 96, 36–43. doi: 10.1016/0013-4694(94)00182-K

Fassnacht, M., and Unterhuber, S. (2016). Consumer response to online/offline price differentiation. *J. Retail. Consum. Serv.* 28, 137–148. doi: 10.1016/j.jretconser.2015.09.005

Gao, L., Melero, I., and Javier, S. F. (2019). Multichannel integration along the customer journey: a systematic review and research agenda. *Serv. Ind. J.* 9, 1–32. doi: 10.1080/02642069.2019.1652600

Gino, M., Marco, M., Sara, P., Monica, R., and Elena, T. (2017). "Logistics in Omni-Channel retailing: Modelling and analysis of three distribution configurations," in *IEEE International Conference On Service Operations And Logistics, And Informatics (Soli)*. Bari, Italy: IEEE.

Hagen, G. F., Gatherwright, J. R., Lopez, B. A., and Polich, J. (2006). P3a from visual stimuli: task difficulty effects. *Int. J. Psychophysiol.* 59, 8–14. doi: 10.1016/j.ijpsycho.2005.08.003

Hamilton, R., and Chernev, A. (2013). Low prices are just the beginning: price image in retail management. *J. Mark.* 77, 1–20. doi: 10.1080/02642069.2019.1652600

Heather, A., Helen, H., and Shaun, S. (2019). Using neuroscience to understand the impact of premium digital out-of-home media. *Int. J. Mark. Res.* 61, 588–600. doi: 10.1177/1470785319851316

Hsu, M. (2017). Neuromarketing: inside the mind of the consumer. *Calif. Manag. Rev.* 59, 5–22. doi: 10.1177/0008125617720208

Hu, X., Pornpattananangkul, N., and Rosenfeld, J. P. (2013). N200 and P300 as orthogonal and integrable indicators of distinct awareness and recognition processes in memory detection. *Psychophysiology* 50, 454–464. doi: 10.1111/psyp.12018

John, P., and Criado, R. J. (2006). Neuropsychology and neuropharmacology of P3a and P3b. *Int. J. Psychophysiol.* 60, 172–185. doi: 10.1016/j.ijpsycho.2005.12.012

Jonathan, R. F., and Cyma, V. P. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology* 45, 152–170. doi: 10.1111/j.1469-8986.2007.00602.x

Jones, W. J., Childers, T. L., and Jiang, Y. (2011). "The shopping brain: neural correlates of buying under different promotional formats," in *Society For Consumer Psychology, Atlanta, GA. Vol. 1*. 1–28.

Jones, W. J., Childers, T. L., and Jiang, Y. (2012). The shopping brain: math anxiety modulates brain responses to buying decisions. *Biol. Psychol.* 89, 201–213. doi: 10.1016/j.biopsycho.2011.10.011

Karmarkar, U. R., Shiv, B., and Knutson, B. (2019). Cost conscious? The neural and behavioral impact of price primacy on decision making. *J. Mark. Res.* 52, 467–481. doi: 10.1509/jmr.13.0488

Kasai, T., Moriya, H., and Hirano, S. (2011). Are objects the same as groups? ERP correlates of spatial Attentional guidance by irrelevant feature similarity. *Brain Res.* 1399, 49–58. doi: 10.1016/j.brainres.2011.05.016

Khan, S., Fazili, A. I., and Bashir, I. (2020). Counterfeit luxury consumption: a review and research agenda. *J. Consum. Behav* 20, 337–367. Early Access: September 2020. doi: 10.1002/cb.1868

Leek, E. C., Roberts, M., Oliver, Z. J., Cristino, F., and Pegna, A. J. (2016). Early differential sensitivity of evoked-potentials to local and global shape during the perception of three-dimensional objects. *Neuropsychologia* 89, 495–509. doi: 10.1016/j.neuropsychologia.2016.07.006

Li, J., Guo, F., Xu, J., and Yu, Z. (2022). What influences consumers' intention to purchase innovative products: evidence from China. *Front. Psychol.* 13:838244. doi: 10.3389/fpsyg.2022.838244

Luck, S. J., and Kappenman, E. S. (2012). *The Oxford Handbook of Event-Related Potential Components*, Oxford New York, Oxford University Press.

Meyerding, S. G. H., and Mehlhose, C. M. (2020). Can Neuromarketing add value to the traditional marketing research? An exemplary experiment with functional near-infrared spectroscopy (fNIRS). *J. Bus. Res.* 107, 172–185. doi: 10.1016/j.jbusres.2018.10.052

Miller, M. W., Rietschel, J. C., Mcdonald, C. G., and Hatfield, B. D. (2011). A novel approach to the physiological measurement of mental workload. *Int. J. Psychophysiol.* 80, 75–78. doi: 10.1016/j.ijpsycho.2011.02.003

Nieuwenhuis, S., Yeung, N., and Cohen, J. D. (2004). Stimulus modality, perceptual overlap, and the Go/No-Go N2. *Psychophysiology* 41, 157–160. doi: 10.1046/j.1469-8986.2003.00128.x

Olteanu, M. D. B. (2015). Neuroethics and responsibility in conducting neuromarketing research. *Neuroethics* 8, 191–202. doi: 10.1007/s12152-014-9227-y

Pandey, A. K., Kamarajan, C., Tang, Y., Chorlian, D. B., Roopesh, B. N., Manz, N., et al. (2011). Neurocognitive deficits in male alcoholics: an ERP/sLORETA analysis of the N2 component in an equal probability Go/NoGo task. *Biol. Psychol.* 89, 170–182. doi: 10.1016/j.biopsycho.2011.10.009

Pawel, T., Katarzyna, J., Artur, M., and Anna, N. (2011). How multiple repetitions influence the processing of self-, famous and unknown names and faces: an ERP study. *Int. J. Psychophysiol.* 79, 219–230. doi: 10.1016/j.ijpsycho.2010.10.010

Pfefferbaum, A., Ford, J. M., Weller, B. J., and Skopell, B. (1985). Erps to response production and inhibition. *Electroencephalogr. Clin. Neurophysiol.* 60, 423–434. doi: 10.1016/0013-4694(85)91017-X

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clin. Neurophysiol.* 118, 2128–2148. doi: 10.1016/j.clinph.2007.04.019

Polich, J., and Comerchero, M. D. (2003). P3a from visual stimuli: typicality, task, and topography. *Brain Topogr.* 15, 141–152. doi: 10.1023/A:1022637732495

Polich, J., and Corey-Bloom, J. (2005). Alzheimers disease and P300: review and evaluation of task and modality. *Curr. Alzheimer Res.* 2, 515–525. doi: 10.2174/156720505774932214

Riquelme, I. P., Roman, S., and Iacobucci, D. (2016). Consumers' perceptions of online and offline retailer deception: a moderated mediation analysis. *J. Interact. Mark.* 35, 16–26. doi: 10.1016/j.intmar.2016.01.002

Salil, H. P., and Pierre, N. A. (2005). Characterization of N200 and P300: selected studies of the event-related potential. *Int. J. Med. Sci.* 2, 147–154. doi: 10.7150/ijms.2.147

Schweinberger, S. R., Pickering, E. C., Jentzsch, I., Burton, A. M., and Kaufmann, J. M. (2002). Event-related brain potential evidence for a response of inferior temporal cortex to familiar face repetitions. *Cogn. Brain Res.* 14, 398–409. doi: 10.1016/S0926-6410(02)00142-8

Shang, Q., Huang, Y., and Ma, Q. (2016). Hazard levels of warning signal words modulate the inhibition of return effect: evidence from the event-related potential P300. *Exp. Brain Res.* 234:1785. doi: 10.1007/s00221-016-4619-3

Sharad, A., and Tanusree, D. (2015). Neuromarketing and consumer neuroscience: current understanding and the way forward. *Decision* 42, 457–462. doi: 10.1007/s40622-015-0113-1

Singh, S. M., and Basu, D. (2009). The P300 event-related potential and its possible role as an endophenotype for studying substance use disorders: a review. *Addict. Biol.* 14, 298–309. doi: 10.1111/j.1369-1600.2008.00124.x

Smith, J. L., Johnstone, S. J., and Barry, R. J. (2007). Response priming in the Go/NoGo task: the N2 reflects neither inhibition nor conflict. *Clin. Neurophysiol.* 118, 343–355. doi: 10.1016/j.clinph.2006.09.027

Smith, J. L., Smith, E. A., Provost, A. L., and Heathcote, A. (2009). Sequence effects support the conflict theory of N2 and P3 in the Go/NoGo task. *Int. J. Psychophysiol.* 75, 217–226. doi: 10.1016/j.ijpsycho.2009.11.002

Sohn, S. (2017). Consumer processing of mobile online stores: sources and effects of processing fluency. *J. Retail. Consum. Serv.* 36, 137–147. doi: 10.1016/j.jretconser.2017.01.008

Solnais, C., Andreu, J., Sánchez-Fernández, J., and Andréu-Abela, J. (2013). The contribution of neuroscience to consumer research: a conceptual framework and empirical review. *J. Econ. Psychol.* 36, 68–81. doi: 10.6084/M9.FIGSHARE.1504027

Somervuori, O., and Ravaja, N. (2013). Purchase behavior and psychophysiological responses to different price levels. *Psychol. Mark.* 30, 479–489. doi: 10.1002/mar.20621

Stefano, C., and Noriaki, M. (2019). Competition between offline and online retailers with heterogeneous customers. *Rev. Ind. Organ.* 10, 1–18. doi: 10.1007/s11151-019-09734-1

Stewart, N., Reimers, S., and Harris, A. J. L. (2015). On the origin of utility, weighting, and discounting functions: how they get their shapes and how to change their shapes. *Manag. Sci.* 61, 687–705. doi: 10.1287/mnsc.2013.1853

Susana, C.-F., Mónica, L., and Fernando, D. (2014). Effects of amnestic mild cognitive impairment on N2 and P3 Go/NoGo ERP components. *J. Alzheimers Dis.* 38, 295–306. doi: 10.3233/JAD-130677

Thaler, R. (2008). Mental accounting and consumer choice. *Mark. Sci.* 4, 199–214. doi: 10.1287/mksc.1070.0330

Voorveld, H. A. M., Smit, E. G., Neijens, P. C., and Bronne, A. E. (2016). Consumers' cross-channel use in online and offline purchases. *J. Advert. Res.* 56, 385–400. doi: 10.2501/JAR-2016-044

Wang, W., and Li, F. (2020). What determines online transaction Price dispersion? Evidence from the largest online platform in China. *Electron. Commer. Res. Appl.* 42:100968. doi: 10.1016/j.elerap.2020.100968

Wiese, H., Altmann, C. S., and Schweinberger, S. R. (2014). Effects of attractiveness on face memory separated from distinctiveness: evidence from event-related brain potentials. *Neuropsychologia* 56, 26–36. doi: 10.1016/j.neuropsychologia.2013.12.023

Wiese, H., and Schweinberger, S. R. (2011). Accessing semantic person knowledge: temporal dynamics of nonstrategic categorical and associative priming. *J. Cogn. Neurosci.* 23, 447–459. doi: 10.1162/jocn.2010.21432

Woldorff, M. G., Fox, P. T., Matzke, M., Lancaster, J. L., Veeraswamy, S., Zamarripa, F., et al. (1997). Retinotopic organization of early visual spatial attention effects as revealed by pet and ERPs. *Hum. Brain Mapp.* 5, 280–286. doi: 10.1002/(SICI)1097-0193(1997)5:4<280::AID-HBM13>3.0.CO;2-I

Wu, K., Vassileva, J., Noorian, Z., and Zhao, Y. (2015). How do you feel when you see a list of prices? The interplay among price dispersion, perceived risk and initial trust in Chinese C2C market. *J. Retail. Consum. Serv.* 25, 36–46. doi: 10.1016/j.jretconser.2015.03.007

Zhu, Z., Jin, Y., Su, Y., Jia, K., Lin, C.-L., and Liu, X. (2022). Bibliometric-based evaluation of the neuromarketing research trend: 2010-2021. *Front. Psychol.* 13:872468. doi: 10.3389/fpsyg.2022.872468

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Neuroaesthetic exploration on the cognitive processing behind repeating graphics

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Repeating graphics are common research objects in modern design education. However, we do not exactly know the attentional processes underlying graphic artifacts consisting of repeating rhythms. In this experiment, the event-related potential, a neuroscientific measure, was used to study the neural correlates of repeating graphics within graded orderliness. We simulated the competitive identification process of people recognizing artifacts with graded repeating rhythms from a scattered natural environment with the oddball paradigm. In the earlier attentional processing related to the P2 component around the Fz electrode within the 150–250 ms range, a middle-grade repeating rhythm (Target 1) did not show a difference from a high-grade repeating rhythm (Target 2). However, in the later cognitive processes related to the P3b component around the Pz electrode within the 300–450 ms range, Target 1 had longer peak latency than Target 2, based on similar waveforms. Thus, we may suppose that the arrangement of the repeating graphics did not influence the earlier attentional processing but affected the later cognitive part, such as the categorization task in the oddball paradigm. Furthermore, as evidenced by the standard deviation wave across the trials, we suggest that the growing standard deviation value might represent the gradual loss of attentional focus to the task after the stimulus onset and that the zero-growth level may represent similar brain activity between trials.

KEYWORDS

event-related potentials, neuroaesthetics, perception, visual attention, graphic design

Introduction

Repeating graphics are ordered repetitions of similar graphics with aesthetic features. The use of repeating graphics is an essential modern design education method (Lupton and Phillips, 2008; Arntson, 2011). Repeating graphics, such as in Mondrian's masterpieces and others, are generally used in the education of university students majoring in architecture and design (Kılıçaslan and Kuloglu, 2015). Moreover, repeating graphics are one of the essential methods for modern architecture and industrial product design, including the outstanding works from Zaha Hadid Architecture Studio (Sonderegger and Sauer, 2015; Whybrow, 2016; Bhooshan, 2017; El-Darwish, 2019). Repeating graphics are the basic patterns with cultural features used in graphic design (Cleveland, 2010; Quispel and Maes, 2014).

Until now, many studies about design education have focused on the design process and exploratory narrative processes (Ulusoy, 1999; Lee, 2009; Stones and Cassidy, 2010; Nicholas and Oak, 2020). Some researchers, such as Alexiou et al. (2009), have tried to combine the techniques from neuroscience and design to explore the neural correlates of participants' design processes and feelings induced by designed products (Alexiou et al., 2009; Goucher-Lambert et al., 2019; Milovanovic et al., 2021). This study is a new attempt to explore the neural cognitive processes elicited by repeating graphics used in the design field. The measures of event-related potential (ERP) and event-related oscillation (ERO) from cognitive neuroscience were utilized for this exploration.

Aesthetics and repeating graphics

Aesthetics as a discipline studies the aesthetic activities of people in the world of intentions and the variable levels of their effect on our daily emotions and experiences (Wassiliwizky and Menninghaus, 2021). At first, research on aesthetics was about fundamental psychology but it was not accepted as a mainstream branch of study until the appearance of neuroscience (Fechner, 1876; Zajonc, 1968; Berlyne, 1973). Neuroaesthetics, which adopts the research methods of neuroscience, was proposed by the French neurobiologist Semir Zeki and others (Kawabata and Zeki, 2004; Freedberg and Gallese, 2007; Chatterjee and Vartanian, 2016; Pearce et al., 2016).

Repeating graphics are seen widely in art and design, with many aesthetic features. Appealing modern paintings such as Piet Mondrian's Composition are constructed by repeating graphics (Kuspit et al., 1993; Deicher, 1999; Locher et al., 2005). **Figure 1** shows the architecture and product design of Alvar Aalto (Finland, 1898–1976). The architecture of the University of Jyväskylä, as illustrated in **Figure 1A** (Alvar Aalto, 1951–1971), and the architecture of Paimio Sanatorium in **Figure 1B** (Alvar Aalto, 1933a) have repeating windows to maintain good illumination. The chairs in **Figure 1C** (Alvar Aalto, 1933b) can be piled quickly based on the use of repeating graphics in their design.

Neuroscientific method

In neuroimaging methods, three parts of the electroencephalogram (EEG) method can be used in cognitive neuroscience. The first one uses spontaneous EEG recording, conducted without any accompanying external stimulus. The second is recording long-term natural stimuli, such as listening to music or watching sequential video images (Cong et al., 2013; Rogenmoser et al., 2016). The last is event-related potential (ERP), elicited by controlled stimuli (Handy, 2005; Luck, 2014). Compared to the two other EEG measures, the ERP signal-acquiring method enables researchers to study the cognitive process of brain-related features in specific categories. For the above reasons, ERP is the most suitable method for investigating brain processes induced by repeating graphics and other visual patterns. Moreover, the oddball paradigm is a typical way to record the ERP signal from the target stimulus (Polich, 2012). In the oddball paradigm, participants view stimuli in random sequences, consisting of about 80% standard stimuli and 20% target or deviation stimuli. In the experiment, participants press a button as quickly as possible when the target stimulus appears and do nothing for the appearance of standard or deviation stimuli. Every stimulus is presented on the screen for a short time, and a blank screen appears after the trigger in the interface (Demiralp et al., 2001; Moore et al., 2019; Teixeira et al., 2020; Sanada et al., 2021).

This study used simple stimuli with basic patterns and the ERP method in the oddball paradigm. It explored the primary neural correlates of repeating graphics in graded orderliness, such as their characteristics in drawing attention and the categorization procedure when the graphics were maintained in the working memory. Moreover, based on the superficial appearance of the stimuli, this study possibly correlated more with the earlier ERP components in cognitive processing, such as P2 and P300 (P3b). The P2 component is a positive ERP component and can be found approximately 200 ms after the appearance of a stimulus in the anterior and central parts of the brain (Luck and Hillyard, 1994). The P300 (P3b) component is the most studied endogenous component in the ERP family, and it has been found in a long and unstable time window of approximately 300 ms (Squires K. C. et al., 1975).

Related objects for the brain research

In the oddball paradigm, there will be a significant P2 component, and it will also appear only when the stimulus is simple (Luck and Hillyard, 1994). One essential feature of

FIGURE 1
(A) University of Jyväskylä (Alvar Aalto, 1951–1971); **(B)** Paimio Sanatorium (Alvar Aalto, 1933a); **(C)** Model 60 stacking stool (Alvar Aalto, 1933b).

the P2 component is that the P2 effect is enhanced when the target stimulus is infrequent and task-related. Regarding the perception features of the P2 component, it has been observed as an index that reflects the attention and discrimination process (Conley et al., 1999). It has been reported that the amplitude of P2 becomes larger if the stimulus is associated with more interest and attention (Eason, 1981; Mangun et al., 1986; Shedden and Nordgaard, 2001). For instance, Omoto et al. (2010) observed that the stimulus with a concave/convex feature motivated a larger P2 amplitude than a stimulus in a flat type. Stahl et al. (2008) observed that participants' P2 response intensity was larger for own-race faces than seeing an other-race face. Participants with more experience communicating with other-race people did not show a difference in the amplitude of P2 between the two kinds of stimuli. However, the attention level for a stimulus should not be confused with the cognitive workload. Studies have found that the P2 amplitude decreased with the increased cognitive workload in a single-task paradigm (Allison and Polich, 2008; Deeny et al., 2014; Horat et al., 2016; Ghani et al., 2020). It meant that a complex stimulus might lead to decreased P2 amplitude compared to a simpler one. Another perception characteristic of the P2 component is its response to a repeated stimulus. Freunberger et al. (2007) designed a visual paradigm to observe the P2 signal feature based on two kinds of stimuli and found that P2 had a larger amplitude if the pair of stimuli were in different categories when they were shown in sequence. Other studies have observed the same kind of phenomenon in both visual and auditory fields (Wiggs and Martin, 1998; Rossell et al., 2003; Gruber and Muller, 2005). In addition, later research reported that facial images led to suppression in the P2 component when the face (stimulus) was of the same race as the participants' (Sheng et al., 2016), and it supported the perception of repetition suppression. It was proposed that the repetition-related feature of P2 is an index that reflects long-term experience with prototypical features of the stimulus (i.e., stimulus features that appear more frequently in daily life).

Beyond the attention feature, P2 has been related to the emotional factors of a stimulus. The visual P2 component has been studied extensively in the area of lexicological psychology. Emotional words can modulate some kinds of ERP components in the earlier time window, such as P2 (Begleiter and Platz, 1969; Schapkin et al., 2000; Herbert et al., 2006). For instance, Kanske and Kotz (2007) found that the stimulus of a word associated with a positive emotion motivated a larger P2 amplitude than a neutral stimulus in a decision-making task. Moreover, similar studies have observed the same phenomenon (Kissler et al., 2006; Herbert et al., 2008; Schacht and Sommer, 2009).

The P300 (P3b) component is an endogenous component in ERP and is found in an unstable time window of approximately 300 ms. Squires N. K. et al. (1975) observed a component called the P3a component at the peak point around the frontal lobe and another one called P3b around the parietal lobe. Unpredictable and infrequent stimuli induce both of these components. However, P3b appears only when the stimulus is task-related, and P300 is usually used to refer to this P3b component. For instance, Kramer et al. (1995) observed that a task-irrelevant auditory stimulus did not generate the P300 (P3b) component. In addition, Miller et al. (2011) found that the P300 component would be more significant for novel stimuli, which grabs more attention than repetitive stimuli. This kind of feature of P300 was also reported by Dyke et al. (2015) in another study. Overall, P300 can be regarded as a measure of the cognitive distribution of attention.

Another exciting feature of P300 is that it has a smaller amplitude if a categorization task becomes more challenging. It has been reported that the amplitude of P300 decreases as the workload increases in an identity task (Goodin et al., 1983; Allison and Polich, 2008). Later, many studies have observed that P3 is related to higher-level cognitive processes such as categorizing stimuli and updating working memory. It has been reported that the latency of P300 represented the workload level and the categorization process. The stimulus was observed to have longer latency if it induced a higher workload. Participants also spent more time on the categorization task in this situation (Combs and Polich, 2006; Horat et al., 2016). The difference in the P300 (P3b) component latency between stimuli in the oddball paradigm meant completing the categorization task.

The stimuli were categorized with different labels and stored in memory (Kutas et al., 1977). In addition, the latency of P300 increased with the participants' age (Gaal et al., 2007).

Additionally, P300 is related to the emotional features of the stimulus. In earlier studies, many researchers have observed that the stimulus with more emotional features motivated a larger amplitude of P300 than a neutral one. Radilova (1982) reported that unpleasant visual stimuli produced a larger P300 amplitude than stimuli without an emotional response. Later, two other studies from Radilova et al. (1983), Radilova (1989) showed that sexual images motivated larger P300 amplitude than landscapes, flowers, and other stimuli which were not erotic. A survey from Muñoz and Martin-Loeches (2015) reported that the P300 increased when participants saw a beautiful stimulus compared to a neutral or negative stimulus. In addition, this phenomenon was primarily found around the frontal distribution.

As for the brain waves in the oddball paradigm and this research, the delta and theta waves are the most relevant. Delta waves are from 0 to 3 Hz (below 4 Hz), and theta waves are from 4 to 7 Hz. These two types of brain waves can be observed by EEG (Brigo, 2011), and it has been reported that delta and theta wave activity is related to the oddball paradigm. It has been reported that the theta waves respond more quickly than the delta waves in the P300 component. The theta waves were around the anterior lobe, while the delta waves were around the posterior lobe. Compared with the theta waves, the delta waves have been observed to be the most pronounced component correlated with the P300 wave (Demiralp et al., 1999). Moreover, the theta and delta waves are enhanced by presenting novel stimuli in the oddball paradigm, especially for the P300 amplitude. Many studies have observed that the anterior theta waves are related to preliminary cognitive processing and that posterior delta waves are relevant for later cognitive processing (Başar-Eroglu et al., 1992; Demiralp et al., 2001). For the type of stimulus, it has been observed that the theta and delta waves were enhanced for old (familiar) words compared to new (unfamiliar) words (Klimesch et al., 2000).

Study overview

The current study simulates a procedure where people recognize graphic artifacts within different grades of repeating rhythm from scattered environments. This study was conducted with simple stimuli in graded orderliness in order to study the neural correlates of repeating graphics. The study was conducted using the event-related potential (ERP) measures and the event-related oscillation (ERO) in the oddball paradigm. The results of earlier components from ERP and ERO indicate significant differences between scattered graphics (as standard stimulus) and repeating graphics in different grades of orderliness (Target1 and Target2). The differences can be related to attention, short-term memory, long-term memory, or the categorization task.

Materials and methods

Participants

Twenty participants (9 female,11 male, mean age ± SD: 22.45 ± 2.41 years) were recruited by an intent questionnaire for a brain signal experiment at the Dalian University of Technology. The participants were right-handed based on the Edinburgh inventory (Oldfield, 1971) and had normal or corrected-to-normal vision. None of the participants had neurological disorders or used psychoactive medications. All participants were provided with informed consent in accordance with the Declaration of Helsinki (BMJ, 1991; 302:1194).

Stimuli

The experiment consisted of three stimuli: standard stimulus, Target 1, and Target 2. The scattered graphic worked as the standard stimulus in the experiment. The graphic in a middle-grade repeating rhythm worked as Target 1, and the graphic in a high-grade repeating rhythm worked as Target 2 (see **Figure 2**). There were six blocks in the whole experiment, and the stimuli in every block were constructed by a specific basic pattern, including circles, triangles, squares, pentagons, hexagons, or heptagons. Taking block 1 as a reference, the standard stimulus was composed of scattered circles with the lowest repeating rhythm. Target 1 was composed of regular circles within the middle-grade repeating rhythm. Target 2 was composed of circles on a straight line, within the high-grade repeating orderliness. Every picture from the stimuli consisted of a black background and white graphics. The graphics in the experiment were in 1182 × 678 pixels with 300 dpi and 32-bit color. The details of the stimuli are shown in **Figure 2**.

Procedure

The ERP experiment was operated by an EEG recording device produced by the ANT Neuro company. The experiment followed the basic construction of the oddball paradigm, with a standard stimulus and two types of target stimuli (Demiralp et al., 2001). The experimental procedures were programmed and behavioral data such as response time (RT) was recorded by E-PRIME 3.0 (MacWhinney et al., 2001). Details about the procedures of the experiment are represented in **Figure 3**. The investigation was separated into six blocks. The standard stimulus, Target 1, and Target 2 blocks were composed of basic patterns with increasing vertexes, including circles, triangles, squares, pentagons, hexagons, and heptagons. Each block was run in two equal parts with a break in between to give participants a more relaxed experimental experience.

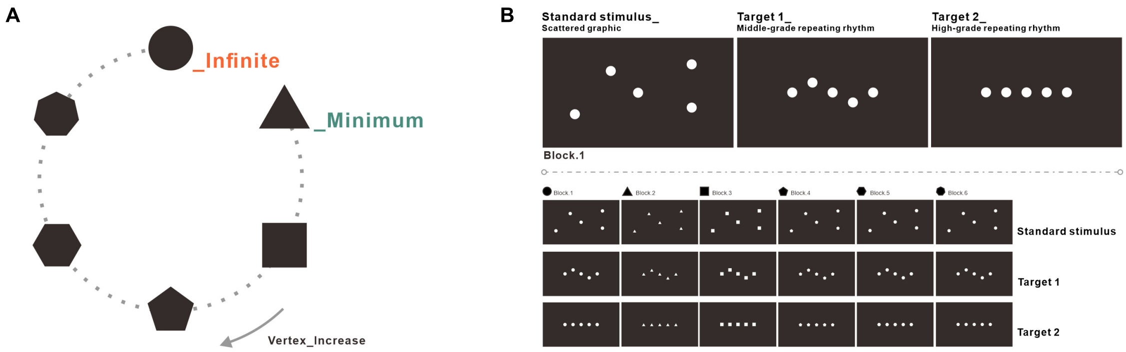

FIGURE 2
Stimuli used in the experiment. **(A)** The stimuli were composed of basic patterns with increasing vertexes, including circles, triangles, squares, pentagons, hexagons, or heptagons. **(B)** The standard stimulus was composed of scattered graphics with the lowest orderliness level. Target 1 was composed of the regular graphic within the middle-grade repeating rhythm. Target 2 was composed of a perfectly arranged graphic within the high-grade repeating rhythm.

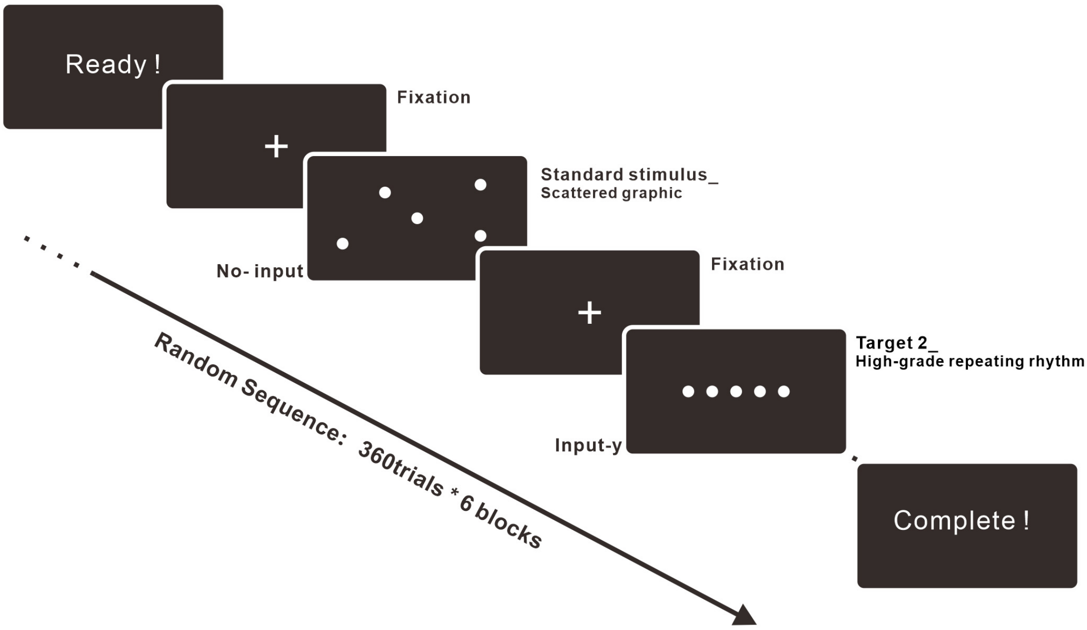

FIGURE 3
Experimental procedure. The experiment included six blocks. Each block consisted of 360 trials, and every trial was composed of fixation (600 ms), stimulus (1500 ms), and ISI (500 ms). The stimulus could be the standard stimulus (70%), Target 1 (15%), or Target 2 (15%). The trials were run in random sequence.

This study was designed to be an explorative but in-depth study of people's neural responses to high-similarity stimuli. Thus, we designed an extended experiment with more trial numbers than other standard ERP research (Kappenman et al., 2021). For the experiment trials, there were 360 trials in each block, 2,160 trials for each participant, and 43,200 trials were collected in total. The standard stimulus accounted for 70% of every block for the experiment. Target 1 within the middle-grade repeating rhythm accounted for 15% and Target 2 within the high-grade repeating rhythm accounted for 15% of the stimuli. At the beginning of each block, there was an instruction to guide participants' actions. Participants were recruited from the Dalian University of Technology in China, and therefore the words on the instruction were in Chinese, based on the participant's native language. When the participants were ready, they pressed "SPACE" to start the block. Then, the trials related to the standard stimulus, Target 1 and Target 2, were displayed on the screen in a random sequence. Each trial consisted of three parts. The first part was the fixation, and it was presented for 600 ms. The next one was the stimulus. If the stimulus was the standard stimulus, participants were told to do nothing and wait for 1,500 ms. If the stimulus was Target 1 or Target 2, the screen was displayed again for 1,500 ms, but they were told to input "y" by the keyboard. The last part of the trial was the interstimulus interval (ISI), which lasted for 500 ms. After half a block or an entire block, there was a waiting page for a break, the length of which was based on participants' preferences. After the break, they input "SPACE" to enter the next part.

Data recording and processing

Electroencephalogram data were recorded with a 1,000 Hz sampling rate with a 64-lead EEG acquisition equipment produced by the ANT Neuro company and resampled to 256 Hz for further processing. The specific electrodes were Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C2, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, P4, P8, Pz, POz, O1, O2, AF7, AF3, AF4, AF8, F5, F1, F2, F6, FC3, FCz, FC4, C5, C1, C2, C6, CP3, CP4, P5, P1, P2, P6, PO5, PO3, PO4, PO6, FT7, FT8, TP7, TP8, PO7, PO8, Oz, M1, M2, and CPz (online reference electrode). The EEG data were pre-processed by EEGLAB 2020 (Delorme and Makeig, 2004). The offline EEG data were re-referenced to the averages of the left mastoid (M1) and right mastoid (M2). Data from the additional EOG electrode were removed due to its lower correlation with this ERP study. Then, the line noise was removed by a notch filter of 49—51 Hz. In the next step, the wave band of data below 0.1 Hz was removed by a high pass filter, and the wave beyond 20 Hz was removed by a low pass filter after that (Lopez-Calderon and Luck, 2014; Widmann et al., 2015; Kappenman et al., 2021). Eye movement artifacts, electromyographic signal, and electro-cardio signal were rejected by the independent component analysis (ICA) (Jung et al., 2000a,b; Mognon et al., 2011).

The continuous EEG data were segmented into epochs (trials) based on the stimulus variety from −200 ms before the stimulus onset to 800 ms after the stimulus onset. The baseline correction was achieved by subtracting the mean amplitude of the baseline (from −200 to 0 ms) period from all time points. Bad trials were rejected by extreme value, and 78% of trials were reserved for each participant (about 1180 trials for the standard stimulus, 254 trials for Target 1 and Target 2). To obtain an equal trial number for the standard stimulus, Target 1, and Target 2, 254 trials from the standard stimulus were randomly selected from 1,180 trials by the "randperm" function in Matlab.

In the time domain analysis, we organized the data set based on trial numbers rather than participants due to a large number of trials per participant. By the average method in the ERP (in the time domain analysis), the final rendering wave did not show a difference in whether the data were averaged from trials directly to the grand average waveform, or first averaged from trials to participants and then to the grand average waveform. However, the ERP waveform organized into trials may express the statistical result more reliably due to the great number of trials. Thus, we collected the data into the fourth-order tensor. The index name of the tensor was channel*time*stimuli*trials, and the size was 61*256*3*5,080. In detail, each participant (20) had 254 trials for each stimulus. Afterward, the ERP waveforms of epochs were averaged based on the standard stimulus, Target 1, and Target 2, from 5,080 trials (Lopez-Calderon and Luck, 2014).

In the time-frequency domain analysis, we first organized the data by averaging the data into participants, as the conventional method. It should be noted that the time-frequency domain analysis could not be organized into trials because the power spectrum would be amplified more than ten times if the unstable single trial was processed by frequency transformation. Therefore, the statistical degrees of freedom (from the paired *t*-test) differed for the time domain analysis and the time-frequency domain analysis. The data became the fourth-order tensor, with the index name of channel*time*stimuli*participants, and the size was 61*256*3*20. In the following part, we computed the time-frequency representations (TFRs) of data averaged into participants based on the complex Morlet continuous wavelet transform (Tallon-Baudry and Bertrand, 1999; Roach and Mathalon, 2008; Cohen, 2014; Herrmann et al., 2014). Bandwidth and center frequency were set to define a complex Morlet used for the mother wavelet. The energies in the different frequency bands were obtained by calculating the square of convolutions between ERP signals, the shifted and scaled mother wavelet (Tallon-Baudry and Bertrand, 1999; Herrmann et al., 2005; Gross, 2014; Zhang et al., 2020b). The specific calculation was based on the toolbox of the ERP_ERO, and it can be downloaded from: http://zhangg.net/publications/ (Zhang et al., 2020a).

Results

Behavioral results

The participant's task was to ignore the standard stimulus in the experiment and to respond to Target 1 and Target 2 with the keyboard. Regarding the behavioral data, the statistic of response time (RT) was calculated in the ERP experiment from six blocks (circles, triangles, squares, pentagons, hexagons, heptagons) and the data were categorized into Target 1 and Target 2. To count all of the experiments' trials, the researchers constructed the RT data into a third-order tensor with the index name trial*block*stimuli.

This research used a within-subject one-way repeated measure analysis of variance (rm-ANOVA) to analyze the significant differences between blocks and the paired *t*-test to explore the difference between RT data separated by Target 1 and Target 2. Details about the response times (RT) are shown in **Figure 4**. For the data between blocks, there were no statistically significant results. Importantly, when we organized the RT into Target 1 and Target 2, the mean response time (RT) for Target 2 was shorter than the mean RT for Target 1, and the significance of the difference was supported by the paired *t*-test, $t(5{,}079) = 13.75$, $p < 0.001$***, Cohen's $d = 0.37$.

The time domain analysis and the time-frequency domain analysis

In the 150—250 ms time window, a significant P2 component was found at the peak point around the Fz electrode (in the frontal lobe) for all stimuli. In the 300—450 ms time window, a significant P300 (P3b) component around the Pz electrode (in the parietal lobe) was found for Target 1 and Target 2. The results are shown in **Figures 5A,B**.

The time domain analysis and the standard deviation analysis

The fourth dimension was averaged from the fourth-order tensor (channel*time*stimuli*trials, 61*256*3*5,080), and the time domain analysis results resulted. Paired *t*-tests were run between stimuli for the time domain analysis (see **Table 1**). Around 150—250 ms, the Fz electrode showed significant P2 components for all stimuli in the time domain analysis. Target 1 and Target 2 had higher signal amplitude than the standard stimulus, but there was no significant difference between Target 1 and Target 2. The ERP wave around the Fz electrode is shown in **Figure 5A**. After establishing an average from 150 to 250 ms around the Fz electrode, the topographies are shown in **Figure 5C**, and the statistical results are shown in **Table 1**. Around the time window from 300 to 450 ms, there were significant P300 (P3b) components around the Pz electrode, induced by Target 1 and Target 2, and the ERP waveform around the Pz electrode is shown in **Figure 5B**. Likewise, the topographies averaged from 300 to 450 ms around the Pz electrode are shown in **Figure 5C**, and the statistical results are shown in **Table 1**.

Furthermore, we relied on the data for the time domain analysis to calculate the dynamic standard deviation waveform between channels and stimuli. For illustration, under one channel and stimulus, the standard deviation value from a specific time point was calculated by the amplitude from 5,080 trials. The standard deviation value represented the degree of dispersion under a particular channel, time point, and stimulus. Details are shown in **Figure 6**. Moreover, we calculated the dynamic 95% confidence interval waves based on the existing standard deviation waves. Due to the excellent trial number (5080 trials for every stimulus), the dynamic 95% confidence intervals were tight, and the widest was about $[\mu - 0.28, \mu + 0.28]$. **Figures 5A,B** show the dynamic 95% confidence intervals as shadowed areas.

Time-frequency domain analysis

Corresponding to the time domain analysis, we also observed a significant difference in the time-frequency domain analysis around the Fz electrode in the time window of 150—250 ms and the Pz electrode in the time window of 300—450 ms between stimuli. Paired *t*-tests were again calculated between the stimuli (see **Table 1**). For the time-frequency domain analysis, Target 1 and Target 2 showed prominent event-related oscillation (ERO) without significant power difference in the low-frequency range from 1 to 3 Hz around the Fz electrode in 150—250 ms. However, the standard stimulus did not show a high-level frequency response. In the 300—450 ms time window, all stimuli showed high energy features from 1 to 3 Hz. Target 1 and Target 2 significantly differed in their frequency response around the Pz electrode, but there was no difference between the standard stimulus and

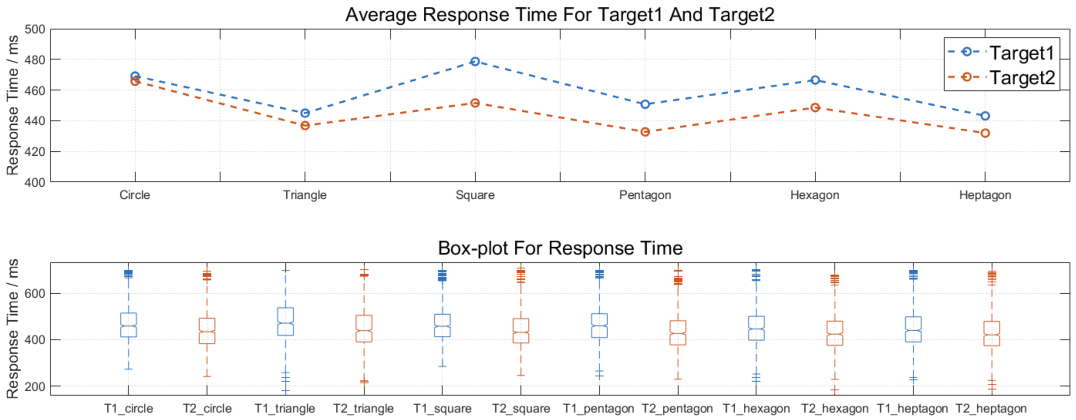

FIGURE 4
The behavioral results between blocks and within blocks. The mean response time (RT) for Target 2 was significantly shorter than the mean RT for Target 1, t (5079) = 13.75, ***$p < 0.001$, Cohen's $d = 0.37$.

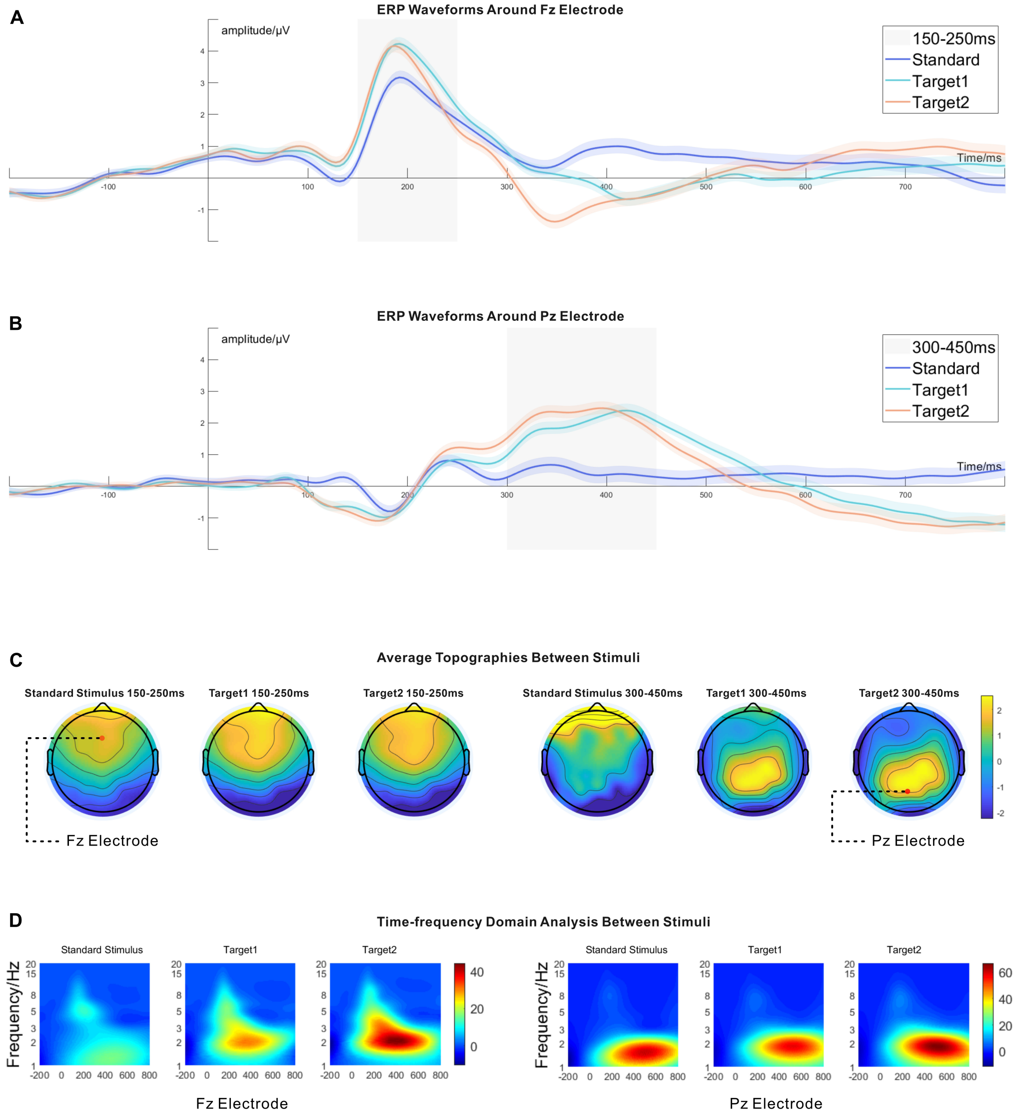

FIGURE 5
(A) The time domain analysis around the Fz electrode. There was no difference between Target 1 and Target 2 around the time window of 150–250 ms. The amplitudes of Target 1 and Target 2 were higher than the standard stimulus around 150–250 ms. The 95% CIs are shown as shadowed areas. **(B)** The time domain analysis around the Pz electrode. Likewise, no significant difference existed between Target 1 and Target 2 around the time window of 300–450 ms. Target 1 and Target 2 had higher amplitudes than the standard stimulus around the time window of 300–450 ms. The 95% CIs are shown as shadowed areas. **(C)** The topographies between stimuli around the time window of 150–250 ms and the time window of 300–450 ms. **(D)** The time-frequency domain analysis around the Fz electrode and the Pz electrode. Target 1 and Target 2 had higher power than the standard stimulus between 1 and 3 Hz, around the Fz electrode at 150–250 ms. However, there was no significant difference between Target 1 and Target 2 around the Fz electrode in 150–250 ms. Around the Pz electrode, only Target 1 and Target 2 had considerable differences at 300–450 ms. The statistical results are shown in **Table 1**.

Target 1 or between the standard stimulus and Target 2. The details are shown in Figure 5D, and the statistical results can be found in Table 1.

Discussion

The current study investigated the brain signal response from stimuli within a repeating rhythm, which are essential elements of paintings, graphic design, and architectural design. The stimuli used in this study were basic and straightforward in appearance. They were represented as components in artwork with an aesthetic appeal (e.g., Deicher, 1999; Locher et al., 2005; Kılıçaslan and Kuloglu, 2015). The experiment simulated the process in which people recognize artifacts with repeating graphics from the natural environment. The scattered graphic was set as the experiment's natural irregular graphic and a

TABLE 1 The paired *t*-test results for the time domain analysis and the time-frequency domain analysis.

Analysis type	Electrode time window	Matched pairs	Coupled difference					*t*	*Df*	Sig. (2 tails)	Cohen's *d*
			Mean	*SD*	S.E. mean	95% CI					
						Lower bound	Higher bound				
Time domain analysis (5080 trials)	Fz electrode_average from 150 to 250 ms	Standard-target1	−0.90	8.06	0.11	−1.12	−0.68	−7.96	5079	<0.001***	−0.22
		Standard-target2	−0.71	8.14	0.11	−0.93	−0.48	−6.17	5079	<0.001***	−0.17
		Target1-target2	0.19	7.96	0.11	−0.02	0.42	1.77	5079	0.071	
	Pz electrode_average from 300 to 450 ms	Standard-target1	−1.49	9.52	0.13	−1.75	−1.22	−11.13	5079	<0.001***	−0.31
		Standard-target2	−1.69	9.75	0.14	−1.96	−1.42	−12.35	5079	<0.001***	−0.34
		Target1-target2	−0.20	8.35	0.12	−0.43	0.03	−1.73	5079	0.076	
Time-frequency domain analysis (20 subjects)	Fz electrode_average from 150 to 250 ms and 1 to 3 Hz	Standard-target1	−5.93	10.05	2.24	−10.64	−1.23	−2.64	19	0.016*	−1.21
		Standard-target2	−8.57	10.21	2.28	−13.35	−3.80	−3.76	19	0.001**	−1.73
		Target1-target2	−2.64	5.88	1.32	−5.39	0.11	−2.01	19	0.059	
	Pz electrode_average from 300 to 450 ms and 1 to 3 Hz	Standard-target1	−0.68	39.00	8.72	−19.38	18.02	−0.08	19	0.940	
		Standard-target2	−3.52	40.09	8.96	−22.28	15.24	−0.39	19	0.699	
		Target1-target2	−2.83	4.27	0.96	−4.83	−0.83	−2.96	19	0.008**	−1.36

The average values are from 150 to 250 ms around the Fz electrode and 300 to 450 ms around the Pz electrode. *$p < 0.01$ and 0.05, **$p < 0.001$ and 0.01, and ***$p < 0.001$.

standard stimulus. Target 1 with a middle-grade repeating rhythm and Target 2 with a high-grade repeating rhythm needed to be recognized from scattered graphics with keyboard input. Moreover, it was a competitive recognition process between Target 1 and Target 2, because they all needed responses from participants. The study explored the neural correlates of the basic cognitive processes, focusing on attention grasping and other processes behind the perception of repeating graphics. The study intended to construct a foundation for future research that may set more complex art pieces composed of repeating graphics as the aesthetic objects in the experiment.

There were significant P2 components around the Fz electrode and the P300 (P3b) components were around the Pz electrode for the variable stimuli. These results were similar to earlier studies on P2 and P300 (P3b) with related topographies. Target 1 and Target 2 had a larger amplitude for the P2 component around the Fz electrode at the time window of 150—250 ms than the standard stimulus. Meanwhile, Target 1 and Target 2 showed considerable P300 (P3b) components compared to the standard stimuli at the time window of 300—450 ms around the Pz electrode (Luck and Hillyard, 1994; Kramer et al., 1995). The time-frequency domain analysis showed that Target 1 and Target 2 induced higher energy than the standard stimulus at a 150—250 ms time window, supporting the P2 components observed in the same time window. In addition, the wave feature of the time-frequency domain analysis in this study corresponded with earlier research, in that delta (0—3 Hz) and theta (4—7 Hz) waves were related to the deviating stimuli (Target 1 and Target 2 here) in the oddball paradigm. Meanwhile, the time-frequency domain analysis showed earlier theta waves around the anterior lobe and later delta waves around the posterior lobe for the three stimuli, also corresponding to earlier research (Başar-Eroglu et al., 1992; Demiralp et al., 2001).

Earlier attention characteristics and later cognitive processes

Regarding earlier attentional processes around the time window of 150—250 ms, we observed that Target 1 and Target 2 showed a higher amplitude level of P2 than the standard stimulus, and that the P2 component amplitude between Target 1 and Target 2 was at the same level. Details are shown in **Figure 5A** and **Table 1**. These results are in line with earlier studies on the visual P2 component and its attention-related features (Wolach and Pratt, 2001; Lefebvre et al., 2005). As in the study of Luck and Hillyard (1994), the wave of the P2 component arose in the oddball paradigm for the infrequent stimuli. The P2 component seems only to appear when the stimulus is very simple (i.e., not complex in its appearance). The P2 component has been identified as an index to reflect an early discrimination process and the level of attention (Conley et al., 1999). Several studies have reported that the P2 amplitude becomes larger if the deviating stimulus grabs more attention from participants (Eason, 1981; Mangun et al., 1986; Shedden and Nordgaard, 2001). In our study, the higher P2 amplitude from Target 1 and Target 2 may be due to their low frequency of occurrence (15% both) in the oddball paradigm compared to the standard stimulus (70%).

Meanwhile, it was found that Target 1 and Target 2 showed no significant difference in the P2 component amplitude. The P2 component working as the earlier attention component is susceptible to the occurrence frequency in the oddball paradigm rather than the comparatively inconspicuous difference (same patterns in variable locations) between Target 1 and Target 2. In other words, the difference between Target 1 and Target 2 was insufficient to induce a considerable difference in the earlier visual attentional processing.

Moreover, several studies have reported that the amplitude of the P2 component decreases when the cognitive workload associated with a stimulus (i.e., its complexity) increases (Allison and Polich, 2008; Deeny et al., 2014; Horat et al., 2016; Ghani et al., 2020). Target 1 and Target 2 did not show considerable differences around the P2 component in this experiment. It further suggested that the difference in the arrangement between Target 1 and Target 2 did not have a statistical discrepancy in the earlier attention workload. Meanwhile, the complexity level and occurrence frequency are more devoted to the P2 component activation level, rather than merely the variable arrangement mode. Based on the above, we cautiously suggest that the aesthetic graphic pattern within the variable repeating arrangement may not significantly influence the viewer's earlier attentional processes.

When it comes to later ERP components, the prominent P3b (P300) component from Target 1 and Target 2 gradually appeared. The ERP component we observed was consistent with earlier studies in that the P3b component was induced by a task-related target stimulus in need of a response, whereas the P3a component is induced by deviant without the need for responses from participants (Squires N. K. et al., 1975; Snyder and Hillyard, 1976; Jeon and Polich, 2001; Miller et al., 2011; Dyke et al., 2015). In our study, the scattered graphic worked as the standard stimulus, whereas the Target 1 and Target 2 stimuli were infrequently appearing and required participants' responses. Both kinds of targets induced the P3b component around the Pz electrode by its task-related feature rather than the P3a component, which is irrelevant to the task and located around the Fz electrode.

For the time domain analysis results in the time window of 300—450 ms, we observed that the P3b components induced by Target 1 and Target 2 were significantly larger than the standard stimulus, and the average amplitude did not show a difference between Target 1 and Target 2. However, we observed that the P3b wave from the targets shared a similar wave appearance, but the waveform of Target 2 was a bit earlier than the waveform of Target 1, accompanied by different peak latency. To study the sustaining tracking phenomenon between Target 1 and Target 2, we calculated the dynamic 95% confidence interval for Target 1 and Target 2, shown as the shadowed areas in **Figure 5B**. The specific calculation method is described in the section "The time domain analysis and the standard deviation analysis," and the standard deviation wave is shown in **Figure 6**. In **Figure 5B**, we can see the amplitude of Target 1 is smaller than that of Target 2 without the confidence interval overlap in the time window of 300—380 ms. The amplitude of Target 1 is then again larger than Target 2 in the time window of 420—500 ms. The potential correlation between the categorization task and the P3b may explain the phenomenon.

Earlier P300 (P3b) studies have reported that the peak point latency of P300 can represent the process of categorizing tasks of stimulus in long-term memory and attention allocation (Combs and Polich, 2006). Moreover, it has been widely accepted that the latency of P300 in the oddball paradigm is related to the completion of the categorization task and that the P300 (P3b) is the most famous endogenous component associated with the updating of working memory (Kutas et al., 1977; Combs and Polich, 2006; Horat et al., 2016). Based on the information mentioned, we supposed that participants spent more time on the classification task of the Target 1 stimulus with attention accompanied due to its longer P3b peak latency and persistently following the wave of Target 2. The behavioral data in **Figure 4** show similar results: participants had a longer response time for Target 1 than for Target 2. Further, Target 1 showed lower energy power than Target 2 in the 1—3 Hz in the time-frequency domain analysis, which may be due to the same phenomenon.

For the experiment, we tried to simulate the cognitive processes of people recognizing artifacts from the scattered environment. Based on the results related to the P2 components around the Fz electrode and earlier research, we suggest that the different grades of arrangement in a repeating rhythm do not affect the earlier attention levels. However, the arrangement mode and the ambiguity level between the standard stimulus and the target stimulus in the oddball paradigm may influence the time required for the categorization task by later cognitive processes.

The standard deviation wave and its tendency

As mentioned above, we calculated the dynamic standard deviation wave from the data based on trials, as shown in **Figure 6**. The original data set was organized as a fourth-order tensor, and the index name is channel*time*stimuli*trials (61*256*3*5080). By computing the 95% confidence interval, we obtained the dynamic confidence interval for the time domain analysis and depicted it as a shadowed area, as shown in **Figures 5A,B**. The confidence interval area may support the analysis results and assist in distinguishing the actual difference between waves in the time domain analysis. Compared to the related method of standard error measurement (Kappenman et al., 2021), the confidence interval area may have a high-level confidence coefficient and thereby improve the accuracy of the data.

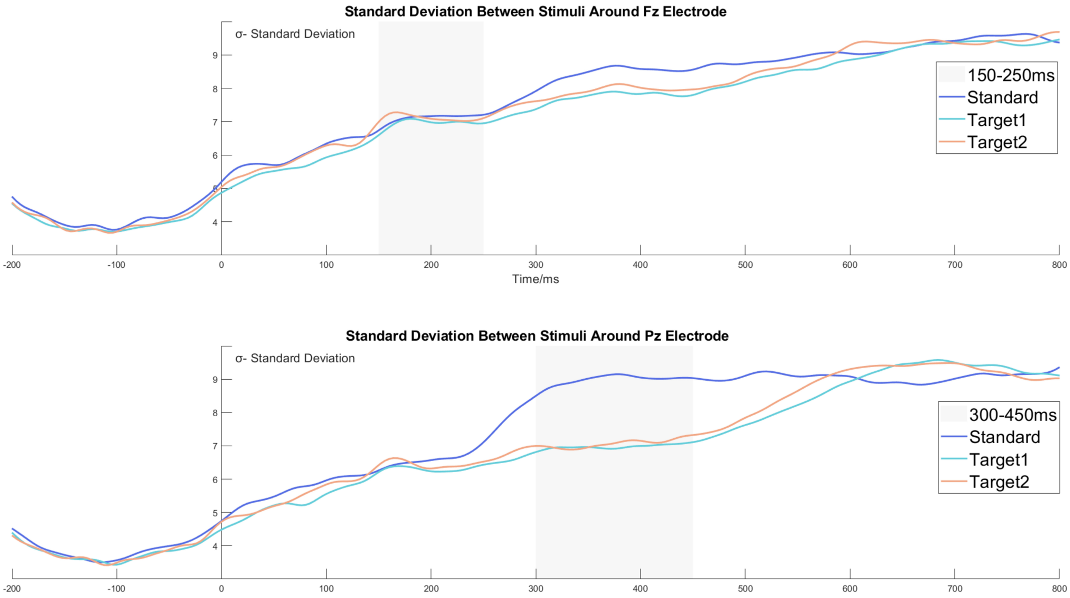

FIGURE 6
The standard deviation waves around the Fz and the Pz electrodes. The standard deviation value from a specific time point was calculated by the amplitude from 5080 trials. The standard deviation value represents the degree of dispersion under a particular channel, time point, and stimulus.

We observed an interesting phenomenon from the standard deviation wave. Due to the baseline correction procedure from −200 to 0 ms, we only discuss the time zone after stimulus onset. In **Figure 6**, we observe that the standard deviation value continued to increase after the appearance of the stimulus. The standard deviation value started around 5 and increased to 9 at 800 ms. The growing standard deviation value (σ) may represent the gradual loss of attentional focus in a task after the stimulus onset. Furthermore, we observed that σ keeps a stable zero-growth level for all stimuli around the Fz electrode at 150−250 ms, and that the σ keeps the zero-growth level for Target 1 and Target 2 around the Pz electrode at 300−450 ms. However, the σ from the standard stimulus grew in advance and maintained a higher value than Target 1 and Target 2 around the Pz electrode at 300−450 ms. The zero-growth level time window was highly correlated with the P2 and P3b time window, and we suppose it also reflected a specific brain activity. Thus, with caution, we put forward a hypothesis that the ERP components may be due to a similar level of amplitude related to the settled time window, and that it contributes to the zero-growth level time in the standard deviation wave. We doubt whether the constantly growing standard deviation value and zero-growth level around the time window of the ERP component are a result of the large number of trials collected in our experiment. Other evidence is still needed to provide further support for the suggested phenomenon.

Conclusion

To summarize, we tried to simulate the cognitive processes where people recognize graphic artifacts within different repeating grades from the scattered environment. In the earlier attentional processing related to the P2 component around the Fz electrode, a middle-grade repeating rhythm (Target 1) did not show a difference from a high-grade repeating rhythm (Target 2). By this evidence, we suggest that mere changes in the arrangement mode of the repeating rhythms do not affect the earlier attention features in oddball tasks. In the later cognitive processing related to the P3b component around the Pz electrode, Target 1 had a similar wave appearance to Target 2, but Target 1 had a longer peak latency than Target 2. It suggests that Target 1 needed a longer categorization time than Target 2, supported by the P3b component's features and the longer response time for Target 1 in the behavioral results. Thus, we suppose that the arrangement mode of repeating rhythms in stimulus may not show a significant difference in earlier attentional processes but can affect later cognitive processing, such as the categorization task in the oddball paradigm. Furthermore, by observing the dynamic standard deviation waveform across trials, we suggest that the growing standard deviation value may represent the gradual loss of attentional focus after the stimulus onset and that the zero-growth level may represent similar brain activity across the trials.

Repeating graphics is one of the essential pattern types in modern art and design. Simple types of repeating graphics are elements of many famous art pieces like Piet Mondrian's Composition. This study focused on stimuli with simple repeating graphics and their associated neural characteristics. We hope these findings may add helpful information for the research in the field of neuroaesthetics.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the School of Biomedical Engineering, Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology. The patients/participants provided their written informed consent to participate in this study.

Author contributions

YQ, LM, and FC contributed to the conception and design of the study. YQ, TK, and JS organized the database. YQ and TK performed the analysis and wrote sections of the manuscript. YQ wrote the first draft of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnins.2022.1025862/full#supplementary-material

References

Alexiou, K., Zamenopoulos, T., Johnson, J. H., and Gilbert, S. J. (2009). Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Des. Stud.* 30, 623–647. doi: 10.1016/j.destud.2009.05.002

Allison, B. Z., and Polich, J. (2008). Workload assessment of computer gaming using a single-stimulus event-related potential paradigm. *Biol. Psychol.* 77, 277–283. doi: 10.1016/j.biopsycho.2007.10.014

Alvar Aalto, (1933a). *Paimio Sanatorium [Architecture]*. Paimio: Paimio Sanatorium.

Alvar Aalto, (1933b). *Model 60 Stacking Stool [Product]*. New York, NY: Museum of Modern Art.

Alvar Aalto, (1951–1971). *Jyvaskyla University [Architecture]*. Jyvaskyla: Jyvaskyla University.

Arntson, A. E. (2011). *Graphic Design Basics*. Boston: Cengage Learning.

Başar-Eroglu, C., Başar, E., Demiralp, T., and Schürmann, M. (1992). P300-response: possible psychophysiological correlates in delta and theta frequency channels. a review. *Int. J. Psychophysiol.* 13, 161–179. doi: 10.1016/0167-8760(92)90055-G

Begleiter, H., and Platz, A. (1969). Cortical evoked potentials to semantic stimuli. *Psychophysiology* 6, 91–100. doi: 10.1111/j.1469-8986.1969.tb02887.x

Berlyne, D. E. (1973). Aesthetics and psychobiology. *J. Aesthet. Art Crit.* 31:553. doi: 10.2307/429334

Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. *Des. Stud.* 52, 115–143. doi: 10.1016/j.destud.2017.05.003

Brigo, F. (2011). Intermittent rhythmic delta activity patterns. *Epilepsy Behav.* 20, 254–256. doi: 10.1016/j.yebeh.2010.11.009

Chatterjee, A., and Vartanian, O. (2016). Neuroscience of aesthetics. *Ann. N.Y.Acad. Sci.* 1369, 172–194. doi: 10.1111/nyas.13035

Cleveland, P. (2010). Style based automated graphic layouts. *Des. Stud.* 31, 3–25. doi: 10.1016/j.destud.2009.06.003

Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*. Cambridge: MIT press. doi: 10.7551/mitpress/9609.001.0001

Combs, L. A., and Polich, J. (2006). P3a from auditory white noise stimuli. *Clin. Neurophysiol.* 117, 1106–1112. doi: 10.1016/j.clinph.2006.01.023

Cong, F., Alluri, V., Nandi, A. K., Toiviainen, P., Fa, R., Abu-Jamous, B., et al. (2013). Linking Brain Responses to Naturalistic Music through Analysis of Ongoing EEG and Stimulus Features. *IEEE Trans. Multimed.* 15, 1060–1069. doi: 10.1109/TMM.2013.2253452

Conley, E. M., Michalewski, H. J., and Starr, A. (1999). The N100 auditory cortical evoked potential indexes scanning of auditory short-term memory. *Clin. Neurophysiol.* 110, 2086–2093. doi: 10.1016/S1388-2457(99)00183-2

Deeny, S., Chicoine, C., Hargrove, L., Parrish, T., and Jayaraman, A. (2014). A simple ERP method for quantitative analysis of cognitive workload in myoelectric prosthesis control and human-machine interaction. *PLoS One* 9:e112091. doi: 10.1371/journal.pone.0112091

Deicher, S. (1999). *Piet Mondrian, 1872-1944: Structures in Space*. Cologne: Taschen.

Delorme, A., and Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

Demiralp, T., Ademoglu, A., Istefanopulos, Y., Başar-Eroglu, C., and Başar, E. (2001). Wavelet analysis of oddball P300. *Int. J. Psychophysiol.* 39, 221–227. doi: 10.1016/S0167-8760(00)00143-4

Demiralp, T., Ademoglu, A., Schürmann, M., Basar-Eroglu, C., and Basar, E. (1999). Detection of P300 waves in single trials by the wavelet transform (WT). *Brain Lang.* 66, 108–128. doi: 10.1006/brln.1998.2027

Dyke, F. B., Leiker, A. M., Grand, K. F., Godwin, M. M., Thompson, A. G., Rietschel, J. C., et al. (2015). The efficacy of auditory probes in indexing cognitive workload is dependent on stimulus complexity. *Int. J. Psychophysiol.* 95, 56–62. doi: 10.1016/j.ijpsycho.2014.12.008

Eason, R. G. (1981). Visual evoked potential correlates of early neural filtering during selective attention. *Bull. Psychono. Soc.* 18, 203–206. doi: 10.3758/BF03333604

El-Darwish, I. I. (2019). Fractal design in streetscape: Rethinking the visual aesthetics of building elevation composition. *Alex. Eng. J.* 58, 957–966. doi: 10.1016/j.aej.2019.08.010

Fechner, G. T. (1876). *Vorschule der Aesthetik*. Wiesbaden: Breitkopf & Härtel.

Freedberg, D., and Gallese, V. (2007). Motion, emotion and empathy in esthetic experience. *Trends Cogn. Sci.* 11, 197–203. doi: 10.1016/j.tics.2007.02.003

Freunberger, R., Klimesch, W., Doppelmayr, M., and Höller, Y. (2007). Visual P2 component is related to theta phase-locking. *Neurosci. Lett.* 426, 181–186. doi: 10.1016/j.neulet.2007.08.062

Gaal, Z. A., Csuhaj, R., and Molnar, M. (2007). Age-dependent changes of auditory evoked potentials–effect of task difficulty. *Biol. Psychol.* 76, 196–208. doi: 10.1016/j.biopsycho.2007.07.009

Ghani, U., Signal, N., Niazi, I., and Taylor, D. (2020). ERP based measures of cognitive workload: A review. *Neurosci. Biobehav. Rev.* 118, 18–26. doi: 10.1016/j.neubiorev.2020.07.020

Goodin, D. S., Squires, K. C., and Starr, A. (1983). Variations in early and late event-related components of the auditory evoked potential with task difficulty. *Electroencephalogr. Clin. Neurophysiol.* 55, 680–686. doi: 10.1016/0013-4694(83)90278-X

Goucher-Lambert, K., Moss, J., and Cagan, J. (2019). A neuroimaging investigation of design ideation with and without inspirational stimuli—understanding the meaning of near and far stimuli. *Des. Stud.* 60, 1–38. doi: 10.1016/j.destud.2018.07.001

Gross, J. (2014). Analytical methods and experimental approaches for electrophysiological studies of brain oscillations. *J. Neurosci. Methods* 228, 57–66. doi: 10.1016/j.jneumeth.2014.03.007

Gruber, T., and Muller, M. M. (2005). Oscillatory brain activity dissociates between associative stimulus content in a repetition priming task in the human EEG. *Cereb. Cortex* 15, 109–116. doi: 10.1093/cercor/bhh113

Handy, T. C. (2005). *Event-Related Potentials: A Methods Handbook*. Cambridge: MIT press.

Herbert, C., Junghofer, M., and Kissler, J. (2008). Event related potentials to emotional adjectives during reading. *Psychophysiology* 45, 487–498. doi: 10.1111/j.1469-8986.2007.00638.x

Herbert, C., Kissler, J., Junghofer, M., Peyk, P., and Rockstroh, B. (2006). Processing of emotional adjectives: Evidence from startle EMG and ERPs. *Psychophysiology* 43, 197–206. doi: 10.1111/j.1469-8986.2006.00385.x

Herrmann, C. S., Grigutsch, M., and Busch, N. A. (2005). "11 EEG oscillations and wavelet analysis," in *Event-Related Potentials: A Methods Handbook*, ed. T. C. Handy (Cambridge: MIT Press).

Herrmann, C. S., Rach, S., Vosskuhl, J., and Strüber, D. (2014). Time–frequency analysis of event-related potentials: a brief tutorial. *Brain Topogr.* 27, 438–450. doi: 10.1007/s10548-013-0327-5

Horat, S. K., Herrmann, F. R., Favre, G., Terzis, J., Debatisse, D., Merlo, M. C., et al. (2016). Assessment of mental workload: a new electrophysiological method based on intra-block averaging of ERP amplitudes. *Neuropsychologia* 82, 11–17. doi: 10.1016/j.neuropsychologia.2015.12.013

Jeon, Y.-W., and Polich, J. (2001). P300 asymmetry in schizophrenia: a meta-analysis. *Psychiatry Res.* 104, 61–74. doi: 10.1016/S0165-1781(01)00297-9

Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., Mckeown, M. J., Iragui, V., et al. (2000a). Removing electroencephalographic artifacts by blind source separation. *Psychophysiology* 37, 163–178. doi: 10.1111/1469-8986.3720163

Jung, T.-P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., and Sejnowski, T. J. (2000b). Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clin. Neurophysiol.* 111, 1745–1758. doi: 10.1016/S1388-2457(00)00386-2

Kanske, P., and Kotz, S. A. (2007). Concreteness in emotional words: ERP evidence from a hemifield study. *Brain Res.* 1148, 138–148. doi: 10.1016/j.brainres.2007.02.044

Kappenman, E. S., Farrens, J. L., Zhang, W., Stewart, A. X., and Luck, S. J. (2021). ERP CORE: An open resource for human event-related potential research. *Neuroimage* 225:117465. doi: 10.1016/j.neuroimage.2020.117465

Kawabata, H., and Zeki, S. (2004). Neural correlates of beauty. *J. Neurophysiol.* 91, 1699–1705. doi: 10.1152/jn.00696.2003

Kılıçaslan, H., and Kuloglu, N. (2015). Visual Literacy during the Period of Architectural Education. *Procedia Soc. Behav. Sci.* 191, 2824–2828. doi: 10.1016/j.sbspro.2015.04.711

Kissler, J., Assadollahi, R., and Herbert, C. (2006). Emotional and semantic networks in visual word processing: insights from ERP studies. *Prog. Brain Res.* 156, 147–183. doi: 10.1016/S0079-6123(06)56008-X

Klimesch, W., Doppelmayr, M., Schwaiger, J., Winkler, T., and Gruber, W. (2000). Theta oscillations and the ERP old/new effect: Independent phenomena? *Clin. Neurophysiol.* 111, 781–793. doi: 10.1016/S1388-2457(00)00254-6

Kramer, A. F., Trejo, L. J., and Humphrey, D. (1995). Assessment of mental workload with task-irrelevant auditory probes. *Biol. Psychol.* 40, 83–100. doi: 10.1016/0301-0511(95)05108-2

Kuspit, D. B., Beuys, J., Warhol, A., Malevič, K., Mondrian, P., Duchamp, M., et al. (1993). *The Cult of the Avant-Garde Artist*. Cambridge: University Press Cambridge. doi: 10.1017/CBO9780511624308

Kutas, M., McCarthy, G., and Donchin, E. (1977). Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science* 197, 792–795. doi: 10.1126/science.887923

Lee, N. (2009). Project methods as the vehicle for learning in undergraduate design education: a typology. *Des. Stud.* 30, 541–560. doi: 10.1016/j.destud.2009.03.002

Lefebvre, C. D., Marchand, Y., Eskes, G. A., and Connolly, J. F. (2005). Assessment of working memory abilities using an event-related brain potential (ERP)-compatible digit span backward task. *Clin. Neurophysiol.* 116, 1665–1680. doi: 10.1016/j.clinph.2005.03.015

Locher, P., Overbeeke, K., and Stappers, P. J. (2005). Spatial balance of color triads in the abstract art of Piet Mondrian. *Perception* 34, 169–189. doi: 10.1068/p5033

Lopez-Calderon, J., and Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Front. Hum. Neurosci.* 8:213. doi: 10.3389/fnhum.2014.00213

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique*. Cambridge: MIT press.

Luck, S. J., and Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *J. Exp. Psychol.* 20:1000. doi: 10.1037/0096-1523.20.5.1000

Lupton, E., and Phillips, J. C. (2008). *Graphic Design: The New Basics*. New York, NY: Princeton Architectural Press.

MacWhinney, B., James, J. S., Schunn, C., Li, P., and Schneider, W. (2001). STEP—A system for teaching experimental psychology using E-Prime. *Behav. Res. Methods Instrum. Comput.* 33, 287–296. doi: 10.3758/BF03195379

Mangun, G. R., Hansen, J. C., and Hillyard, S. A. (1986). *The spatial orienting of attention: Sensory facilitation or response bias?* La Jolla, CA: California University San Diego La Jolla Department Of Neurosciences.

Miller, M. W., Rietschel, J. C., McDonald, C. G., and Hatfield, B. D. (2011). A novel approach to the physiological measurement of mental workload. *Int. J. Psychophysiol.* 80, 75–78. doi: 10.1016/j.ijpsycho.2011.02.003

Milovanovic, J., Hu, M., Shealy, T., and Gero, J. (2021). Characterization of concept generation for engineering design through temporal brain network analysis. *Des. Stud.* 76:101044. doi: 10.1016/j.destud.2021.101044

Mognon, A., Jovicich, J., Bruzzone, L., and Buiatti, M. (2011). ADJUST: An automatic EEG artifact detector based on the joint use of spatial and temporal features. *Psychophysiology* 48, 229–240. doi: 10.1111/j.1469-8986.2010.01061.x

Moore, M., Shafer, A. T., Bakhtiari, R., Dolcos, F., and Singhal, A. (2019). Integration of spatio-temporal dynamics in emotion-cognition interactions: A simultaneous fMRI-ERP investigation using the emotional oddball task. *Neuroimage* 202:116078. doi: 10.1016/j.neuroimage.2019.116078

Muñoz, F., and Martin-Loeches, M. (2015). Electrophysiological brain dynamics during the esthetic judgment of human bodies and faces. *Brain Res.* 1594, 154–164. doi: 10.1016/j.brainres.2014.10.061

Nicholas, C., and Oak, A. (2020). Make and break details: The architecture of design-build education. *Des. Stud.* 66, 35–53. doi: 10.1016/j.destud.2019.12.003

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 9, 97–113. doi: 10.1016/0028-3932(71)90067-4

Omoto, S., Kuroiwa, Y., Otsuka, S., Baba, Y., Wang, C., Li, M., et al. (2010). P1 and P2 components of human visual evoked potentials are modulated by depth perception of 3-dimensional images. *Clin. Neurophysiol.* 121, 386–391. doi: 10.1016/j.clinph.2009.12.005

Pearce, M. T., Zaidel, D. W., Vartanian, O., Skov, M., Leder, H., Chatterjee, A., et al. (2016). Neuroaesthetics: The Cognitive Neuroscience of Aesthetic Experience. *Perspect. Psychol. Sci.* 11, 265–279. doi: 10.1177/1745691615621274

Polich, J. (2012). "Neuropsychology of P300," in *The Oxford Handbook of Event-Related Potential Components*, eds S. J. Luck and E. S. Kappenman (Oxford: Oxford University Press), 159–188.

Quispel, A., and Maes, A. (2014). Would you prefer pie or cupcakes? Preferences for data visualization designs of professionals and laypeople in graphic design. *J. Vis. Lang. Comput.* 25, 107–116. doi: 10.1016/j.jvlc.2013.11.007

Radilova, J. (1982). The late positive component of visual evoked response sensitive to emotional factors. *Act. Nerv. Super.* 3, 334–337.

Radilova, J. (1989). P300 and emotional states studied by psychophysiological methods. *Int. J. Psychophysiol.* 7, 364–365. doi: 10.1016/0167-8760(89)90297-3

Radilova, J., Figar, S., and Radil, T. (1983). Sexual arousal and visual-perception. *Act. Nerv. Super.* 25, 168–170.

Roach, B. J., and Mathalon, D. H. (2008). Event-related EEG time-frequency analysis: an overview of measures and an analysis of early gamma band phase locking in schizophrenia. *Schizophr. Bull.* 34, 907–926. doi: 10.1093/schbul/sbn093

Rogenmoser, L., Zollinger, N., Elmer, S., and Jancke, L. (2016). Independent component processes underlying emotions during natural music listening. *Soc. Cogn. Affect. Neurosci.* 11, 1428–1439. doi: 10.1093/scan/nsw048

Rossell, S. L., Price, C. J., and Nobre, A. C. (2003). The anatomy and time course of semantic priming investigated by fMRI and ERPs. *Neuropsychologia* 41, 550–564. doi: 10.1016/S0028-3932(02)00181-1

Sanada, M., Kuwamoto, T., and Katayama, J. (2021). Deviant consonance and dissonance capture attention differently only when task demand is high: An ERP study with three-stimulus oddball paradigm. *Int. J. Psychophysiol.* 166, 1–8. doi: 10.1016/j.ijpsycho.2021.04.008

Schacht, A., and Sommer, W. (2009). Time course and task dependence of emotion effects in word processing. *Cogn. Affect. Behav. Neurosci.* 9, 28–43. doi: 10.3758/CABN.9.1.28

Schapkin, S. A., Gusev, A. N., and Kuhl, J. (2000). Categorization of unilaterally presented emotional words: an ERP analysis. *Acta Neurobiol. Exp.* 60, 17–28.

Shedden, J. M., and Nordgaard, C. L. (2001). ERP time course of perceptual and post-perceptual mechanisms of spatial selection. *Cogn. Brain Res.* 11, 59–75. doi: 10.1016/S0926-6410(00)00064-1

Sheng, F., Han, X., and Han, S. (2016). Dissociated neural representations of pain expressions of different races. *Cereb. Cortex* 26, 1221–1233. doi: 10.1093/cercor/bhu314

Snyder, E., and Hillyard, S. A. (1976). Long-latency evoked potentials to irrelevant, deviant stimuli. *Behav. Biol.* 16, 319–331. doi: 10.1016/S0091-6773(76)91447-4

Sonderegger, A., and Sauer, J. (2015). The role of non-visual aesthetics in consumer product evaluation. *Int. J. Hum. Comput. Stud.* 84, 19–32. doi: 10.1016/j.ijhcs.2015.05.011

Squires, K. C., Squires, N. K., and Hillyard, S. A. (1975). Decision-related cortical potentials during an auditory signal detection task with cued observation intervals. *J. Exp. Psychol.* 1:268. doi: 10.1037/0096-1523.1.3.268

Squires, N. K., Squires, K. C., and Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalogr. Clin. Neurophysiol.* 38, 387–401. doi: 10.1016/0013-4694(75)90263-1

Stahl, J., Wiese, H., and Schweinberger, S. R. (2008). Expertise and own-race bias in face processing: an event-related potential study. *Neuroreport* 19, 583–587. doi: 10.1097/WNR.0b013e3282f97b4d

Stones, C., and Cassidy, T. (2010). Seeing and discovering: How do student designers reinterpret sketches and digital marks during graphic design ideation? *Des. Stud.* 31, 439–460. doi: 10.1016/j.destud.2010.05.003

Tallon-Baudry, C., and Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends Cogn. Sci.* 3, 151–162. doi: 10.1016/S1364-6613(99)01299-1

Teixeira, M., Nascimento, S., Almeida, V., Simoes, M., Amaral, C., and Castelo-Branco, M. (2020). The conscious experience of color constancy and neural responses to subliminal deviations – A behavioral and EEG/ERP oddball study. *Conscious. Cogn.* 84:102987. doi: 10.1016/j.concog.2020.102987

Ulusoy, Z. (1999). To design versus to understand design: the role of graphic representations and verbal expressions. *Des. Stud.* 20, 123–130. doi: 10.1016/S0142-694X(98)00030-1

Wassiliwizky, E., and Menninghaus, W. (2021). Why and How Should Cognitive Science Care about Aesthetics? *Trends Cogn. Sci.* 25, 437–449. doi: 10.1016/j.tics.2021.03.008

Whybrow, B. (2016). KAPSARC – tensile fabric building skin. *Procedia Eng.* 155, 89–102. doi: 10.1016/j.proeng.2016.08.010

Widmann, A., Schröger, E., and Maess, B. (2015). Digital filter design for electrophysiological data–a practical approach. *J. Neurosci. Methods* 250, 34–46. doi: 10.1016/j.jneumeth.2014.08.002

Wiggs, C. L., and Martin, A. (1998). Properties and mechanisms of perceptual priming. *Curr. Opin. Neurobiol.* 8, 227–233. doi: 10.1016/S0959-4388(98)80144-X

Wolach, I., and Pratt, H. (2001). The mode of short-term memory encoding as indicated by event-related potentials in a memory scanning task with distractions. *Clin. Neurophysiol.* 112, 186–197. doi: 10.1016/S1388-2457(00)00501-0

Zajonc, R. B. (1968). Attitudinal effects of mere exposure. *J. Pers. Soc. Psychol.* 9, 1–27. doi: 10.1037/h0025848

Zhang, G., Zhang, C., Cao, S., Xia, X., Tan, X., Si, L., et al. (2020b). Multi-domain features of the non-phase-locked component of interest extracted from ERP data by tensor decomposition. *Brain Topogr.* 33, 37–47. doi: 10.1007/s10548-019-00750-8

Zhang, G., Li, X., and Cong, F. (2020a). Objective extraction of evoked event-related oscillation from time-frequency representation of event-related potentials. *Neural Plast.* 2020:8841354. doi: 10.1155/2020/8841354

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Improving fluid intelligence of children through working memory training: The role of inhibition control

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Intelligence is strongly associated with working memory. Working memory training can improve fluid intelligence, but the underlying mechanism requires further investigation. Because inhibition control may play a key role in working memory training, this study investigated this process from an electrophysiological perspective. In total, 40 children aged 9 to 11 years were enrolled and randomly divided into a training group ($n = 20$) and a control group ($n = 20$). The training group received 20 days of working memory training, whereas the control group did not receive any training. Before and after the training period, all participants were tested using Raven's Standard Progressive Matrices (RSPM), and electrophysiological indicators were recorded while they performed go/no-go and Stroop tasks. The results revealed that relative to the control group, the training group had significantly improved RSPM scores in the test conducted after their training. For the go/no-go tasks, the training group exhibited a significant decrease in N2 amplitude, a significant increase in P3 amplitude, a significant decrease in theta band energy, and an improvement in response inhibition ability. No significant change was observed for the Stroop task. Correlation analysis revealed that an improvement in individual response inhibition can positively predict an improvement in fluid intelligence. These results suggest that working memory training enhances the fluid intelligence of children by enhancing their response inhibition ability.

KEYWORDS
fluid intelligence, working memory, inhibition control, N2, P3

Introduction

Intelligence comprises two components, namely fluid intelligence, which is closely related to problem solving and abstract reasoning and crystalized intelligence, which pertains to knowledge accumulation (Gray et al., 2003; Gray and Thompson, 2004). Studies have indicated that the ability of an individual to engage in abstract reasoning, problem solving, and fast learning is highly dependent on their working memory ability (Colom et al., 2004; Oberauer et al., 2005). Some researchers have argued that the function and structure of working memory are the basis of fluid intelligence (Oberauer et al., 2007).

Studies have discovered that the effects of working memory training can be transferred to fluid intelligence (Jaeggi et al., 2008). In a study by Zhao et al. (2011), 16 children aged 9–11 years received working memory training for 15 days, after which their fluid intelligence was improved. The effect of working memory training has also been verified in children with cognitive deficits. This form of training not only improves cognitive deficits associated with learning disabilities but also improves the working memory, fluid intelligence, and math performance of children with learning disabilities (Chen et al., 2017).

Although scholars have verified that working memory training has a far-transfer effect on the fluid intelligence of children, the related neural mechanisms are not well understood. Chein and Morrison (2010) argued that working memory training transfers the training effect to fluid intelligence by improving inhibition control (Kane et al., 2001; Engle, 2002; Klingberg et al., 2002; Klingberg, 2010; Au et al., 2015; Greenwood and Parasuraman, 2015; Au et al., 2016; Ye et al., 2018), which is a core component of the executive function of working memory. Furthermore, inhibition control is a top-down ability that enables an individual to actively interrupt or delay their behavior (Clark, 1996; DeWall et al., 2011; Brydges et al., 2012; Diamond, 2013) and engage in the purposeful detection and monitoring of target-oriented behaviors (Cattell, 1963; Kane and Engle, 2002; Rueda, 2018; Rico-Picó et al., 2021). Children and adults with higher fluid intelligence exhibit higher inhibition control and efficiency (Burgess et al., 2011); this suggests that inhibition control is a core component of fluid intelligence, possibly because of their shared neural mechanisms (Duncan and Owen, 2000; Cowan et al., 2006; Jung and Haier, 2007). Fjell et al. (2015) examined the development of the cerebral cortex and fluid intelligence and reported a significant positive correlation between fluid intelligence and prefrontal lobe development, especially the development of the anterior cingulate cortex (ACC). The ACC is a key node in the inhibition control network and plays a crucial role in the development of fluid intelligence.

Demetriou et al. (2008) proposed a hierarchical model of intelligence in which fluid intelligence (with reasoning as its core) is based on inhibition control, processing efficiency, and other related low-level cognitive processes. Studies have demonstrated that children with higher fluid intelligence can inhibit interference more effectively in tests, and on this basis, they can employ cognitive strategies to create, update, maintain, and manipulate abstract representations to achieve better fluid intelligence outcomes (Rueda, 2018). Wiley et al. (2011) further linked this process to working memory, arguing that inhibition control can explain why people with superior working memory perform better on Raven's Standard Progressive Matrices (RSPM; Raven, 2000). When individuals must adhere to new rules in problem-solving situations, the rules that they previously learned and applied may affect their problem-solving efficiency. Compared with individuals with superior working memory, those with poorer working memory find it more difficult to refocus away from the previously learned rules and they persist in applying these outdated rules to solve new problems. Their problem-solving ability is thus negatively affected. Gray et al. (2003) revealed that for high-load updating tasks, participants with higher fluid intelligence had a higher task accuracy rate. The results of multiple regression analysis suggested that the lateral prefrontal cortex and frontoparietal lobe may mediate the relationship between fluid intelligence and working memory. The discussed results suggest that inhibition control plays an essential role in the connection between working memory and fluid intelligence. However, few studies have used event-related potential to explore the change in inhibition control during the transfer of working memory training effects to fluid intelligence.

Researchers have categorized inhibition control into interference inhibition and response inhibition (Nigg, 2000; Johnstone et al., 2009; Diamond, 2013). Interference inhibition (also referred to as conflict resolution and executive attention) is the ability of individuals to focus their attention on the current task through willful effort, with the aim of excluding or inhibiting interfering information that is unrelated to the task. Conversely, response inhibition refers to the ability of individuals to inhibit behavioral responses that do not meet their current needs (Johnstone et al., 2009; Diamond, 2013). Various theories for explaining the inhibition control mechanism have been proposed, and the major ones are feature integration theory (Nieuwenhuis et al., 2003; Hommel et al., 2004; Fischer et al., 2010; Ye et al., 2019) and conflict monitoring theory (Botvinick et al., 2001; Milham et al., 2003; Carter and van Veen, 2007; Clayson and Larson, 2011). Under feature integration theory, the inhibition control process is automatic. An individual reacts accordingly when they encounter a stimulus. At this point, the brain integrates and stores stimulus and response features. When the individual is executing subsequent tasks, the reappearance of these stimulus features automatically triggers the response that is associated with them, thereby reducing the individual's response time and producing an adaptation effect. However, when the individual encounters a completely new stimulus feature, the feature conflicts with their stored integration mode such that a longer response time is required. Under conflict monitoring theory, a cognitive system is required to exert active control in the process of inhibition control. During the early stage of inhibition control, the ACC is activated when interference information appears, and this process plays a role in conflict monitoring and exploration. When conflict is detected, conflict signals from the ACC increase the activity in the prefrontal cortex, which, in turn, enhances top-down cognitive control. Although interference control and response inhibition are collectively referred to as inhibition control, these two inhibition processes exhibit different patterns in terms of their activation of inhibition behavior, namely top-down cognitive drive and bottom-top stimulus drive. Hong et al. (2017) manipulated go/no-go tasks, which pertain to response inhibition, and their results suggested that an individual's top-down cognitive drive is a fundamental prerequisite for such inhibition. Interference control that inhibits task-irrelevant information is regarded as being determined by bottom-top stimulation processing. The features of an interfering stimulus automatically activate the cognitive representation of the relevant response of the individual that would occupy cognitive resources and thus create interference for the individual (Avital-Cohen and Tsal, 2016). Therefore, the present study used go/no-go and Stroop tasks to comprehensively explore the role of inhibition control in the transfer of working memory training effects to fluid intelligence.

The N2 is an event-related potential (ERP) indicator of response inhibition control or conflict monitoring. During the execution of Stroop and go/no-go tasks, N2 components appear after a stimulus triggers inhibitory control (Folstein and Petten, 2008). Source localization findings suggest that N2 is derived from activation of the ACC, reflecting the top-down monitoring of conflict and amount of effort required to complete an inhibition control task (Nieuwenhuis et al., 2003; Pires et al., 2014). Generally, larger N2 amplitude indicates superior conflict monitoring capability. However, developmental studies have reported that N2 amplitude decreases with age, which can be interpreted as an increase in conflict monitoring efficiency (Lo, 2018). P3 components are related to the inhibition control process, and studies have reported that individuals with high fluid intelligence exhibited higher P3 amplitude after completing an inhibition control task, which could reflect a greater degree of mature inhibition control (Wessel, 2018; Rico-Picó et al., 2021).

The ERP index only indicates that a brain is time- and phase-locked to the onset of a stimulus or a response. However, the electrophysiological activity of a brain that is time-locked but not phase-locked to the onset of a stimulus or response (i.e., event-related spectral perturbation [ERSP]) may reveal novel neural mechanisms that are involved in conflict detection, monitoring, and resolution (Makeig et al., 2004). A study demonstrated that inhibition control tasks are accompanied by theta (4–8 Hz) and alpha (8–13 Hz) energy changes. An increase in theta band energy in the prefrontal lobe may reflect top-down inhibition control of a resource input during the processes of individual identification, monitoring, and problem solving (Nigbur et al., 2012; PastöTter et al., 2013; Cavanagh and Frank, 2014). An intensely debated topic is the change in the alpha band energy in the parietal lobe, which may reflect the investment of inhibition control resources and reinforcement of inhibition control by a task-independent brain (Pfurtscheller et al., 1996; Klimesch et al., 2007; Klimesch, 2012).

The present study primarily aimed to explore the role of inhibition control during the transfer of working memory training effects to fluid intelligence in children from the perspective of electrophysiology. Therefore, we compared the electrophysiological performance of two groups of children with respect to the execution of inhibition control tasks. Studies have indicated that the gradual transition from bottom-top stimulation drive to top-down cognitive control is the basis for enhancing the mental representation of children. This transition ability enables children to better inhibit previously applied rules during fluid intelligence tasks, focus their attention on cues that are relevant to the current task, and respond flexibly to new situations (Munakata et al., 2012). We hypothesized that the significant improvement in the fluid intelligence of the children in the training group was influenced by the improvement in top-down internally driven response inhibition that was achieved through working memory training; by contrast, no significant change in bottom-top stimulus-driven interference inhibition was detected during this process. In other words, the N2 amplitude significantly decreased, P3 amplitude significantly increased, theta energy level increased, and alpha energy level decreased during the execution of go/no-go tasks. No significant change was detected for Stroop task indices.

Materials and methods

Participants

The desired sample size was calculated by performing a G*Power analysis. With $f=0.25$, $\alpha=0.05$, and power $=0.8$, we obtained a recommended sample size of 34 participants (Faul et al., 2007). In total, 40 children (aged between 10 and 11 years) from a primary school in Nanjing were enrolled and randomly divided into two groups with 20 children each, namely the control group (mean age, 10.35 ± 0.64 years; 10 boys and 10 girls) and training group (mean age, 10.36 ± 0.49 years; 12 boys and 8 girls). No significant difference in age was observed between the two groups ($t=0.058$, $p=0.954$). None of the participants had previously participated in a similar study. The experimental procedures were approved by the Ethics Committee of the Department of Psychology, Nanjing University, and they were performed in accordance with approved guidelines. In accordance with the Declaration of Helsinki, informed consent was obtained from the parents and teachers of the participants.

Materials and procedure

Training tasks

In the present study, an original training program was optimized to develop a new version of adaptive working memory training task software (Zhao et al., 2011). During training tasks, various animals, numbers, and robots were presented sequentially in the center of a computer screen. The participants did not know the number of animals, numbers, and robots that would appear during each trial and were instructed to memorize the identity of the final three animals or numbers that appeared during each trial. They had to continually update their memory and thus train their working memory because they did not know how many animals, numbers, and robots would be presented. Each training task comprised 30 trials that were separated into six blocks of 5 trials. At the beginning of training, each item was presented for 1.750 ms. This duration was reduced by 100 ms for the subsequent block if a participant provided correct responses for three or more trials in a given block. The duration of training that a participant

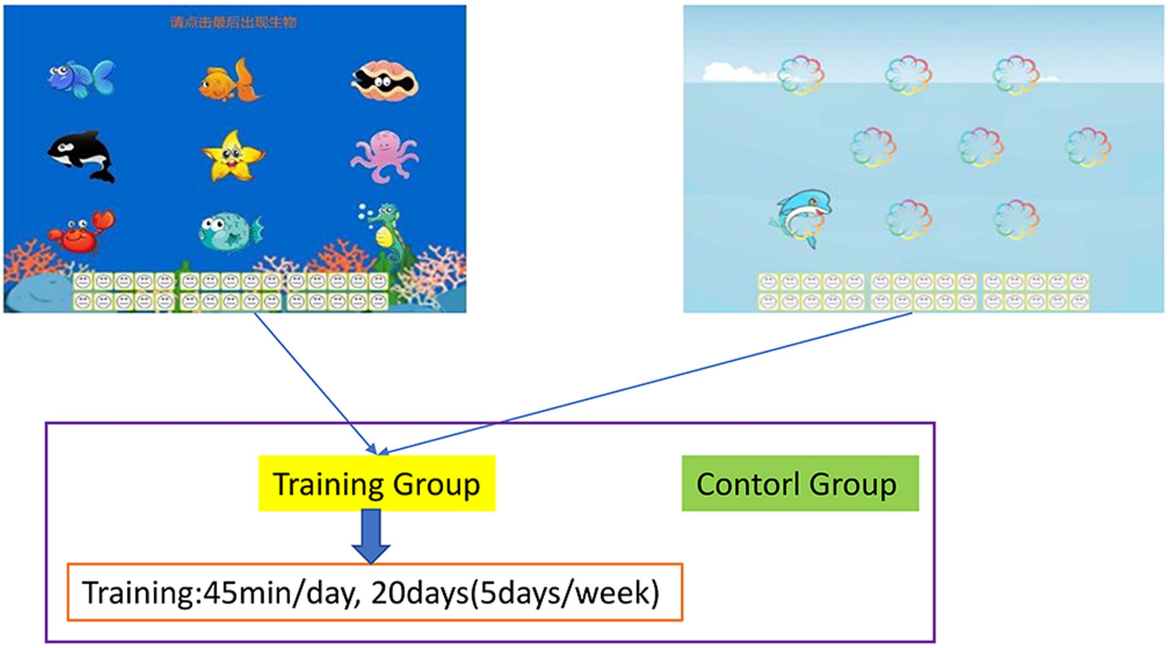

FIGURE 1
Working memory training task. Participants were required to memorize the final three images that were presented. The training task was divided into six blocks of five trials. When a participant's correct response rate increased, their stimulus presentation time was reduced by 100ms for the subsequent block, which increased the difficulty of the task.

received on a subsequent day was determined by the duration of the participant's last block on a given day. The participants received feedback on their overall performance (Figure 1).

Evaluation of training outcomes

RSPM

An RSPM test was performed to measure the fluid intelligence of the participants. RSPM is a reasoning problem that comprises abstract geometric figures or line segments. This test is divided into five components (A, B, C, D, and E) that each comprise 12 questions (i.e., the test has 60 questions in total). Each correct answer was assigned 1 point. An improvement in RSPM score is analogous to an improvement in fluid intelligence. In accordance with the protocol used by Jaeggi et al. (2008), we divided the test into two equal parts on the basis of pen-and-paper administration. All participants completed the test in a school classroom under the guidance and supervision of professional trainers. On average, the participants required 20 min or less to complete 30 questions.

Stroop task

In the present study, the Stroop task was used to evaluate the conflict inhibition of the participants (Liu et al., 2011). The experimental program was developed using the E-prime software, and its screen background and stimulus material were black and white, respectively. The distance between a participant and the screen was 70–100 cm. Each participant was asked to compare the numerical values of two white single-digit numbers against a gray background. To reduce the effect of distance, one digit in each number pair was programmed to be greater than the other by a value of 3 (i.e., 1–4, 2–5, 3–6, 4–7, 5–8, and 6–9). The numerically greater digit was presented randomly. The participants were exposed to one of three conditions, namely the congruent, incongruent, and neutral conditions. Each condition was tested twice (pretraining and posttraining). Under the congruent condition, the numerically greater digit (200 points) was physically larger than the other (140 points). Under the incongruent condition, the numerically greater digit was physically smaller than the other. Under the neutral condition, both digits had physically identical size (half of 140 points and half of 200 points). During execution of a Stroop task, each trial began with a fixation cross "+" for 200 ms, which was displayed randomly on the screen for 800–1,200 ms after stimulus presentation. The subjects were asked to judge which number was large (i. e. to judge which number has a large value, ignoring the physical size of the number), if the large number is on the left, press the "1" key on the digital keypad; if the large number is on the right, press the "3" key on the digital keypad. The stimulus remained for a period of time (5,000 ms) or until a response was given. The next trial was introduced after 1,000 to 2,000 ms, that is, the intertrial intervals varied between 1,000 and 2,000 ms. The timing of the trial times under consistent, inconsistent, and neutral conditions was randomized, but the same key was not allowed to appear for more than four consecutive times, and the same condition was not allowed to be applied for more than three consecutive times (Figure 2).

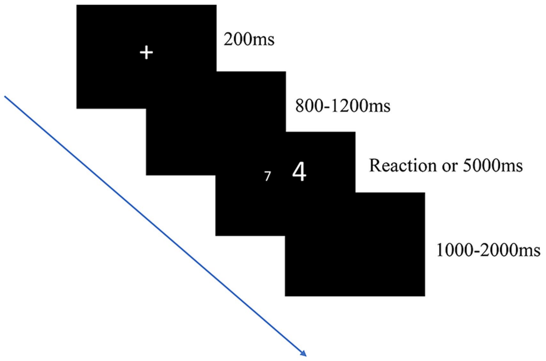

FIGURE 2
Digital Stroop task. The participants judged the numerical value of the number shown on the screen while ignoring its physical size. Three conditions were applied (incongruent, congruent, and neutral conditions), with the probability of each condition occurring being 0.33.

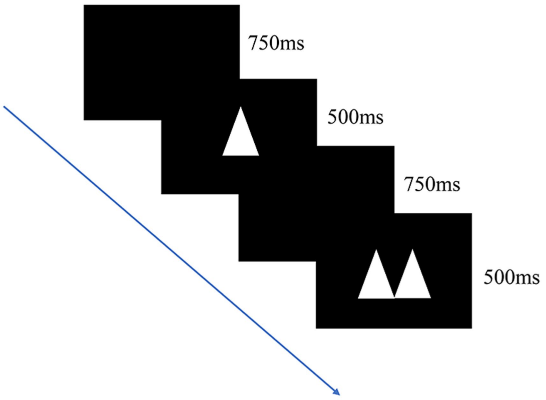

FIGURE 3
Digital go/no-go task. The participants responded to images displayed on screen by pressing "/" button when double triangles appeared but not when a single triangle appeared. Each trial had a 60% chance of being a go trial and 40% chance of being a no-go trial.

Go/no-go task

The response inhibition ability of the participants was measured using the go/no-go task. The task requires a participant to react when they observe a target stimulus but not when they observe a nontarget stimulus. The stimulus material comprised double and single triangles, and the order in which double and single triangles were presented was fully randomized. The task consisted of a practice block and three formal experimental blocks. During the formal experiment, the ratio of go trials to no-go trials was 60%:40%. The participants were required to press the "/" button when they observed double triangles (go trial) and to not press any button when they observed a single triangle ("no-go" trial). Each block comprised 100 trials for a total of 300 trials. During each trial, a triangle was randomly presented in the center of the computer screen for 500 ms, after which a blank screen was displayed for 750 ms prior to the start of the subsequent trial (Figure 3).

Design and procedure

The working memory of the experimental group was trained. The training consisted of 20 sessions. Each session lasted between 15 and 20 min, and between three and four training sessions were conducted on a weekly basis. The training program was conducted using adaptive working memory training software developed on the basis of the findings of Zhao et al. (2011). The participants completed the computer-based training during the daily noon break (12:00 to 1:30 p.m.) in their school's computer room under the guidance and supervision of professional trainers. The experiment comprised two components, namely the pretraining and posttraining tests (test sequence: rspm, stroop, and go/no-go). The posttraining test was conducted after the experimental group had completed the 20 training sessions. The experimental group received the training and completed all of the tests, whereas the control group did not receive any specific training and only completed the tests. Both groups completed the same tasks and tests.

Electroencephalography data collection and analysis

We recorded EEG data while the participants completed the Stroop and go/no-go tasks. A Neuroscan 40-channel portable amplifier was used to record EEG data through DC sampling. Electrodes were arranged on a cap in accordance with the standard international 10–20 system. The reference electrodes were attached to the mastoids in the left ear, and the obtained data were converted into a mean reference for bilateral mastoids during our offline analysis. The sampling rate was 1,000 Hz, and the recording bandwidth was 0.01–100 Hz. The ground electrode was attached to the midpoint AFz of the FCz and Fz connection. HEOG data were recorded by electrodes placed on the lateral side of both eyes, and VEOG data were recorded by electrodes placed on the above and below sides of the left eye. Reference electrodes were attached to the left mastoid process, and the input impedance of all recording electrodes was less than 10 kΩ. Because the acquisition environment was not electromagnetically shielded, a 50-Hz notch filter was used to subtract urban electrical interference.

EEG data were processed using the EEGLAB 2019 toolkit (Delorme and Makeig, 2004), which is based on the MATLAB2019b platform. Continuous EEG data were filtered using a 40-Hz low-pass filter and a 0.1-Hz high-pass filter and subsequently re-referenced to an average signal. The data were segmented with a time window of 900 ms (100 ms before stimulation and 800 ms after stimulation) and a prestimulus baseline of 100 ms. Trials with considerable drift were manually removed, and those that were contaminated by eye blinks were corrected using an independent component analysis algorithm (infomax; Delorme and Makeig, 2004). Across the participants, 3 ± 2 independent components of artifacts were identified as ocular artifacts through visual inspection and were rejected. Only correct trials were included in the final analysis. Finally, the trials in which amplitude values exceeding ±75 μV were obtained for any electrode were excluded from the analysis.

The channels and time windows for the analyses were selected on the basis of the literature regarding developmental samples (Wessel, 2018; Rico-Picó et al., 2021; Fu et al., 2022). Imperative No-go stimuli typically produce a negative deflection in the ERP around 200–300 milliseconds, the N2, that is maximal over fronto-central regions (Van Veen and Carter, 2002). For the N2 component, Fz was selected for analysis. The average amplitude of the EEG data within the 290–360 ms time window after stimulation served as the N2 for analyzing the Go/no-go, and the average amplitude of the EEG data within the 280–350 ms time window after stimulation served as the N2 for analyzing the Stroop task. The channels Fz and Cz were used to examine P3. For both tasks, the selected time window for P3 was between 350 and 500 ms after the stimulation.

For the time–frequency analysis, Letswave7, which is based on the MATLAB 2019b platform, was used to perform a continuous Morlet wavelet transform of the data, and oscillation power was estimated using single-trial EEG epochs. To simultaneously obtain favorable temporal and spatial resolutions, a frequency range of 1–30 Hz and data in the range of −600 to 800 ms were selected for segmentation in steps of 10 ms. To prevent edge effects during a continuous Morlet wavelet transform, the prestimulus time interval (−400 to −200 ms) was used as the baseline interval. For the go/no-go and Stroop tasks, channels were selected on the basis of the findings of other studies (Klimesch, 2012; Cavanagh and Frank, 2014). Specifically, the channel Fz was selected for the analysis of theta band energy for the Stroop task (frequency range, 4–8 Hz; time window, 150–350 ms), and the channel Cz was selected for the analysis of alpha band energy (frequency range, 8–13 Hz; time window, 400–650 ms).

Results

RSPM

RSPM scores were subjected to 2 (training group and control group) × 2 (pretest and posttest) repeated-measures analysis of variance (RM-ANOVA). The RM-ANOVA revealed the following results. The main effect of time was nonsignificant (F (1, 38) = 2.274, $p = 0.140$, $\eta^2 = 0.056$), the main effect of group was significant (F (1, 38) = 13.909, $p = 0.001$, $\eta^2 = 0.268$), and the interaction between time and group was significant (F (1, 38) = 7.503, $p = 0.009$, $\eta^2 = 0.165$). Simple effect analysis revealed that the RSPM scores of the training group were significantly enhanced after the training (F (1, 38) = 9.019, $p = 0.005$, $\eta^2 = 0.192$), whereas those of the control group did not differ significantly between the start and end of the present study (F (1, 38) = 0.758, $p = 0.389$, $\eta^2 = 0.02$) (Figure 4).

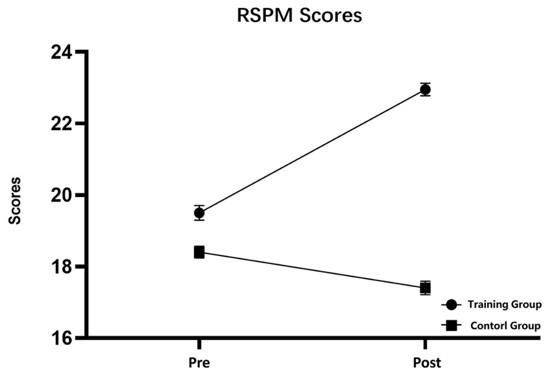

FIGURE 4
Raven's Standard Progressive Matrices scores of the participants in the pretest and posttest. The training group had significantly improved RSPM scores after receiving working memory training. No significant difference in scores was detected in the control group. Pre, training group pretest and Control-pre; Post, training group posttest and Control-post, error bars are standard error.

Go/no-go task

No-go trials tested the response inhibition of the participants. Thus, only the amplitude of the no-go responses of the participants was analyzed. This principle was applied as follows.

N2

N2 average amplitude data were subjected to 2 (training group and control group) × 2 (pretest and posttest) RM- ANOVA, which revealed the following results. The main effect of time was significant (F (1, 38) = 4.811, $p = 0.034$, $\eta^2 = 0.112$), the main effect of group was nonsignificant (F (1, 38) = 0.627, $p = 0.433$, $\eta^2 = 0.016$), and the interaction between time and group was significant (F (1, 38) = 4.272, $p = 0.046$, $\eta^2 = 0.101$). Simple effect analysis indicated that the N2 amplitude of the training group was significantly decreased after the training, F (1, 38) = 9.075 $p = 0.005$, $\eta^2 = 0.193$). By contrast, that of the control group did not differ significantly between the start and end of the present study (F (1, 38) = 0.008, $p = 0.929$, $\eta^2 < 0.001$; Figure 5).

P3

P3 average amplitude data were subjected to 2 (training group and control group) × 2 (pretest and posttest) × 2 (Fz and Cz) RM-ANOVA. The main effect of time was significant (F (1, 38) = 5.654, $p = 0.023$, $\eta^2 = 0.130$), and the interaction between time and channels was significant (F (1, 38) = 18.592, $p < 0.001$, $\eta^2 = 0.329$). The data on the mean amplitude of P3 along the channels Fz and Cz were subjected to 2 (training group and

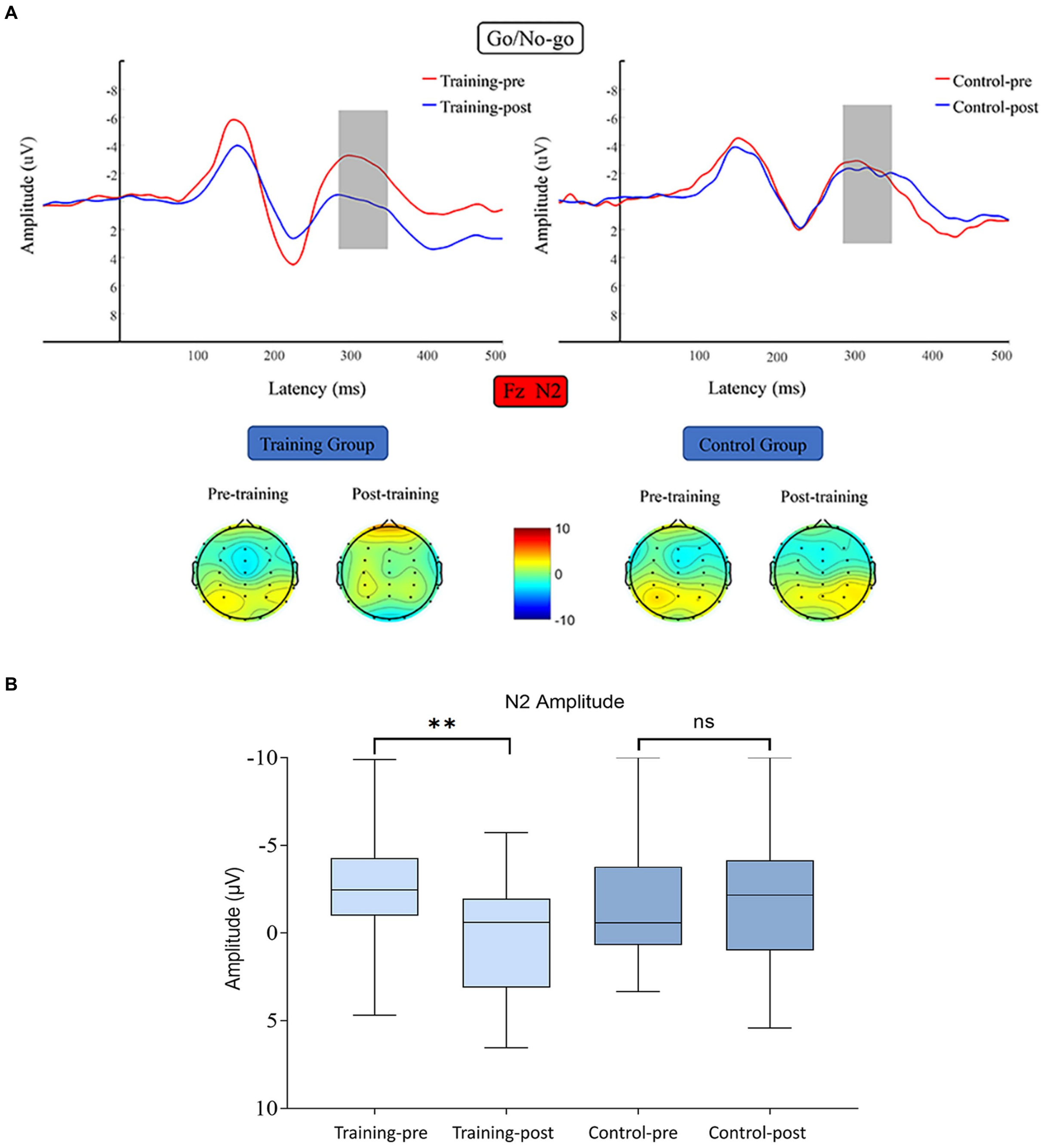

FIGURE 5
(A) Waveforms and topographical maps of N2 for the two groups. Topographical maps were constructed using the mean amplitude for the N2 period (290–360ms). **(B)** Bar chart of the amplitude of N2 along the Fz channel between 290 and 360ms. Bars represent the confidence interval. *6 edges ***p*<0.01, *ns* indicates *p*> 0.05. Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

control group) × 2 (pretest and posttest) RM-ANOVA. Regarding the Fz channel, the main effect of time was marginally unsignificant (F (1, 38) = 2.052, p = 0.160, η^2 = 0.051), and the interaction between time and group was significant (F (1, 38) = 13.539, p = 0.001, η^2 = 0.263). Simple effect analysis revealed that the P3 amplitude along the Fz of the training group was significantly enhanced after the training (F (1, 38) = 13.066, p = 0.001, η^2 = 0.256), whereas that of the control group did not differ significantly between the start and end of the study (F (1, 38) = 2.525, p = 0.120, η^2 = 0.062). Regarding the Cz channel, the main effect of time was unsignificant (F (1, 38) = 2.890, p = 0.097, η^2 = 0.071), and the interaction between time and group was significant (F (1, 38) = 9.294, p = 0.004, η^2 = 0.197). Simple effect analysis indicated that the P3 amplitude along the Cz channel was

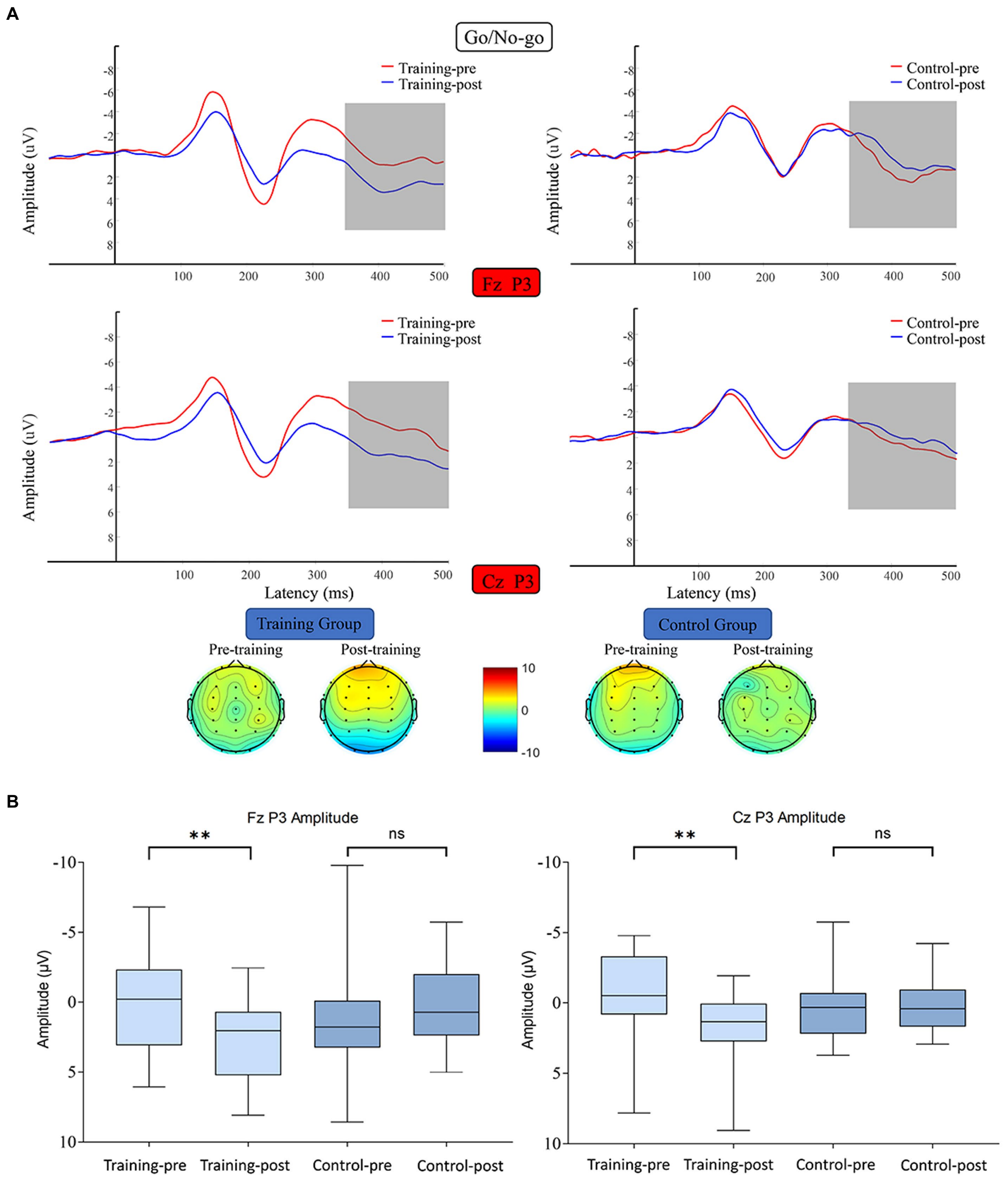

FIGURE 6
(A) Waveforms and topographical maps of P3 for the two groups along Fz and Cz. Topographical maps were constructed using the mean amplitude for the P3 period (350–500ms). **(B)** Bar chart of the amplitude of P3 along the Fz and Cz channels between 350 and 500ms. Bars represent the confidence interval. *6 edges ***p*<0.01, *ns* indicates *p*> 0.05. Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

significantly enhanced after the training in the training group (F (1, 38) = 11.274, $p = 0.002$, $\eta^2 = 0.229$), whereas in the control group, this amplitude did not differ significantly between the start and end of the study (F (1, 38) = 0.910, $p = 0.346$, $\eta^2 = 0.023$) (Figure 6).

Time–frequency analysis

For the Fz channel, theta energy data were subjected to 2 (training group and control group) × 2 (pretest and posttest) RM-ANOVA, which revealed the following. The main effect of time was significant (F (1, 38) = 6.954, $p = 0.012$, $\eta^2 = 0.155$), the main effect

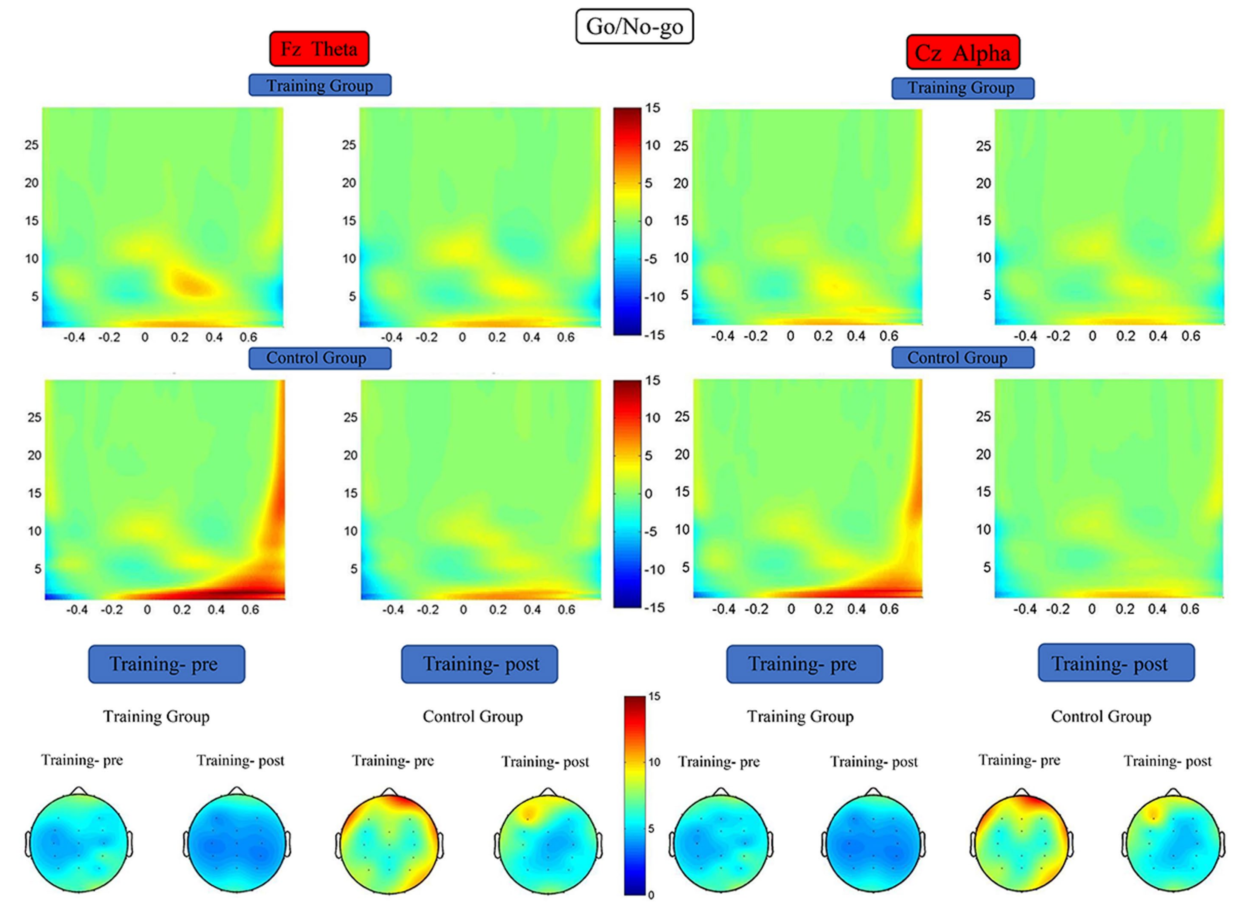

FIGURE 7
Spectrograms of mean ERSP of the two groups at electrodes Fz and Cz. Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

of group was significant (F (1, 38) = 5.228, $p = 0.028$, $\eta^2 = 0.121$), and the interaction between time and group was significant (F (1, 38) = 5.063, $p = 0.030$, $\eta^2 = 0.118$). Simple effect analysis indicated that the theta energy level of the training group was significantly higher after the training (F (1, 38) = 11.942, $p = 0.001$, $\eta^2 = 0.239$), whereas that of the control group did not differ significantly between the start and end of the study (F (1, 38) = 0.075, $p = 0.786$, $\eta^2 = 0.002$). For the Cz channel, alpha energy data were subjected to 2 (training group and control group) × 2 (pretest and posttest) RM-ANOVA, which did not reveal any significant difference in the alpha energy levels of the two groups before versus after the training period (Figure 7).

Stroop task

The amplitude under the incongruent condition within the Stroop task reflected the response inhibition of the participants. Thus, the amplitude obtained under only the incongruent condition was analyzed.

N2

The N2 average amplitude data were subjected to 2 (training group and control group) × 2 (pretest and posttest) RM-ANOVA, which did not reveal any significant difference in N2 average amplitude before versus after the training period (Figure 8).

P3

P3 average amplitude data were subjected to 2 (training group and control group) × 2 (pretest and posttest) × 2 (Fz, Cz) RM-ANOVA, which revealed the following. The main effect of time was significant (F (1, 38) = 29.259, $p < 0.001$, $\eta^2 = 0.435$), and a significant channels × time × group interaction (F (1, 38) = 66.474, $p = 0.031$, $\eta^2 = 0.117$), with no other significant. The data on the mean amplitude of P3 along the Fz and Cz channels were subjected to 2 (training group, control group) × 2 (pretest, posttest) RM- ANOVA, which did not reveal any significant difference in alpha energy before versus after the training period (Figure 9).

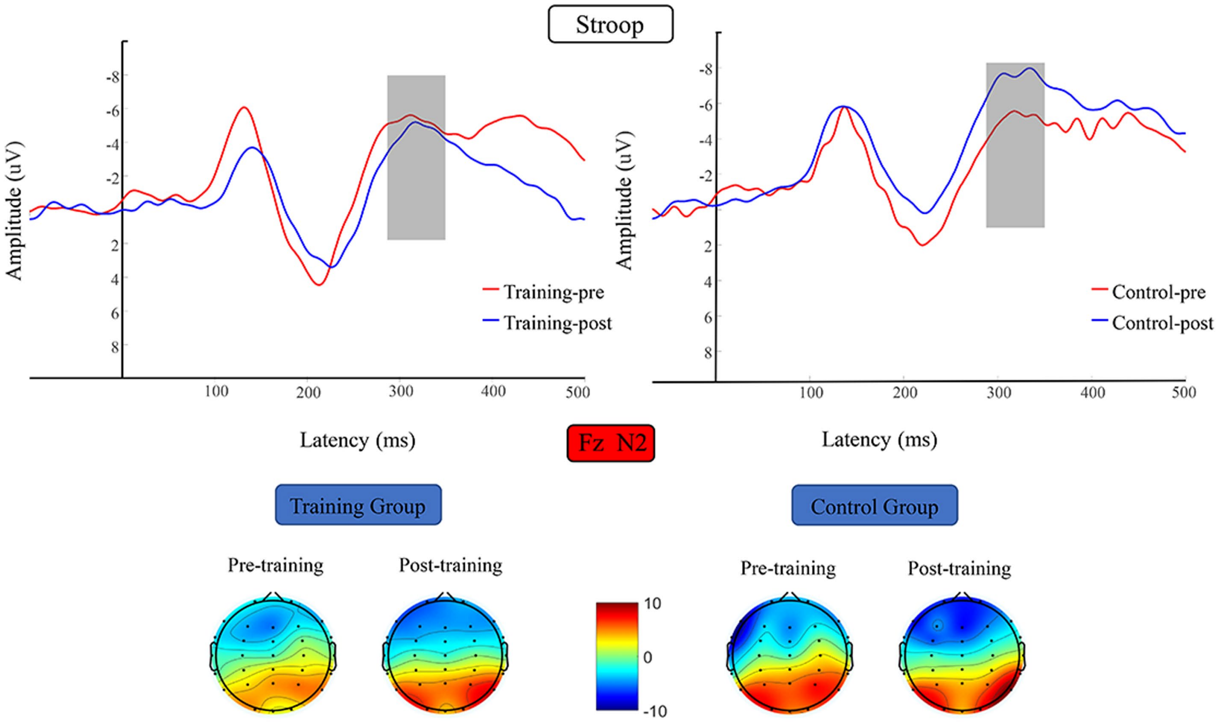

FIGURE 8
Waveforms and topographical maps of N2 for the two groups. Topographical maps were constructed using the mean amplitude in the N2 period (280–350ms). Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

Time–frequency analysis

The RM-ANOVA results did not indicate any significant difference in theta and alpha energy before versus after the training period (Figure 10).

Pearson's correlation

Pearson's correlation analysis was performed for the index data for which significant changes were detected in the training group.

The results indicated that the change in fluid intelligence was positively correlated with the change in the mean amplitude of N2 along Fz ($r = 0.436$, $p = 0.055$), the mean amplitude of P3 along Cz ($r = 0.400$, $p = 0.081$), and the change in theta energy ($r = 0.432$, $p = 0.057$) for the go/no-go task (Figure 11).

Discussion

In the present study, we investigated changes in inhibition control during far transfer of the effects of working memory training to fluid intelligence from an electrophysiological perspective. The results indicated that after 20 days of working memory training, the experimental group participants' fluid intelligence performance and response inhibition were significantly improved. Specifically, the N2 and P3 average amplitude levels of the experimental group participants during no-go trials, which reflected their individual response inhibition, changed significantly. For the Stroop task, no significant change was detected in any indicator that reflected individual interference control. Contrary to our hypothesis, the individual theta band energy level was lower after the training. The Pearson's correlation and regression analyses revealed that the improvement in response inhibition was a significant predictor of improved fluid intelligence.

Studies have demonstrated that the training effect of working memory can be far transferred to fluid intelligence and other cognitive abilities (Jaeggi et al., 2011). Zhao et al. (2011) reported that the fluid intelligence of children was significantly improved after they had received working memory training. This finding was then validated in children with learning disabilities, suggesting that this far-transfer effect is widespread (Chen et al., 2017). Our results verify this finding.

In the present study, the electrophysiological indexes of the participants' response inhibition had changed significantly after they had received 20 days of working memory training. Specifically, this change manifested as a significant decrease in the amplitude of N2 during no-go trials. Rico-Picó et al. (2021) compared the N2 amplitudes of children with various levels of fluid intelligence and reported that the N2 amplitude level of children with high fluid intelligence was significantly lower than

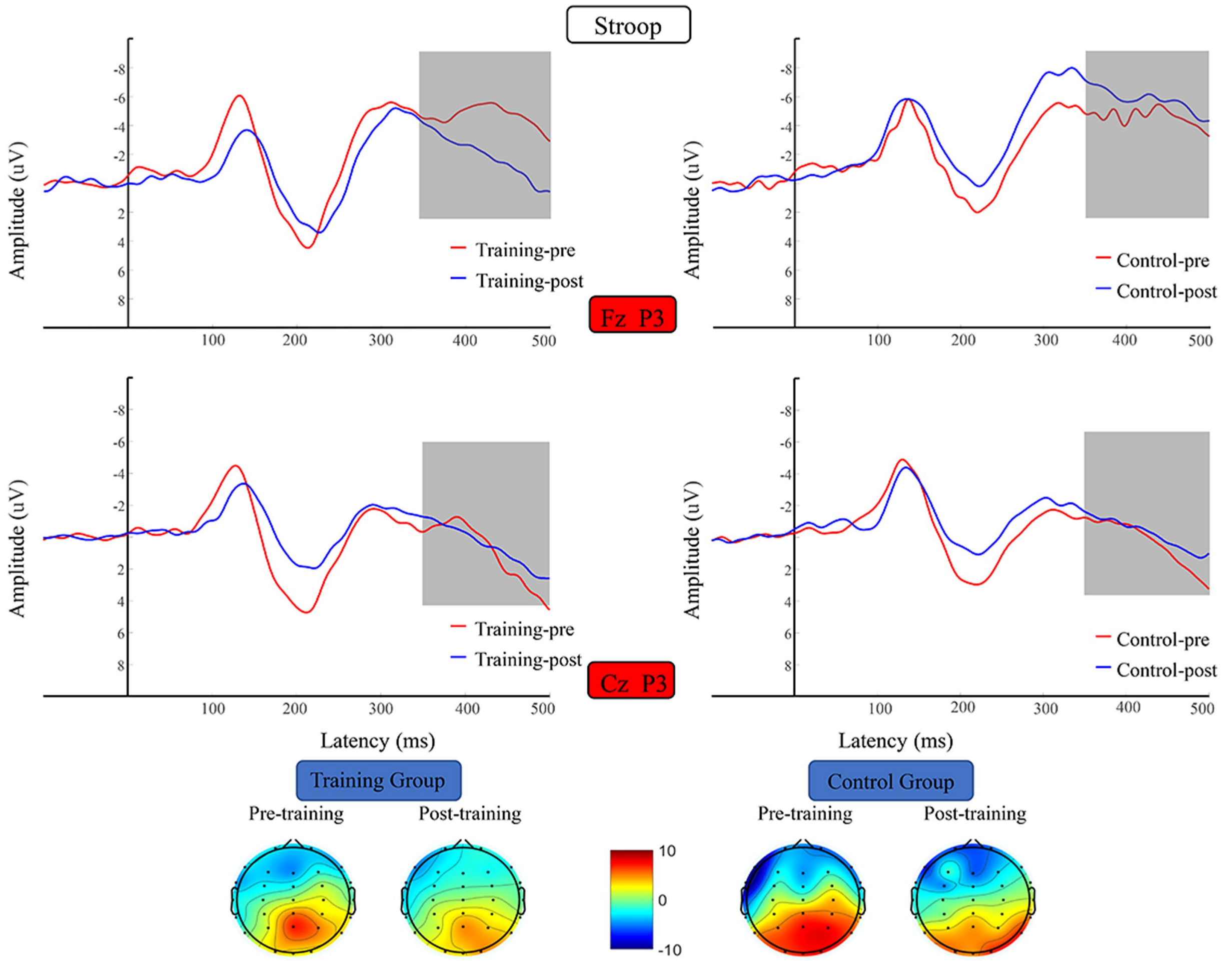

FIGURE 9
Waveforms and topographical maps of N2 for the two groups. Topographical maps were constructed using the mean amplitude in the N2 period (350–500ms). Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

that of children with low fluid intelligence. This finding is consistent with the results of the present study. N2 is a key component of conflict monitoring and represents the level of involvement of an individual's top-down response inhibition. Larger N2 amplitude indicates investment of more individual response inhibition resources. However, developmental studies have demonstrated that the amplitude of N2 decreases with age, which may be attributed to a gradual increase in an individual's inhibition control efficiency with age (Hämmerer et al., 2010; Lo, 2018). The aforementioned findings indicate that working memory training increases the effectiveness of an individual's conflict monitoring, and processing efficiency is a key factor influencing fluid intelligence (Hilger et al., 2017a).

The present study revealed that participants who received 20 days of working memory training exhibited significantly decreased P3 amplitude under no-go conditions when they were completing the response inhibition task. Several studies have asserted that P3 reflects individual response inhibition, whereas others have argued that P3 represents an overall evaluation of the inhibition control process (Righi et al., 2009; Wessel, 2018). The results of the present study support the first view, that is, the P3 component is more related to individual response inhibition than to overall inhibition control. This finding is consistent with those of most studies (Benikos et al., 2013; Wessel, 2018). The present study also discovered that the amplitude of P3 under no-go conditions was significantly higher after the training. Benikos et al. (2013) suggested that the P3 induced under no-go conditions is related to the selective attention and behavior selection process. Larger P3 amplitude after training indicates that individuals can better use inhibitory control resources to select behaviors during the response inhibition process.

In the present study, the theta band energy level of the participants was significantly lower after they had received the training. An increase in theta energy in the frontal lobe represents the level of top-down resource input that is involved during the process of identifying, monitoring, and resolving a problem as

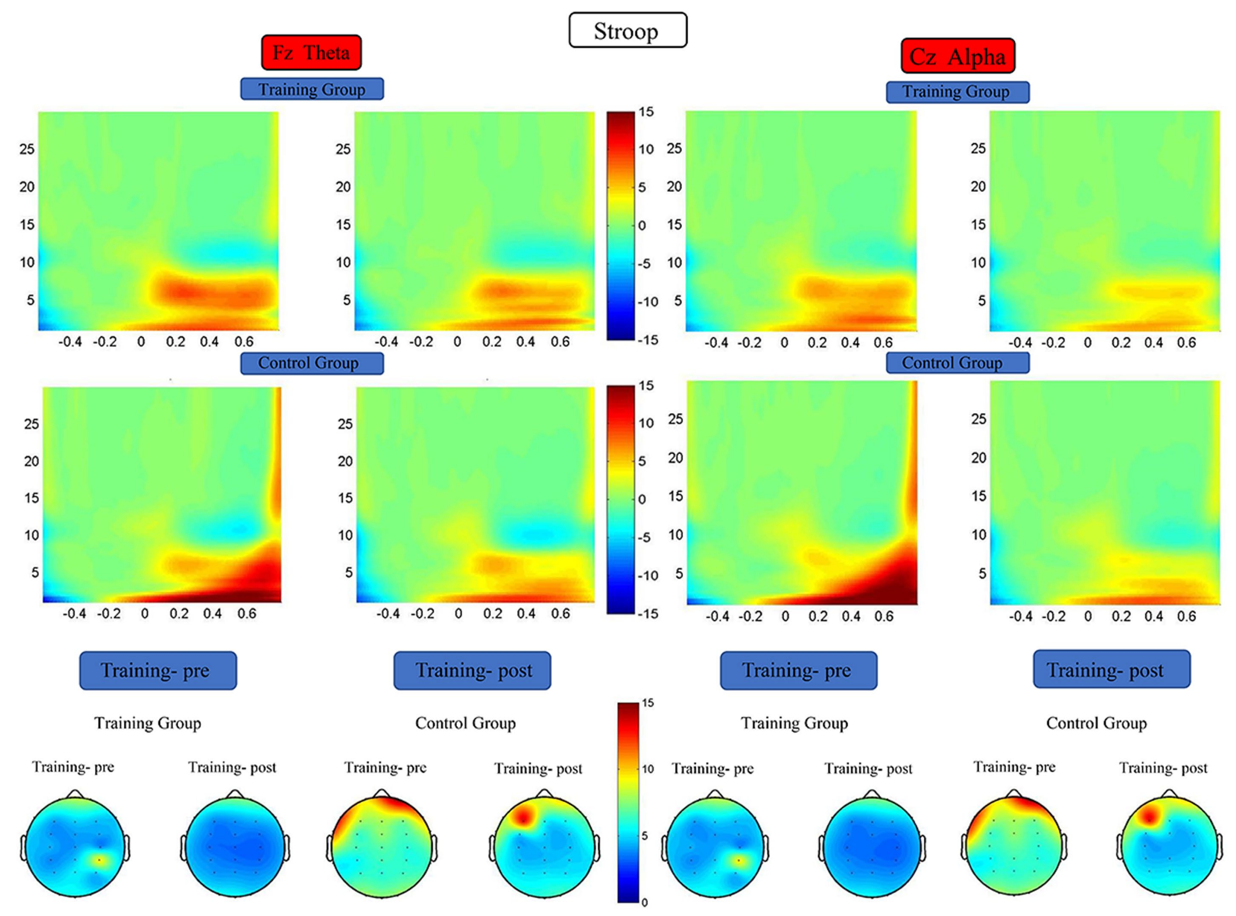

FIGURE 10
Spectrograms of mean ERSP of the two groups at electrode Fz and Cz. Training-pre, training group pretest; Training-post, training group posttest; Control-pre, control group pretest; Control-post, control group posttest.

part of an inhibition control task (Nigbur et al., 2012; PastöTter et al., 2013; Cavanagh and Frank, 2014). In the present study, the theta energy level in the prefrontal cortex of the participants who received training was significantly decreased, suggesting an improvement in the efficiency of individual response inhibition. When the change in N2 components is also considered, the findings collectively suggest that the effect of working memory training on individual response inhibition is similar to the results of normal individual development and that working memory training further promotes development of individual response control, which is consistent with the neural efficiency hypothesis (Micheloyannis et al., 2006).

The results of the present study revealed that the participants' alpha band energy levels were not significantly different after they had received the training. The idling hypothesis posits that a change in alpha band energy is related to brain excitability and represents an individual's investment of attention resources in the current task and the degree of inhibitory control that they have over irrelevant brain regions (Pfurtscheller et al., 1996). However, the present study did not reveal any significant change in alpha band energy after the training, which may have been related to the excessively short reaction time window that was set in the experimental program.

Consistent with our hypothesis, the working memory training did not cause the participants to undergo a significant change for the Stroop task. This finding is consistent with those of previous research. In a study conducted by Zhao et al. (2018), participants received 14 days of working memory training, and the results indicated that the training effects did not transfer to the Stroop task. This finding was also supported by the results of subsequent studies (Zhao et al., 2020). Although the Stroop and go/no-go tasks both involve individual inhibition control, they are essentially different. Friedman and Miyake (2004) argued that interference control occurs at a later time point than response inhibition. To fully implement interference control, interference information must first be distinguished and this is then followed by a response. By contrast, the completion of response inhibition only requires the current reaction to be stopped in time, so smaller resources are required for inhibition control than for interference control. Therefore, from the perspective of improving go/no-go task indicators, working memory training improves the efficiency with which individuals use inhibition control resources, but this

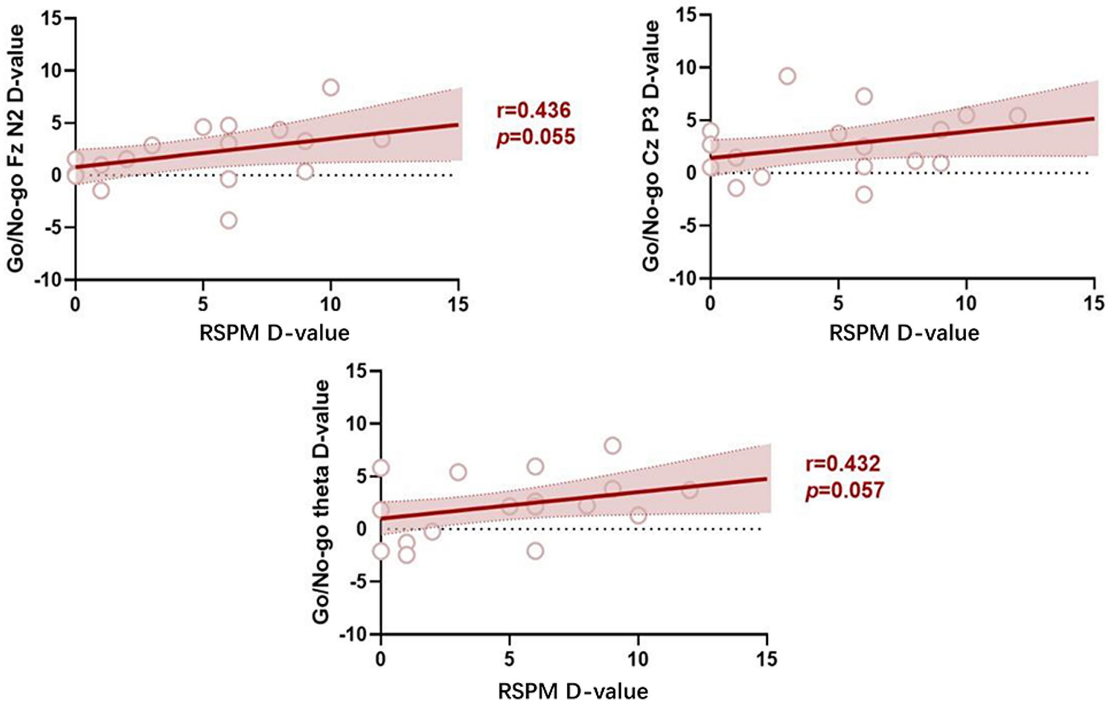

FIGURE 11
Correlations pertaining to differences in indicator values before versus after the training.

improvement can only be transferred to go/no-go tasks that require smaller cognitive resources. Nevertheless, other possible explanations cannot be ruled out. For example, the Stroop and go/no-go tasks involve different cognitive processes. From the perspective of attentional control, the Stroop task involves an inhibitory response to input stimuli, which emphasizes bottom-top cognitive processing. Conversely, the go/no-go task involves an individual's inhibition of their own response output, which emphasizes top-down cognitive processing (Avital-Cohen and Tsal, 2016; Hong et al., 2017). Several studies have reported that, from the perspective of attention training, the efficiency of an individual's attention network is considerably improved after they have received working memory training, and the activation mode is more mature (Rueda et al., 2005, 2012). This improvement may have a positive effect on top-down cognitive processing patterns, such that the training transfer effect for a go/no-go task is stronger.

Finally, Pearson's correlation was performed in the present study to examine significant changes in index values after the training. The results indicated that improvement of response inhibition is a positive predictor of improved fluid intelligence. This finding suggests that the effect of working memory training on fluid intelligence can be achieved by enhancing response inhibition.

Various intelligence theories have posited that individual fluid intelligence is strongly correlated with inhibition control because of large overlapping networks in the brain (Rueda, 2018). Brain imaging studies have demonstrated that specific frontoparietal networks involved in inhibitory control are activated when individuals perform tasks requiring fluid intelligence, with these networks including the dorsolateral, ventrolateral prefrontal, and dorsal cingulate networks (Duncan et al., 2000; Duncan and Owen, 2000). This finding is consistent with the parietofrontal integration theory of intelligence. This theory holds that individual fluid intelligence is based on the information integration ability of the frontoparietal network, and information-processing efficiency is related to the level of individual fluid intelligence (Jung and Haier, 2007; Langer et al., 2012;Hilger et al., 2017b). From the perspective of individual brain development, the development trajectory of individual inhibition control ability overlaps extensively with that of fluid intelligence, and the frontoparietal network of children with higher fluid intelligence has a more efficient information-processing mode (Langeslag et al., 2013; Vendetti and Bunge, 2014; Fjell et al., 2015). Munakata et al. (2012) also argued that children who are more efficient at implementing internally driven (top-down) response inhibition are better at internalizing and manipulating abstract representations. Stimulus-driven (bottom-top) behavioral inhibition does not contribute to this phenomenon (Liu et al., 2022; Munakata et al., 2012). The results of the present study further validate the aforementioned concept, that is, the response inhibition of children can be increased through working memory training. This is a more mature response inhibition model that contributes to the improvement of fluid intelligence and is primarily based on reasoning.

Nevertheless, the present study has several limitations. For example, it demonstrated a significant positive correlation between fluid intelligence and response inhibition but did not clearly prove a causal relationship between these two factors. In addition, the small sample size and lack of an active control group also limit the generalizability of the results. However, the results partly reflect the role of response inhibition during transfer of the effects of working memory training to fluid intelligence. Future studies should explore the dynamic development of this transfer process, the duration of the transfer effect, and the factors that influence the transfer effect.

Conclusion

The results of the present study suggest that working memory training can effectively improve the fluid intelligence of children, which is achieved by improving their individual response inhibition ability. This conclusion is that working memory training is an effective intervention method, which is of important implications to the intervention research on improving children's fluid intelligence in the future. Inhibition control or attention control is one of the important factors of children's fluid intelligence. Inhibitory control or attentional control ability is one of the important factors of fluid intelligence in children, and there is an interaction between individual intelligence system and inhibitory control system (Ye et al., 2017). This provides a theoretical basis for improving children's fluid intelligence by intervention with the inhibition control ability of individuals. The intervention of fluid intelligence in the future should be explored from the aspect of individual response inhibition to further clarify its role in the development of individual fluid intelligence.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Department of Psychology, Nanjing University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

LW analyzed the data and drafted the manuscript. AS designed the study, recruited participants, and conducted training sessions. LC edited the manuscript. RZ analyzed the data and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Au, J., Buschkuehl, M., Duncan, G. J., and Jaeggi, S. M. (2016). There is no convincing evidence that working memory training is NOT effective: a reply to Melby-Lervåg and Hulme (2015). *Psychon. Bull. Rev.* 23, 331–337. doi: 10.3758/s13423-015-0967-4

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., and Jaeggi, S. M. (2015). Improving fluid intelligence with training on working memory: a meta-analysis. *Psychon. Bull. Rev.* 22, 366–377. doi: 10.3758/s13423-014-0699-x

Avital-Cohen, R., and Tsal, Y. (2016). Top-down processes override bottom-up interference in the flanker task. *Psychol. Sci.* 27, 651–658. doi: 10.1177/0956797616631737

Benikos, N., Johnstone, S. J., and Roodenrys, S. J. (2013). Short-term training in the go/Nogo task: Behavioural and neural changes depend on task demands. *Int. J. Psychophysiol.* 87, 301–312. doi: 10.1016/j.ijpsycho.2012.12.001

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., and Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychol. Res.* 108, 624–652. doi: 10.1037/0033-295X.108.3.624

Brydges, C. R., Clunies-Ross, K., Clohessy, M., Lo, Z. L., Nguyen, A., Rousset, C., et al. (2012). Dissociable components of cognitive control: an event-related potential (ERP) study of response inhibition and interference suppression. *PLoS One* 7:e34482. doi: 10.1371/journal.pone.0034482

Burgess, G. C., Gray, J. R., Conway, A. R. A., and Braver, T. S. (2011). Neural mechanisms of interference control underlie the relationship between fluid intelligence and working memory span. *J. Exp. Psychol. Gen.* 140, 674–692. doi: 10.1037/a0024695

Carter, C. S., and van Veen, V. (2007). Anterior cingulate cortex and conflict detection: an update of theory and data. *Cogn. Affect. Behav. Neurosci.* 7, 367–379. doi: 10.3758/CABN.7.4.367

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: a critical experiment. *J. Educ. Psychol.* 54, 1–22. doi: 10.1037/h0046743

Cavanagh, J. F., and Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends Cogn. Sci.* 18, 414–421. doi: 10.1016/j.tics.2014.04.012

Chein, J. M., and Morrison, A. B. (2010). Expanding the mind's workspace: training and transfer effects with a complex working memory span task. *Psychon. Bull. Rev.* 17, 193–199. doi: 10.3758/PBR.17.2.193

Chen, X., Ye, M., Chang, L., Chen, W., and Zhou, R. (2017). Effect of working memory updating training on retrieving symptoms of children with learning disabilities. *J. Learn. Disabil.* 51, 507–519. doi: 10.1177/0022219417712015

Clark, J. M. (1996). Contributions of inhibitory mechanisms to unified theory in neuroscience and psychology. *Brain Cogn.* 30, 127–152. doi: 10.1006/brcg.1996.0008

Clayson, P. E., and Larson, M. J. (2011). Conflict adaptation and sequential trial effects: support for the conflict monitoring theory. *Neuropsychologia* 49, 1953–1961. doi: 10.1016/j.neuropsychologia.2011.03.023

Colom, R., Rebollo, I., Palacios, A., Juan-Espinosa, M., and Kyllonen, P. C. (2004). Working memory is (almost) perfectly predicted by g. *Intelligence* 32, 277–296. doi: 10.1016/j.intell.2003.12.002

Cowan, N., Fristoe, N. M., Elliott, E. M., Brunner, R. P., and Saults, J. S. (2006). Scope of attention, control of attention, and intelligence in children and adults. *Mem. Cogn.* 34, 1754–1768. doi: 10.3758/BF03195936

Delorme, A., and Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

Demetriou, A., Mouyi, A., and Spanoudis, G. (2008). Modelling the structure and development of g. *Intelligence* 36, 437–454. doi: 10.1016/j.intell.2007.10.002

DeWall, C. N., Baumeister, R. F., Mead, N. L., and Vohs, K. D. (2011). How leaders self-regulate their task performance: evidence that power promotes diligence, depletion, and disdain. *J. Pers. Soc. Psychol.* 100, 47–65. doi: 10.1037/a0020932

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Duncan, J., and Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci.* 23, 475–483. doi: 10.1016/S0166-2236(00)01633-7

Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., et al. (2000). A neural basis for general intelligence. *Science* 289, 457–460. doi: 10.1126/science.289.5478.457

Engle, R. W. (2002). Working memory capacity as executive attention. *Curr. Dir. Psychol. Sci.* 11, 19–23. doi: 10.1111/1467-8721.00160

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Fischer, R., Plessow, F., Kunde, W., and Kiesel, A. (2010). Trial-to-trial modulations of the Simon effect in conditions of attentional limitations: evidence from dual tasks. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 1576–1594. doi: 10.1037/a0019326

Fjell, A. M., Westlye, L. T., Amlien, I., Tamnes, C. K., Grydeland, H., Engvig, A., et al. (2015). High-expanding cortical regions in human development and evolution are related to higher intellectual abilities. *Cereb. Cortex* 25, 26–34. doi: 10.1093/cercor/bht201

Folstein, J. R., and Petten, C. V. (2008). Influence of cognitive control and mismatch on the n2 component of the erp: a review. *Psychophysiology* 45, 152–170. doi: 10.1111/j.1469-8986.2007.00602.x

Friedman, N. P., and Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *J. Exp. Psychol. Gen.* 133, 101–135. doi: 10.1037/0096-3445.133.1.101

Fu, X., Ye, C., Hu, Z., Li, Z., Liang, T., and Liu, Q. (2022). The impact of retro-cue validity on working memory representation: evidence from electroencephalograms. *Biol. Psychol.* 170:108320. doi: 10.1016/j.biopsycho.2022.108320

Gray, J. R., Chabris, C. F., and Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nat. Neurosci.* 6, 316–322. doi: 10.1038/nn1014

Gray, J. R., and Thompson, P. M. (2004). Neurobiology of intelligence: health implications? *Discov. Med.* 4, 157–162. PMID: 20704978

Greenwood, P. M., and Parasuraman, R. (2015). The mechanisms of far transfer from cognitive training: review and hypothesis. *Neuropsychology* 30, 742–755. doi: 10.1037/neu0000235

Hämmerer, D., Li, S. C., Müller, V., and Lindenberger, U. (2010). An electrophysiological study of response conflict processing across the lifespan: assessing the roles of conflict monitoring, cue utilization, response anticipation, and response suppression. *Neuropsychologia* 48, 3305–3316. doi: 10.1016/j.neuropsychologia.2010.07.014

Hilger, K., Ekman, M., Fiebach, C. J., and Basten, U. (2017a). Efficient hubs in the intelligent brain: nodal efficiency of hub regions in the salience network is associated with general intelligence. *Intelligence* 60, 10–25. doi: 10.1016/j.intell.2016.11.001

Hilger, K., Ekman, M., Fiebach, C. J., and Basten, U. (2017b). Intelligence is associated with the modular structure of intrinsic brain networks. *Sci. Rep.* 7, 1–12. doi: 10.1038/s41598-017-15795-7

Hommel, B., Proctor, R. W., and Vu, K. P. (2004). A feature-integration account of sequential effects in the Simon task. *Psychol. Res.* 68, 1–17. doi: 10.1007/s00426-003-0132-y

Hong, X., Wang, Y., Sun, J., Li, C., and Tong, S. (2017). Segregating top-down selective attention from response inhibition in a spatial cueing go/nogo task: an erp and source localization study. *Sci. Rep.* 7:9662. doi: 10.1038/s41598-017-08807-z

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proc. Natl. Acad. Sci. U. S. A.* 105, 6829–6833. doi: 10.1073/pnas.0801268105

Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Shah, P. (2011). Shortand long-term benefits of cognitive training. *Proc. Natl. Acad. Sci. U. S. A.* 108, 10081–10086. doi: 10.1073/pnas.1103228108

Johnstone, S. J., Barry, R. J., Markovska, V., Dimoska, A., and Clarke, A. R. (2009). Response inhibition and interference control in children with AD/HD: a visual ERP investigation. *Int. J. Psychophysiol.* 72, 145–153. doi: 10.1016/j.ijpsycho.2008.11.007

Jung, R. E., and Haier, R. J. (2007). The Parieto-frontal integration theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behav. Brain Sci.* 30, 135–154. doi: 10.1017/S0140525X07001185

Kane, M. J., Bleckley, M. K., Conway, A. R., and Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *J. Exp. Psychol. Gen.* 130, 169–183. doi: 10.1037/0096-3445.130.2.169

Kane, M. J., and Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: an individual differences perspective. *Psychon. Bull. Rev.* 9, 637–671. doi: 10.3758/BF03196323

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends Cogn. Sci.* 16, 606–617. doi: 10.1016/j.tics.2012.10.007

Klimesch, W., Sauseng, P., and Hanslmayr, S. (2007). Eeg alpha oscillations: the inhibition-timing hypothesis. *Brain Res. Rev.* 53, 63–88. doi: 10.1016/j.brainresrev.2006.06.003

Klingberg, T. (2010). Training and plasticity of working memory. *Trends Cogn. Sci.* 14, 317–324. doi: 10.1016/j.tics.2010.05.002

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. *J. Clin. Exp. Neuropsychol.* 24, 781–791. doi: 10.1076/jcen.24.6.781.8395

Langer, N., Pedroni, A., Gianotti, L. R. R., Hanggi, J., Knoch, D., and Jäncke, L. (2012). Functional brain network effciency predicts intelligence. *Hum. Brain Mapp.* 33, 1393–1406. doi: 10.1002/hbm.21297

Langeslag, S. J. E., Schmidt, M., Ghassabian, A., Jaddoe, V. W., Hofman, A., Van Der Lugt, A., et al. (2013). Functional connectivity between parietal and frontal brain regions and intelligence in young children: the generation R study. *Hum. Brain Mapp.* 34, 3299–3307. doi: 10.1002/hbm.22143

Liu, X., Liu, R., Guo, L., Astikainen, P., and Ye, C. (2022). Encoding-specificity instead of online integration of real-world spatial regularities for objects in working memory. *J. Vis.* 22, 8–20. doi: 10.1167/jov.22.9.8

Liu, T., Xiao, T., Shi, J., and Zhao, D. (2011). Response preparation and cognitive control of highly intelligent children: a go-nogo event-related potential study. *Neuroscience* 180, 122–128. doi: 10.1016/j.neuroscience.2011.02.022

Lo, S. L. (2018). A meta-analytic review of the event-related potentials (ern and n2) in childhood and adolescence: providing a developmental perspective on the conflict monitoring theory. *Dev. Rev.* 48, 82–112. doi: 10.1016/j.dr.2018.03.005

Makeig, S., Debener, S., Onton, J., and Delorme, A. (2004). Mining event-related brain dynamics. *Trends Cogn. Sci.* 8, 204–210. doi: 10.1016/j.tics.2004.03.008

Micheloyannis, S., Pachou, E., Stam, C. J., Vourkas, M., and Tsirka, V. (2006). Using graph theoretical analysis of multichannel eeg to evaluate the neural efficiency hypothesis. *Neurosci. Lett.* 402, 273–277. doi: 10.1016/j.neulet.2006.04.006

Milham, M. P., Banich, M. T., Claus, E. D., and Cohen, N. J. (2003). Practice-related effects demonstrate complementary roles of anterior cingulate and prefrontal cortices in attentional control. *NeuroImage* 18, 483–493. doi: 10.1016/S1053-8119(02)00050-2

Munakata, Y., Snyder, H. R., and Chatham, C. H. (2012). Developing Cognitive Control: three Key Transitions. *Current Directions in Psychological Science,* 21, 71–77. doi: 10.1177/0963721412436807

Nieuwenhuis, S., Yeung, N., Wildenberg, W., and Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: effects of response conflict and trial type frequency. *Cogn. Affect. Behav. Neurosci.* 3, 17–26. doi: 10.3758/CABN.3.1.17

Nigbur, R., Cohen, M., Ridderinkhof, K., and Stürmer, B. (2012). Theta dynamics reveal domain-specific control over stimulus and response conflict. *J. Cogn. Neurosci.* 24, 1264–1274. doi: 10.1162/jocn_a_00128

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: views from cognitive and personality psychology and a working inhibition taxo Nomy. *Psychol. Bull.* 126, 220–246. doi: 10.1037/0033-2909.126.2.220

Oberauer, K., Schultze, R., Wilhelm, O., and Süß, H.-M. (2005). Working memory and intelligence – their correlation and their relation: comment on Ackerman, Beier, and Boyle. *Psychol. Bull.* 131, 61–65. doi: 10.1037/0033-2909.131.1.61

Oberauer, K., Sü, H.-M., Wilhelm, O., and Sander, N. (2007). "Individual differences in working memory capacity and reasoning ability," in *Variation in Working Memory*. eds. A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake and J. N. Towse (Oxford University Press), 49–75.

PastöTter, B., Dreisbach, G., and BäUml, K. H. T. (2013). Dynamic adjustments of cognitive control: oscillatory correlates of the conflict adaptation effect. *J. Cogn. Neurosci.* 25, 2167–2178. doi: 10.1162/jocn_a_00474

Pfurtscheller, G., Stancak, A. J., and Neuper, C. (1996). Event-related synchronization (ers) in the alpha band - an electrophysiological correlate of cortical idling: a review. *Int. J. Psychophysiol.* 24, 39–46. doi: 10.1016/S0167-8760(96)00066-9

Pires, L., Leito, J., Guerrini, C., and Simes, M. R. (2014). Event-related brain potentials in the study of inhibition: cognitive control, source localization and age-related modulations. *Neuropsychol. Rev.* 24, 461–490. doi: 10.1007/s11065-014-9275-4

Raven, J. (2000). The Raven's progressive matrices: change and stability over culture and time. *Cogn. Psychol.* 41, 1–48. doi: 10.1006/cogp.1999.0735

Rico-Picó, J., Hoyo, A., Guerra, S., Conejero, A., and Rueda, M. R. (2021). Behavioral and brain dynamics of executive control in relation to children's fluid intelligence. *Intelligence* 84, 101513–101511. doi: 10.1016/j.intell.2020.101513

Righi, S., Mecacci, L., and Viggiano, M. P. (2009). Anxiety, cognitive self-evaluation and performance: erp correlates. *J. Anxiety Disord.* 23, 1132–1138. doi: 10.1016/j.janxdis.2009.07.018

Rueda, M. R. (2018). Attention in the heart of intelligence. *Trends Neurosci. Educ.* 13, 26–33. doi: 10.1016/j.tine.2018.11.003

Rueda, M. R., Checa, P., and Cómbita, L. M. (2012). Enhanced efficiency of the executive attention network after training in preschool children: immediate changes and effects after two months. *Dev. Cogn. Neurosci.* 2, S192–S204. doi: 10.1016/j.dcn.2011.09.004

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., and Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proc. Natl. Acad. Sci. U. S. A.* 102, 14931–14936. doi: 10.1073/pnas.0506897102

Van Veen, V., and Carter, C. S. (2002). The tinning of action-monitoring processes in the anterior cingulate cortex. *J. Cogn. Neurosci.* 14, 593–602. doi: 10.1162/08989290260045837

Vendetti, M. S., and Bunge, S. A. (2014). Evolutionary and developmental changes in the lateral frontoparietal network: a little goes a long way for higher-level cognition. *Neuron* 84, 906–917. doi: 10.1016/j.neuron.2014.09.035

Wessel, J. R. (2018). Prepotent motor activity and inhibitory control demands in different variants of the go/no-go paradigm. *Psychophysiology* 55:e12871. doi: 10.1111/psyp.12871

Wiley, J., Jarosz, A. F., Cushen, P. J., and Colflesh, G. (2011). New rule use drives the relation between working memory capacity and raven's advanced progressive matrices. *J. Exp. Psychol. Learn. Mem. Cogn.* 37, 256–263. doi: 10.1037/a0021613

Ye, C., Hu, Z., Li, H., Ristaniemi, T., Liu, Q., and Liu, T. (2017). A two-phase model of resource allocation in visual working memory. *J. Exp. Psychol. Learn. Mem. Cogn.* 43, 1557–1566. doi: 10.1037/xlm0000376

Ye, C., Sun, H., Xu, Q., Liang, T., Zhang, Y., and Liu, Q. (2019). Working memory capacity affects trade-off between quality and quantity only when stimulus exposure duration is sufficient: evidence for the two-phase model. *Sci. Rep.* 9:8727. doi: 10.1038/s41598-019-44998-3

Ye, C., Xu, Q., Liu, Q., Cong, F., Saariluoma, P., Ristaniemi, T., et al. (2018). The impact of visual working memory capacity on the filtering efficiency of emotional face distractors. *Biol. Psychol.* 138, 63–72. doi: 10.1016/j.biopsycho.2018.08.009

Zhao, X., Dang, C., and Maes, J. (2020). Effects of working memory training on eeg, cognitive performance, and self-report indices potentially relevant for social anxiety. *Biol. Psychol.* 150:107840. doi: 10.1016/j.biopsycho.2019.107840

Zhao, X., Wang, Y., Liu, D., and Zhou, R. (2011). Effect of updating training on fluid intelligence in children. *Chin. Sci. Bull.* 56, 2202–2205. doi: 10.1007/s11434-011-4553-5

Zhao, X., Xu, Y., and Maes, J. (2018). Are training and transfer effects of working memory updating training modulated by achievement motivation? *Mem. Cogn.* 46, 398–409. doi: 10.3758/s13421-017-0773-5

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The effect of color coding and layout coding on users' visual search on mobile map navigation icons

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Color and spatial layout are important factors that affect users' icon cognition and play a huge role in the visual search process of icons. Guided by the user's interactive needs, this paper aims to improve the visual search efficiency of mobile map navigation icons. The mixed design within and between subjects is adopted through the combination of theoretical and experimental research, and the subjective questionnaire method is used to explore the research. This paper explores the visual search problem of mobile map navigation icons based on color coding and layout coding. The experimental results mainly include reaction time, accuracy rate, user experience, and statistical and variance analysis. The results show that the layout of the mobile map navigation icons significantly impacts the user's visual search. The navigation icons that use color for layout coding have the highest visual search efficiency and better user experience. Among the icons, the layout with regular color distribution and a larger area of the same color has the highest visual search efficiency for users and the best user experience; the visual search efficiency of navigation icons using color for layout coding is significantly higher than that of mobile map navigation icons.

Relevance to industry: The user scale of mobile information maps is huge and the usage rate is high, but the large number of navigation icons increases the burden of user information identification and acquisition. As a result, the efficiency of user information acquisition is low, and the user experience is reduced. A clear, easy-to-search navigation icon design can enhance the user experience of the entire product. The results of this research provide theoretical support and practical guidance for the design optimization and improvement of mobile map navigation icons.

KEYWORDS

color coding, spatial layout, mobile interface, navigation icons, visual search, eye tracking

Introduction

The development and popularization of network communication technology have facilitated the life and travel of users. With the development of science and technology, the development of mobile terminals, and the maturity of 4G and 5G, the mobile map has developed rapidly. In 2008, policies related to mobile maps were introduced, which brought the industry into a period of rapid development. In 2021, the number of mobile map users in China will reach 800 million (IIMedia Research Center for Life and Travel Industry, 2019). The mobile map has the characteristics of easy portability, accurate positioning, and comprehensive data. It plays an important role in people's travel and has a broad market and far-reaching influence.

People obtain services through mobile information maps, such as route navigation, real-time positioning, location search, location sharing, and surrounding discovery. This information is presented in the navigation system of the mobile map in the form of icons. Icons can quickly transmit information, highly condense information, and facilitate information memory. The good design and application of navigation icons greatly help to improve users' visual search efficiency and experience when using information maps on mobile terminals. Recognition and recognition of navigation icons rely on visual search, users' visual search for navigation icons directly affects the efficiency of using mobile maps. Visual search is a complex cognitive process and is a common experimental paradigm for studying visual perception processing and attention mechanisms. Visual search is inseparable from attentional processing. The main factors affecting attentional processing are object features and locations. Therefore, feature attention and spatial attention are important factors affecting visual search. Only by refining and structuring the navigation icons of the mobile map in terms of features and spatial layout can the user's visual search efficiency for navigation icons be improved, and it is convenient for people to browse and understand quickly and easily. At the same time, the user experience of the mobile map is improved.

Visual search for icon colors

Color plays a very obvious role in the various factors that affect visual search. As the most direct and effective coding method, the first thing users see is color information. Designers use different colors to categorize interface information to help people find icons and buttons. Consistent and easy-to-understand color coding can help users easily understand their internal connections and help them search more accurately (Steven, 2008). Preferential assignment of colors by vision relies on selective processing of attention (Li and Xue, 2016). When users search for icons, they will first classify different icons by vision, code them according to color, then pay attention to processing to filter and layer the icons, and finally, pay attention to in-depth processing to focus on the target. Research on attentional capture of color has shown that users will have a layered effect on visual perception in the process of color coding, which affects the attention order of information and search performance (Li et al., 2018). Users will have a psychological sense of advance and retreat for different colors, then form different perception depths, that is, color perception distances, leading to visual perception stratification. Color coding can guide the user's visual behavior in the icon search process, and users can effectively improve cognitive performance by color coding through visual perception hierarchy. The visual layering method was proposed by Laar (2001a,b) in the study of color-enhancing visual display design. The research on color perception distance believes that the three attributes of lightness, hue and saturation (Munsell color stereo) are in line with the three-dimensional equidistance of people's vision. Therefore, the same perceived distance is one of the variables to be controlled when selecting the icon color. The CIE L*a*b color space is the most comprehensive representation of the spectrum seen by the human eye and provides a reference for most common color spaces. Therefore, the icon colors in the experimental materials should use the colors with the same perceptual distance in the CIE Lab space.

Studies have examined the effect of display chromaticity contrast on multicolor GUIs (Bodrogi, 2003). The research on the color change of interactive elements by the eye control system verifies that color saturation and brightness can affect the users' visual search efficiency (Niu et al., 2022). Related research on factors such as different background color classification of icons and color combinations between icons and backgrounds have found that color significantly impacts icon visual search. Color features play an important role in visual pre-attention processing. The smaller the icon background area divided by color, the lower the users' visual search efficiency (Michalski and Grobelny, 2008; Michalski, 2014). In addition to the research on the icons' background color, the related research on the color of the icon itself and other physical properties has confirmed that color coding is the most effective coding method for the usability of the icon. The effectiveness of shape coding is higher than that of icon size (Nowell, 1997). The research on color perception distance believes that the three attributes of lightness, hue, and saturation (Munsell color stereo) align with the three-dimensional equidistance of users' vision. A study was conducted on users' icon cognition through attributes such as hue, saturation, and brightness, and it was found that color significantly impacted users' visual search (Hsieh, 2017). Dennis (2008) pointed out through research that using color attributes such as lightness, hue, and saturation to design relevant information can help users identify information and improve search efficiency (Huang, 2008). Wu and Chen (2009) studied 18 GUIs containing color attributes of sofa appearance and found that color grouping was one of the most important factors affecting users' performance and satisfaction. Previous studies have studied the effect of icon and background color combination and icon and background area ratio on visual search efficiency. The research found that the color combination significantly impacts the icons' visual search efficiency. The visual search efficiency of the icon with black blue and black yellow color matching is higher than white-yellow or white-blue, and the visual search efficiency of an icon with an area ratio of 90% to the background is higher than that of an icon with an area ratio of 70% (Huang, 2008). The consistency and number of icon colors will affect the visual search of icons. Increasing the number of colors will reduce the visual search efficiency of icons to a certain extent. Using colors to increase the difference between icons can effectively improve the visual search efficiency of icons (Gong et al., 2016a). The research found that the shape of smartphone application icons has no significant impact on visual search; the color contrast significantly impacts icon visual search, and low-contrast icons can attract users' attention more than high-contrast icons. Icons are more efficient for visual search than icons combined with graphic and text patterns (Jiang et al., 2015). In smartphone interfaces, research on the search efficiency of icon colors and borders shows that icons' different colors and rounded square borders can improve users' visual search efficiency and reduce cognitive load (Liu et al., 2021). In the process of complex information transmission, color plays a huge role in visual perception and cognition, and color coding is an important information coding method of visual search. Therefore, it is significant to study the effect of color coding on the interaction interface on the visual search of user icons. It is necessary to further explore how users search for navigation icons of different colors when using mobile phone maps.

Visual search for icon space layout

Spatial layout plays an important role in visual search, and interface icon design is inseparable from the spatial layout design. The layout of icons refers to the arrangement and design of related elements such as icons in the interface. By arranging and designing the position, color, and size of the icons in the interface, it helps users to quickly find the target content on the interface (Peng, 2021). The spatial layout design of the human-computer interaction interface is mainly to regularize and organize the information and establish a visual structure. The information processing capability of the human visual system is limited, and the layout of interface information has a huge impact on the user's visual search efficiency (Wolfe and Horowitz, 2007). In the human-computer interaction interface, the perceptual sequence plays an important role in guiding the information encoding of the brain, and a good information layout and visualization structure can reduce the occurrence of cognitive load problems of users (Li, 2018). The brain processing of perceptual order is based on the principle of spatiotemporal proximity. Users can associate visual elements acquired at different times to form spatial structures according to the sequence, location, interval and other attributes of interface information, and perform cognitive processing on different structures according to the time sequence (Amiez and Petrides, 2007). The information coding basis of perceptual order is the principle of spatial configuration. The spatial configuration is the input of information direction and position, and the output of information association based on information and spatial structure characteristics (Li, 2018). According to the principle of space configuration, the layout design and visual structure design of icons can help users to configure the interface icons. From the above research, it is not difficult to find that most of the research on the effect of color on the visual search of icons is related to the spatial layout. And the results show that feature attention and spatial in visual search are carried out simultaneously.

The related research on icon grouping layout design and visual search shows that the display method of classifying icons can significantly improve visual search efficiency (Niemelä and Saarinen, 2000). The experimental results combined with eye movement features show that grouped icons have fewer fixations than randomly arranged icons, and users of grouped icons have higher visual search efficiency, further confirming this result (Murata and Furukawa, 2005). Fleetwood et al. used the adaptive control of thought-rational/perceptual motor (ACT-R/PM) model of the adaptive control system, combined with eye movement experiments to study the users' visual search strategy. They examined the influence of the icon frame, icon quality, text and other factors on the visual search efficiency, and the results found that when searching for high-quality icons in interference icons, the subjects will use the group search strategy; when searching for low-quality icons, the subjects will change the search Strategies are searched by text (Fleetwood and Byrne, 2002, 2006). Spatial layout factors affecting icons' visual search include color matching, arrangement, and target location. The eye smooth pursuit study by Euclidean algorithm pointed out that the variable in the center position has the greatest influence on the tracking efficiency (Niu et al., 2021). When the navigation panel is located in different positions on the screen, it will impact the users' visual search performance. When the navigation panel is located at the top or left of the screen, the users' search efficiency is more efficient (Schaik and Lin, 2001). In a similar study, through the study of different positions of the icon panel, it was found that when the panel is located on the left, right, or top and bottom of the interface, there is no significant difference in the users' search efficiency (Pearson and Schaik, 2003). In the experiment on the number of icons, arrangement, icon panel structure, and other factors affecting the users' response time, it is found that the user operation efficiency of the compact square structure icon panel is the highest, followed by the horizontal arrangement, and finally the vertical arrangement (Grobelny et al., 2005). Based on previous research, Michalski et al. found that when the icons are arranged vertically, they is located on the screens' left or right side, does not significantly impact the users' visual search time (Michalski et al., 2006). A recent study by domestic scholars examined the effect of different icon structures and positions on user search efficiency. The results found that the icons with a square layout have the highest operating efficiency for users, while the circular layout has the lowest operational efficiency. There is no significant difference between icons' horizontal and vertical distribution (Chen and Chiang, 2011). Further combining the eye movement experiment and the ACT-R model, through the analysis of eye movement data such as eye movement trajectory and visual heat map, it is found that there is also a relationship between color and shape and visual search. Users will first use color during the search process to implement a 'grouping strategy' to improve search efficiency (Wang et al., 2016). Gong et al. (2016a) investigated the influence of factors such as icon size, icon panel distribution direction, layout, and icon location on users' visual search. The results showed that the smaller the icon, the lower the users' search efficiency. The larger the aspect ratio of the icon panel, the lower the search efficiency. When the icon is located at the top of the screen, the users' visual search efficiency is higher than that at the bottom. The visual search efficiency of the horizontally distributed icons is higher than that of the vertically distributed icons. The difference in search efficiency between the horizontal and vertical distribution of icons varies with the aspect ratio value of the icon panel (Gong et al., 2013). Different layout structures of icons affect the users' visual search efficiency. The search efficiency is the lowest when the icon layout structure is annular. When the icon layout structure is rectangular or round, there is no significant difference in the users' visual search efficiency (Kong, 2021). The visual characteristics and number of icons also affect the layout of icons. When the number of icons is 6, the visual characteristics of icons are the main factors affecting users' visual search. When the number of icons is 15, the layout is the main factor affecting visual search, and the horizontal Distributed icons are most efficient for visual search (Jin et al., 2021). The above research shows that the spatial layout of icons through grouping and other means can effectively suppress the interference of non-target stimuli, thereby improving the visual search efficiency of icons.

Mobile phone map navigation icons are usually presented in a random arrangement of 3–4 colors. How different layouts affect users' visual search needs further analysis.

Purpose of the study

At this stage, the problems related to the presentation and visualization of the navigation icon interface of the mobile map are discussed more from the product itself. There are few pieces of research on the visual design of the mobile map, and there are very few interface designs specifically for navigation icons.

This research will analyze the navigation icons of the mobile map, use the selective color simplification method to process the icons, and design and carry out the visual search experiment of the icons under the user's color coding and different spatial layout combination designs. At the same time, the research investigates the subjects' subjective feelings, studies the visual search efficiency of users under different colors and layouts, and compares the visual search levels of users under different color coding. Finally, this paper will propose the color and layout scheme of the best mobile map navigation icons based on visual search and provide a scientific basis for the design of mobile terminal navigation icons.

Materials and methods

Experiment design

The experiment adopts the experimental method of within-subject and between-subject mixed design. The research includes two independent variables, color (R, G, B) and grouping method (G0 is a single color without grouping, G1 is a random distribution grouping method, G2 (1 × 5), G3 (3 × 5)), color is a between-subject variable, and grouping method is a within-subject variable. Therefore, this is a 3 × 4 mixed design experiment. The experiment includes six experimental conditions, R, G, B, G1, G2, and G3, of which R, G, and B are all grouped by G0 (as shown in Table 1). The experiment was conducted in three groups, and each participant completed one of the tasks. Under any experimental condition, subjects need to complete 10 search tasks. In order to increase the randomness during the experiment, the target will not appear in 3 search tasks. Therefore, each subject needs to complete 40 visual search tasks.

Experiment material

In the experiment, the CIE Lab color space is used as a color coding tool. In the CIE Lab color space, red (R), green (G), and blue (B) with the same perceptual distance are selected as the icon colors. The specific color specifications are shown in Table 2. In order to make the experiment more in line with the real icon search

TABLE 1 Six experimental conditions and their layout.

Serial number	Color	Layout	Icon Form	G1	G2	G3
1	R	-	G0	*(1)		
2	G	-	G0		*(1)	
3	B	-	G0			*(1)
4	-	Random	G1	*(2)	*(2)	*(2)
5	-	1*5	G2	*(3)	*(3)	*(3)
6	-	3*5	G3	*(4)	*(4)	*(4)

*represents the number of experiments under this test condition.

TABLE 2 Colors used in icons.

Color	Color sample	CIE LAB	Decimal RGB	Color pantone
R	🟥	(58, 49, 17)	(221, 101, 114)	# DD 65 72
G	🟩	(58, −47, 29)	(36, 159, 85)	# 24 9F 55
B	🟦	(58, −14, −45)	(18, 150, 219)	# 12 96 DB

situation, this experiment selected a representative mobile map - AutoNavi map navigation icon interface for design, including icon content (with AutoNavi map navigation icon as reference), icon type (Select the flat icons used in the mobile map navigation icons) and the icon arrangement (5 icons in a row) to ensure that the display effect of the icons seen by the subjects in the experiment is the same as the presentation effect of the real mobile map navigation icons. The experimental materials are presented together with icons and text, and the way in which the experimental materials are presented will not affect the subjects. Zhang Yue studied the visual cognition of the design of the APP interface navigation system and found that when the text is used as auxiliary information next to the icon, the user can directly identify it through the icon, and the auxiliary text is mostly ignored by the user (Zhang, 2017). In order to ensure the randomness of the experiment, the design of monochrome mobile map navigation icons is retained in this experiment. Figure 1A is the current mobile map navigation icon interface, Figure 1B is the single-color icon interface G0, and

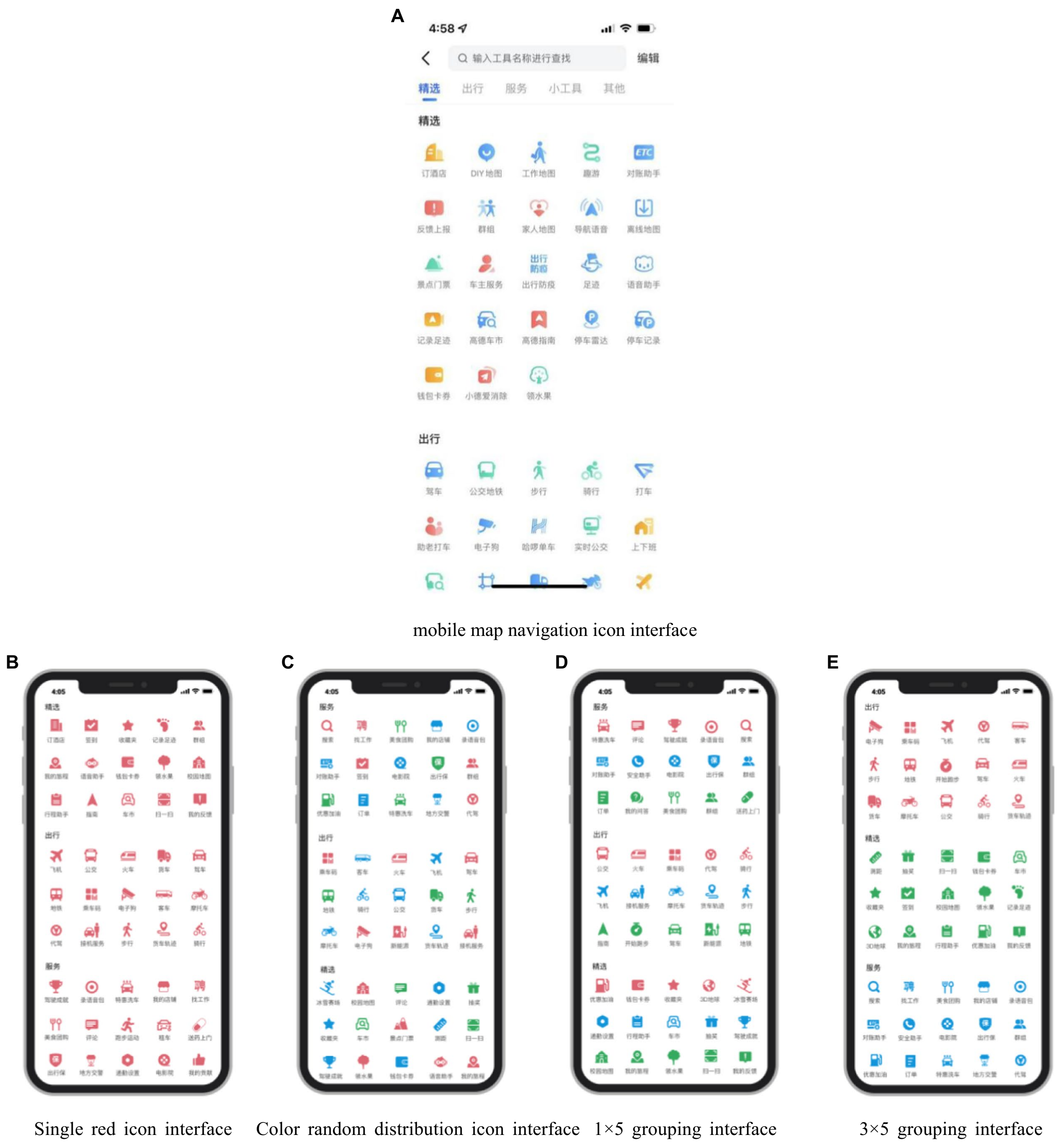

FIGURE 1
The icon interface used in the experiment. **(A)** mobile map navigation icon interface. **(B)** Single red icon interface **(C)** Color random distribution icon interface **(D)** 1×5 grouping interface **(E)** 3×5 grouping interface.

Figure 1C is the three-color combination randomly distributed icon interface G1 (in this experiment, the existing mobile map navigation icon interface), Figure 1D is the 1 × 5 layout icon interface G2, Figure 1E is the 3 × 5 layout icon interface G3.

Experiment equipment

The experiment was written and controlled through the Experiment Builder program, and the behavioral data of the subjects were automatically recorded in a text file. The eye tracking instrument is the EyeLink1000 desktop eye tracker (as shown in Figure 2) produced by SR Company in Canada, and the sampling frequency of the eye tracker is 1,000 times/s. Stimulus material was displayed in the center of a 19-inch Dell computer monitor with a resolution of 1,024 × 768 pixels and a refresh rate of 100 Hz. The distance between the subjects' eyes and the computer screen was about 50 cm. The subjects completed the experimental tasks by pressing the keys on the keyboard. Figure 3 was taken during the operation of the tested experiment.

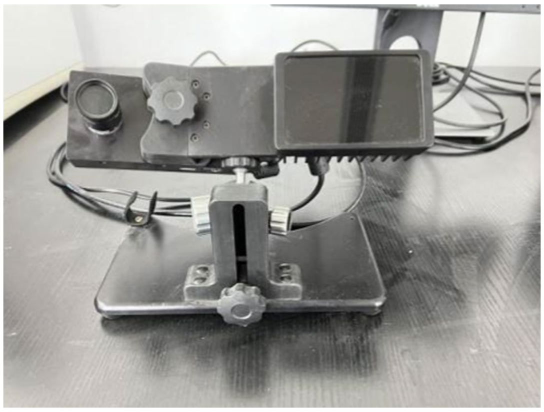

FIGURE 2
EyeLink1000 Desktop Eye Tracker.

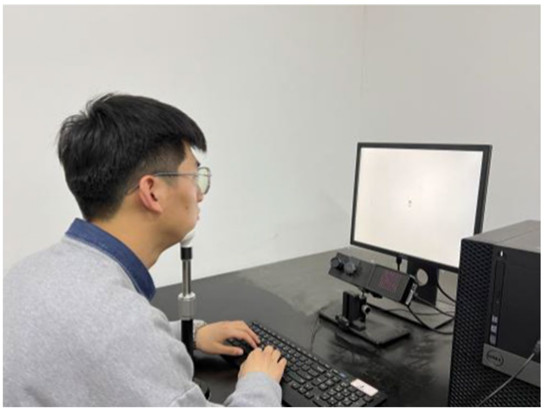

FIGURE 3
Photo of participant participating in the experiment.

Participants

The experimental subjects were 30 undergraduate and postgraduate students, including 13 boys and 17 girls, aged 21–29. All subjects were right-handed with normal or corrected-to-normal vision and no color blindness or color weakness. All the subjects have not done similar experiments before, and they can get a certain reward after the experiment.

Procedure

The whole experiment is divided into two parts, the first part is a behavioral experiment and eye movement experiment, and the second part is a subjective questionnaire. Behavioral and eye-movement experiments were conducted on an individual basis. After the subjects entered the laboratory, they first sat in front of the test machine with their eyes perpendicular to the screen and then supported their chins on the fixed bracket to keep their heads still to ensure the accurate tracking of the eyes by the experimental equipment. Before the start of the normal laboratory, the first is to conduct a practice experiment. The main tester presents the experimental instructions to the subjects through the monitor to ensure that the subjects understand the experimental procedures. Then perform eye calibration through the eye tracker, and then start the practice experiment. The practice experiment performs four keystroke responses. The operation of the practice experiment is consistent with the formal experiment to ensure that the subjects are proficient in key-pressing tasks and reduce experimental errors. After completing the practice experiment, the subjects rested for 10 s and then started the formal experiment. The first target icon is displayed in the center of the screen, the icon disappears after 2000 ms, and the navigation icon interface under a certain experimental condition is displayed in the center of the screen. The subject needs to search for the target icon that appeared before in the interface. If the target icon is found, press the "f" key; if not found, press the "j" key. After pressing the button, the masking stimulus is presented in the center of the screen, and the experiment ends here. At this point, a search task is completed. A random screen displays the target icon for the second search mission, which starts. This is done in sequence until the subjects complete all the search tasks. Figure 4 shows an example of the experimental process.

The subjective questionnaire includes three dimensions, satisfaction, usability, and preference. The questionnaire adopts the 9-level Likert scale evaluation method, and there are 15 questions on all the scales.

Results

The experimental results include behavioral data and eye movement data. The behavioral data includes reaction time and accuracy, and the eye movement data includes the number of gazes, Gaze time, and saccade length. Behavioral data were recorded by EB, and eye movement data were recorded and

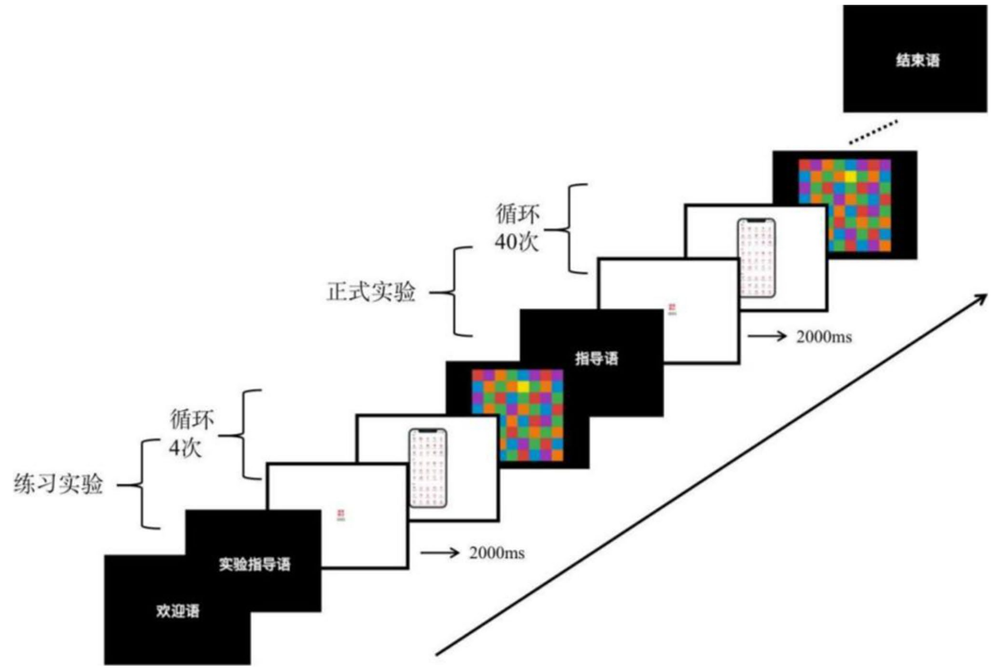

FIGURE 4
Experimental procedure example.

exported by DateViewer. The behavioral and eye movement data were processed and analyzed by SPSS.

Behavioral experimental data

The experimental behavioral data of the subjects under the six experimental conditions are counted, and the specific conditions are shown in Table 3.

Repeated measures ANOVA was performed on response time, and the results given in Table 4 shows that the main effect of layout was very significant, $F(2, 54) = 35.409$, $p < 0.05$; the main effect of color was not significant, $F(2, 54) = 0.717$, $p = 0.497$; the interaction of color and layout was not significant, $F(4, 54) = 1.540$, $p = 0.102$. For further analysis of the layout, the pairwise comparison results showed that the difference between G1 and G2 was significant ($p < 0.001$), the difference between G1 and G3 was significant ($p < 0.001$), and the difference between G2 and G3 was not significant ($p < 0.001) = 0.332$). This result shows that color is not the main factor affecting the visual search efficiency of icons, and the spatial layout design can significantly improve the visual search efficiency of users. Since the monochrome navigation icon interface does not belong to any layout method, the monochrome navigation icon interface G0 is not involved in the previous pairwise comparison.

In order to further explore the influence of different layout methods on the visual search efficiency of icons, a one-way analysis of variance was performed on the response time data of 4 different layout methods. The results are shown in Table 5, the difference between G0 and G2 was significant ($p < 0.001$), and the difference between G0 and G3 was significant ($p < 0.001$); the difference between G1 and G2 was significant ($p < 0.001$), and the difference between G1 and G3 was significant ($p = 0.006$).); the difference between G2 and G3 was not significant ($p = 0.769$). The result shows that, compared with the monochromatic navigation icon interface, the icon interface using color for layout coding has higher visual search efficiency. The visual search efficiency of the layout method with random color distribution is not significantly different from that of the monochrome icon interface, but the visual search efficiency of the layout method with more regular color distribution (G2, G3) is significantly higher than that of the random distribution layout method.

Repeated-measures ANOVA was performed at the correct rate, and the results as Table 6. showed that the main effect of the layout was significant, $F(2, 54) = 3.578$, $p = 0.035$, indicating differences among different layouts of G1, G2, and G3. The interaction between color and layout is not significant, $F < 1$. The output of the between-subject variable showed that the main effect of color was not significant, $F(2, 54) = 1.056$, $p = 0.362$. The generalized linear model analysis of the layout method shows that the difference between G1 and G2 is significant ($p = 0.030$), the difference between G1 and G3 is not significant ($p = 0.088$), and the difference between G2 and G3 is not significant ($p = 0.642$). This result shows that the search accuracy rate of the subjects is not affected by color, but there are significant differences in the layout. The icon interface G1 with random color distribution has the lowest search accuracy rate of 85.71%, and the color distribution regular G2 and G3 grouping search. The correct rate

TABLE 3 Behavioral data for six experimental conditions.

Color	Layout	Average response time/ms		Average correct rate/%	
		Average	Standard deviation	Average	Standard deviation
R	G0	3,678.577	1,078.053	88.57	1.127
G		4,257.810	1,227.204	90.00	1.355
B		3,086.516	1,495.224	80.00	1.205
	G1	2,958.876	909.632	85.71	1.353
	G2	2,105.345	466.730	92.38	1.109
	G3	2,272.131	575.173	90.95	1.155

TABLE 4 Results of repeated measures ANOVA on visual search time.

Factor	df	*F*	*p*
Layout	2	35.409	0.000
Color	2	0.717	0.497
Layout × color	4	1.540	0.204

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

is higher than that of G1, and the correct rate of G3 is higher than that of G2, indicating that in different layout methods, the grouping arrangement (G3) with a larger area of the same color has a higher search accuracy.

Further one-way ANOVA was performed on the correct rates of the four different layout methods. The results are shown in Table 7, the difference between G0 and G2 is marginally significant ($p = 0.053$), and the difference between G0 and the other two layout methods, G1 and G3, is not significant ($p > 0.05$); the difference between G1 and G2 Significant ($p = 0.037$), the difference between G1 and G3 was not significant ($p = 0.101$); the difference between G2 and G3 was not significant ($p = 0.653$). The result shows that for the correct rate, there are differences between G2 with regular color distribution, G0 with monochrome navigation icon interface, and G1 with the random color distribution. Among the icons with regular color distribution, the icon layout (G3) with a larger area of the same color has a higher visual search accuracy.

Eye movement data

Table 8 shows the eye movement data of the subjects under the six experimental conditions, including the number of fixations, fixation time, saccade length, and their mean and standard deviation.

TABLE 5 One-way ANOVA test for different layouts (reaction time).

	G0	G1	G2	G3
G0	×	0.103	0.000	0.000
G1		×	0.000	0.006
G2			×	0.769
G3				×

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

TABLE 6 Results of repeated measures ANOVA on correct rate.

Factor	df	*F*	*p*
Layout	2	3.578	0.035
Color	2	1.056	0.362
Layout × color	4	0.845	0.503

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

TABLE 7 One-way ANOVA test for different layouts (correct rate).

	G0	G1	G2	G3
G0	×	0.881	0.053	0.135
G1		×	0.037	0.101
G2			×	0.653
G3				×

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

The number of fixations is the number of all the fixation points of the subjects during the visual search during the period of interest and the area of interest. The number of fixation points can indicate the depth of information processing by the subjects during visual search. In this experiment, the more the number of fixations, the deeper the information processing, and the lower the search efficiency. Through repeated measures ANOVA on number of fixations (Table 9), it was found that the main effect of grouping mode was very significant, $F(2, 54) = 10.106$, $p < 0.01$. The interaction between color and different layouts was not significant, $F(4, 54) = 1.044$, $p > 0.05$. The output of the between-subject variable showed that the main effect of color was not significant, $F(2, 54) < 1$, $p = 0.528$. Further generalized linear model analysis was conducted on different layouts of navigation icons. The results showed that the number of fixations between G1 and G2 was significantly different ($p = 0.016$), the number of fixations between G1 and G3 was significantly different ($p = 0.011$), and the number of fixations between G1 and G3 was significant ($\mathrm{p} = 0.011$). The difference in the number of fixations with G3 was not significant ($p = 0.899$). The result shows that in the mobile map navigation icon interface, when users search for icons, the color has no significant impact on the number of gazes, and the layout significantly affects the number of fixations when users search for icons. And the number of fixations of the subjects in the navigation icon interface with regular color distribution is less than that of icons with a random color distribution.

In order to further explore the influence of different layout methods on the number of subjects' fixations, a one-way analysis of variance was performed on the four different layout methods.

TABLE 8 Eye movement data for six experimental conditions.

Color	Layout	Number of fixations/time		Fixations time/ms		Saccade length/rad	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
R	G0	20.363	5.301	5,316.125	1,605.910	46.749	16.040
G		21.410	3.756	5,612.895	1,013.379	51.371	10.823
B		17.355	6.147	4,725.907	1,329.726	41.167	14.737
	G1	16.296	3.603	4,421.482	875.517	36.022	11.172
	G2	14.233	3.529	3,953.692	742.815	27.417	10.260
	G3	14.124	2.718	4,077.282	974.845	29.728	7.453

TABLE 9 Results of repeated measures ANOVA on number of fixations.

Factor	df	F	p
Layout	2	10.106	0.000
Color	2	0.654	0.528
Layout × color	4	1.044	0.393

*p <0.05. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

TABLE 10 One-way ANOVA test for different layouts (number of fixations).

	G0	G1	G2	G3
G0	×	0.040	0.000	0.000
G1		×	0.172	0.070
G2			×	1.000
G3				×

*p <0.05. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

The results are shown in Table 10. The difference between G0 and G1 was significant ($p = 0.040$), the difference between G0 and G2 was significant ($p < 0.001$), and the difference between G0 and G3 was significant ($p < 0.001$), the difference among G1, G2, G3 was not significant ($p > 0.05$). The result shows that the number of fixations of monochrome navigation icons is more than that of navigation icons laid out by color. There is no significant difference in the number of fixations between navigation icons laid out by color.

The fixation time is the sum of the durations of all fixation points in the period or area from the time the subject's fixation point enters the interest period or area of interest until the fixation point leaves the period or area. The fixation time indicates the time spent by the subjects in visual search in a certain period or area. In this experiment, the longer the subject's fixation time, the more time the subject spends on the search task, and the lower the visual search efficiency. Using repeated measures ANOVA to analyze fixation time, the results (as Table 11) showed that the main effect of the layout was significant, $F(2, 54) = 4.893$, $p = 0.011$. The interaction between color and layout was insignificant, $F < 1$, $p > 0.05$. The output of the between-subject variable showed that the main effect of color was not significant, $F(2, 54) = 0.417$, $p = 0.663$. Further pairwise comparison of different layouts shows that the difference between G1 and G2 is significant ($p = 0.037$), the difference between G1 and G3 is not significant ($p = 0.125$), and the difference between G2 and G3 is not significant ($p = 0.125$). 0.582). The result shows that the fixation time of the navigation icons with random color distribution is higher than that of the navigation icon interface with a regular color distribution. In the navigation icon interface with regular color distribution, subjects in the same layout with a larger color distribution area, their fixation time is shorter than in the same layout with a smaller color distribution area.

Further one-way analysis of variance was performed on the four different layout methods, and it was found that the effect of layout methods on fixation time was consistent with the analysis results of fixation times. The difference between G0 and G1 was significant ($p = 0.040$), the difference between G0 and G2 was significant ($p < 0.001$), and the difference between G0 and G3 was significant ($p < 0.001$); The difference was not significant ($p > 0.05$). The result shows that the fixation time of monochrome navigation icons is more than that of navigation icon interfaces that use color for layout coding. There is no significant difference in fixation time between navigation icons laid out by color coding.

The saccade length is the sum of all distances from the gaze point to different positions in a certain interest period or area of interest. In this experiment, the longer the saccade length, the more disordered the subjects' gaze in the search task, and the lower the visual search efficiency. Repeated measures ANOVA of saccade length (as Table 12) showed that the main effect of layout was significant, $F(2, 54) = 12.928$, $p < 0.05$. The interaction between layout and color was not significant, $F(4, 54) = 1.313$, $p > 0.05$. The output of the between-subject variable showed that the main effect of color was not significant, $F(2, 54) = 0.182$, $p = 0.835$. Further generalized linear model analysis of the layout method shows that the saccade length between G1 and G2 is significantly different ($p = 0.001$), the saccade length between G1 and G3 is significantly different ($p = 0.012$), and the difference between G2 and G3 is significant ($p = 0.012$). The difference in saccade length was not significant ($p = 0.359$). The result shows that the saccade length of navigation icons with random color distribution is longer than that of navigation icons with regular color distribution, Among the navigation icons with regular color distribution, the difference in saccade length between different layouts is not significant.

Further one-way analysis of variance was conducted on the four different layouts, and the results found that the results of the saccade length analysis of the four layouts were consistent with the results of the number of fixation points and fixation time. The results show that the saccade length of the monochrome navigation icons on the mobile map is longer than that of the color-coded navigation icons, and there is no significant difference in the saccade length between the color-coded navigation icons.

The impact of different layout methods on user experience

The subjective questionnaire takes satisfaction, ease of use, and emotional preference scores as dependent variables, and the layout of mobile map navigation icons as independent variables. One-way analysis of variance was performed on the scoring results, and the results showed that the main effect of satisfaction was significant, $F(3, 87) = 13.911$, $p < 0.05$; The main effect of availability was significant, $F(3, 87) = 13.911$, $p < 0.05$; the main effect of emotional preference was significant, $F(3, 87) = 13.911$, $p < 0.05$, This result shows that users have obvious subjective preferences for mobile map navigation icons with different layouts. Further analysis of the scoring situation shows that the average satisfaction scores given by the subjects to G0, G1, G2, and G3 are 4.233, 3.867, 6.167, and 5.833, respectively. It shows that the satisfaction of the subjects with the navigation icons of the color distribution is higher than that of the monochrome navigation icons and the navigation icons with the random color distribution. The average ease of use scores given by the subjects to G0–G3 were 3.733, 3.7, 6.167, and 5.833, which indicated that the subjects believed that the ease of use of the mobile map navigation icons with regular color distribution was better than that of the monochrome navigation icon interface and the Navigation icons with the random color distribution. The average scores of G0–G3's emotional convenience are 3.6, 3.8, 6.1, and 5.867, which indicates that the subjects prefer the mobile map navigation icons with regular color distribution to the monochrome navigation icon interface and the layout with random color distribution Way. Table 13 shows the further within-subject comparative analysis of the four layout methods. The results show that the results of satisfaction, ease of use, and emotional preference are consistent, and the difference between G0 and G1 is not significant ($p > 0.05$). The difference between G0 and G2 was significant ($p < 0.05$), and the difference between G0 and G3 was significant ($p < 0.05$); the difference between G1 and G2 was significant ($p < 0.05$), and the difference between G1 and G3 was significant ($p < 0.05$); the difference between G2 and G3 was not significant ($p > 0.05$). This result shows that the subjects have higher scores for the navigation icons with regular color distribution, which shows that the layout mode is very important to the user experience, and the layout mode with the same color area and the larger area has the best experience.

TABLE 11 Results of repeated measures ANOVA on fixation time.

Factor	df	*F*	*p*
Layout	2	4.893	0.011
Color	2	0.417	0.663
Layout × color	4	0.797	0.532

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

TABLE 12 Results of repeated measures ANOVA on saccade length.

Factor	df	*F*	*p*
Layout	2	12.928	0.000
Color	2	0.182	0.835
Layout × color	4	1.313	0.277

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

Discussion

The above research results show that the layout method significantly impacts the visual search and experience of the navigation icons of the mobile map, and the eye movement data provides an objective basis for this conclusion.

The impact of layout method on visual search efficiency

The research results show that the layout method has a significant impact on the visual search of the user's mobile map

TABLE 13 One-way ANOVA test of subjective preference with different layout methods.

	Satisfaction				Ease of use				Emotional preference			
	G0	G1	G2	G3	G0	G1	G2	G3	G0	G1	G2	G3
G0	×	0.458	0.000	0.002	×	0.458	0.000	0.002	×	0.674	0.000	0.000
G1		×	0.000	0.000		×	0.000	0.000		×	0.000	0.000
G2			×	0.499			×	0.499			×	0.623
G3				×				×				×

*$p < 0.05$. *Based on the estimated marginal mean. The mean difference was significant at 0.05 level. 95% confidence interval.

navigation icons, and the navigation icons that use color for layout coding have the highest visual search efficiency and better user experience.

Among the navigation icons that use color for layout coding, the layout with regular color distribution and a larger area of the same color has the highest visual search efficiency and the best user experience. This result is verified not only in the data analysis of visual search time and accuracy but also in the results of eye movement data analysis. According to the feature integration theory, the user performs visual processing on the basic features in the pre-attention stage (Treisman and Gelade, 1980). In this stage, the user mainly detects the features of stimuli, and color is the most basic detection feature. Numerous studies have shown that color is the most important factor affecting users' visual search in the pre-attention stage (Steven, 2008). Gestalt theory believes that human vision is holistic, and the visual system automatically constructs a structure for the input content and perceives the objects seen (Treisman and Gormican, 1988). People group similar-looking objects into groups. Therefore, when color is used as a variable, the user will automatically group icons of the same color. In this experiment, the layout-encoded information using color is presented in a more structured way for users to browse and understand more quickly and easily. Because in the search process, the visual hierarchy makes it easier to skip irrelevant information so that the subjects can quickly find the target and improve the efficiency of the visual search (Johnson, 2014). Wu and Chen (2009) confirmed that color grouping is one of the most important factors affecting subjects' performance and satisfaction. The visual search efficiency of the navigation icons coded by color is significantly higher than that of the monochrome navigation icon interface. In this experiment, for a single-color icon interface, the visual system searches according to the joint features of color and shape, and the interference items are all icons in the interface. When searching for a grouped icon interface composed of two colors, the visual system can improve the classification and recognition speed of icons through color coding. Users can quickly reduce the number of interfering icons, reduce search time, and improve visual search efficiency. Therefore, when the icons of the navigation icon interface are of a single color, the color of the icons will not affect the user's visual search efficiency. Gong et al. (2016b) confirmed this result. They pointed out that when the icon colors are inconsistent, the subject's pre-attention processing is more, the saccade can quickly point to the target, the subject's perceptual breadth is greater at this time, and the search efficiency is more efficient. High (Gong et al., 2016b). In this experiment, among the layout methods with the regular color distribution, the visual search efficiency of the subjects with the layout method with a larger area of the same color is higher. It is because the icons arranged in groups will form different visual search areas, and the layout with the same color area is larger. The user only needs to perform a visual search in a smaller range. Under such conditions, the user can eliminate more interference items. At this time, the subjects searched for fewer items, and the saccade distance was shorter. When subjects searched for an interface with a large color area grouping, the grouped items could be accepted or rejected together, and if accepted, the search could simply be performed within the group (Friedman-Hill and Wolfe, 1995). Item grouping reduced the number of items to be searched. For the grouping method with a small color area, although the color can help the user to classify the icons, the abnormally active color interference will distract some attention and reduce the search efficiency of the target icon. In addition, the presentation of icons with smaller color areas requires more attention span. Under such conditions, users can only adopt an extremely inefficient one-by-one search strategy, which further reduces the search efficiency of icons. Therefore, a layout with a larger color area has higher visual search efficiency.

The impact of layout method on user experience

In this experiment, the user experience data is analyzed according to its components. The specific components are satisfaction, ease of use, and user preference.

The impact of layout method on satisfaction

Satisfaction is a user's perception, feeling, and thought about a product (Rubin and Chisnell, 2017). In this experiment, when the navigation icon can better meet the user's needs and provide better satisfaction, the user's performance will be better when using the mobile map navigation icon. The analysis results of the subjective evaluation data show that the satisfaction of the subjects with the navigation icons with a regular color distribution is higher than that of the monochrome navigation icons and the navigation icons with a random color distribution. Zhang et al. (2019) took the user experience as the starting point and pointed out that the user experience depends on the presentation of the user interface. Spatial layout is an important presentation method of interactive interface and has an important impact on user satisfaction. Although users do not pay too much attention to good visual hierarchies, bad visual hierarchies can be highlighted in use, degrading the user experience (Susurratescape, n.d.). Compared with monochrome navigation icons and navigation icons with random color distribution, the layout of navigation icons with regular color distribution has a clearer visual hierarchy, more complete and coherent information display, and higher user satisfaction.

The impact of layout method on ease of use

Ease of use mainly includes efficiency and effectiveness. Efficiency is the agility of users to complete tasks accurately and completely, which can be reflected by reaction time. Effectiveness is how easy it is for users to use a product, usually measured in terms of correctness or error (Lioli and Komninos, 2016). This experiment found that the mobile map navigation icons with regular color distribution have better usability than monochrome navigation icons and navigation icons with a random color distribution. Xiong (2019) pointed out that visual interface design is an important factor affecting user usability. As we all know, layout is an important element of interface design. It carries the area division of the information. Therefore, the layout has a significant impact on the user's usability. Navigation icons with regular color distribution are easier to help users establish a clear visual hierarchy and divide visual areas. Navigation icons with random color distribution will make the visual hierarchy of the interface cluttered, interfere with the user's perception of information, and affect the user's ease of use. Users cannot establish a perceptible visual system for the monochrome navigation icons, so the usability of the monochrome navigation icons is low.

The impact of layout method on users' emotional preference

The user's emotional preference depends on the user experience. The most important thing about the user experience is to maximize the humanization of the product or interface, ensure the user's operating experience and correctness, and meet the user's ideas and expectations. User experience design can be designed from the four dimensions of brand, usability, function and content analysis (Chen et al., 2021). Cyr et al. (2006) studied how design aesthetics affect user loyalty to a product, and the results show that good visual design has a significant impact on perceived usefulness, ease of use, and pleasure. By optimizing the design of these factors, user loyalty can be improved. In this experiment, through the analysis of the behavior data of the subjects, it was found that the navigation icons with regular color distribution had shorter operation times and higher accuracy. The result shows that the navigation icons with regular color distribution are more effective, and the subjects are more efficient in completing the operational tasks. Moreover, the subjects were more satisfied with the mobile map navigation icons in this layout, which indicated that the layout had the best usability, so the user preference for navigation icons with regular color distribution was higher.

Limitations and future work

There are several limitations. First, the experiment uses the computer interface instead of the mobile interface and uses the keyboard to replace the touch screen operation. Although this experimental paradigm can accurately record the experimental data, it is different from the real use scene. In subsequent studies, experiments can be performed using real mobile devices.

Second, the eye-tracking data in this experiment were collected by the EyeLink fixed eye-tracking instrument. During the experiment, although the data collection of the eye-tracking instrument with the fixed head was accurate, it could not restore the actual usage of mobile devices. In future experiments, head-mounted eye-tracking equipment can be used to make the user's experimental process more realistic.

Third, the research objects of this study are undergraduates and postgraduates. This group may have certain common characteristics and cannot represent all user groups, and the sample is slightly insufficient. In the follow-up research, the sample can be expanded to make the experimental data more objective and accurate.

Fourth, the visual search experimental paradigm in this study is to present the target icon first, then the interference icon interface, and ask the subjects to find the target icon in the interference icon interface. There are some differences between the real mobile information map usage scenarios and this experimental paradigm. The experimental paradigm can be improved in subsequent studies.

Conclusion

This study firstly analyzes the navigation icons of the mobile map and designs the navigation icons based on color coding and spatial layout, and then conducts an experimental study on the visual search efficiency of the mobile map navigation icons based on color coding and spatial layout. The main conclusions are as follows: First, the layout of the mobile map navigation icons has a significant impact on the user's visual search. Among them, the navigation icons that use color for layout coding have the highest visual search efficiency and better user experience. Second, among the navigation icons that use color for layout coding, the layout with regular color distribution and a larger area of the same color has the highest visual search efficiency for users and the best user experience. Third, the visual search efficiency of navigation icons using color for layout coding is significantly higher than that of monochrome navigation icons. The research results have certain practical significance. This research provides design guidance for the design of mobile phone map navigation icons, and provides an important theoretical basis for the design of human-computer interaction interface and user experience. In the future, we can further combine eye tracking technology to conduct in-depth research on icon visual search strategies, and further explore the impact of different methods or number of layouts on users' visual search.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MZ conceived and conducted experiments and wrote most of the manuscript. YG proposed research topics and invited experimental subjects. RD made article fixes. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Amiez, C., and Petrides, M. (2007). Selective involvement of the mid-dorsolateral prefrontal cortex in the coding of the serial order of visual stimuli in working memory. *PNAS Proc. Natl Acad. Sci. U. S. A.* 104, 13786–13791.

Bodrogi, P. (2003). Chromaticity contrast in visual search on the multi-colour user interface. *Displays* 24, 39–48. doi: 10.1016/S0141-9382(02)00070-7

Chen, C.-H., and Chiang, S.-Y. (2011). The effects of panel arrangement on search performance. *Displays* 32, 254–260. doi: 10.1016/j.displa.2011.05.003

Chen, X., Huang, L., and Li, M. (2021). Visual search performance of intercity logistics APP Interface navigation design. *Packing Eng.* 42, 198–204.

Cyr, D., Head, M., and Ivanov, A. (2006). Design aesthetics leading to m-loyalty in mobile commerce. *Inf. Manag.* 43, 950–963. doi: 10.1016/j.im.2006.08.009

Dennis, M. P. (2008). Perceiving hierarchy through intrinsic color structure. *Vis. Commun.* 7, 199–228. doi: 10.1177/1470357208088759

Fleetwood, M. D., and Byrne, M. D. (2002). Modeling icon search in ACT-R/PM. *Cogn. Syst. Res.* 3, 25–33. doi: 10.1016/S1389-0417(01)00041-9

Fleetwood, M. D., and Byrne, M. D. (2006). Modeling the visual search of displays: a revised ACT-R model of icon based on eye-tracking data. *Hum. Comput. Interact.* 21, 153–197. doi: 10.1207/s15327051hci2102_1

Friedman-Hill, S., and Wolfe, J. M. (1995). Second-order parallel processing: visual search for the odd item in a subset. *J. Exp. Psychol. Hum. Percept. Perform.* 21, 531–551. doi: 10.1037/0096-1523.21.3.531

Gong, Y., Yang, Y., Zhang, S., and Qian, X. (2013). Event-related potential study on concretness effects to icon comprehension. *J. Zhejiang Univ.* 47, 1000–1005. doi: 10.3785/j.issn.1008-973X.2013.06.010

Gong, Y., Zhang, S., Liu, Z., and Shen, F. (2016a). Eye movement study on color effects to icon visual search efficiency. *J. Zhejiang Univ.* 50, 1987–1994. doi: 10.3785/j.issn.1008-973X.2016.10.020

Gong, Y., Zhang, S., Shen, F., and Liu, Z. (2016b). Effect of color combination on graphical symbol visual search efficiency. *J. Comput. Aided Des. Comput. Graphics* 28, 1115–1120.

Grobelny, J., Karwowski, W., and Drury, C. (2005). Usability of graphical icons in the design of human-computer interfaces. *Int. J. Hum. Comput. Interact.* 18, 167–182. doi: 10.1207/s15327590ijhc1802_3

Hsieh, T.-J. (2017). Multiple roles of color information in the perception of icon-type images. *Color. Res. Appl.* 42, 740–752. doi: 10.1002/col.22140

Huang, K. C. (2008). Effects of computer icons and figure/background area ratios and color combinations on visual search performance on an LCD monitor. *Displays* 29, 237–242. doi: 10.1016/j.displa.2007.08.005

IIMedia Research Center for Life and Travel Industry (2019). 2019Q1 China Mobile map industry market monitoring report. Available at: https://www.iimedia.cn/c400/64147.html (Accessed November 19, 2021).

Jiang, W., Yang, Z., Jiang, M., Li, M., Tian, J., Lu, D., et al. (2015). A study on usability of application icon Design in Smart Phones. *Chin. J. Ergon.* 21, 21–24. doi: 10.13837/j.issn.1006-8309.2015.03.0005

Jin, T., Ming, C., Zhou, S., and He, J. (2021). Impact mechanism of icon layout on visual search performance. *J. Northeast. Univ.* 42, 1579–1584. doi: 10.12068/j.issn.1005-3026.2021.11.009

Johnson, J. (2014). *Designing with the Mind in Mind: Simple Guide to Understanding User Interface Design Guidelines.* Beijing, China: Posts & Telecom Press, 27–32.

Kong, X. (2021). Influence of background mode and icon presentation method on search efficiency of mobile phone floating ball user interface icons. *Tianjin Norm. Univ.* doi: 10.27363/d.cnki.gtsfu.2021.000599

Laar, D. L. V. (2001a). Psychological and cartographic principles for the production of visual layering effects in computer displays. *Displays* 22, 125–135. doi: 10.1016/S0141-9382(01)00059-2

Laar, D. L. V. (2001b). "Color coding with visual layers can provide performance enhancements in control room displays." in Proceedings of people in control. International conference on human interfaces in control rooms, cockpits and command centers, Manchester, United Kingdom, 481.

Li, J. (2018). *Coding and Research of Human-Computer Interface Information for Balancing Cognitive Load.* Jiangsu, China: Southeast University Press, 9.

Li, J., and Xue, C. (2016). Color encoding research of digital display Interface based on the visual perceptual layering. *J. Mech. Eng.* 52, 201–208. doi: 10.3901/JME.2016.24.201

Li, J., Yu, S., and Wu, X. (2018). Effects of shape character encodings in the human-computer Interface on visual cognitive performance. *J. Comput. Aided Des. Comput. Graphics* 30, 163–179. doi: 10.3724/SP.J.1089.2018.16101

Lioli, D., and Komninos, A. (2016). Icon Design for Landmark Importance in Mobile maps. *Informatics.* 1–6. doi: 10.1145/3003733.3003742

Liu, W., Cao, Y., and Robert, W. P. (2021). How do app icon color and border shape influence visual search efficiency and user experience? Evidence from an eye-tracking study. *Int. J. Ind. Ergon.* 84:103160. doi: 10.1016/j.ergon.2021.103160

Michalski, R. (2014). The influence of color grouping on users' visual search behavior and preferences. *Displays* 35, 176–195. doi: 10.1016/j.displa.2014.05.007

Michalski, R., and Grobelny, J. (2008). The role of colour preattentive processing in human-computer interaction task efficiency: a preliminary study. *Int. J. Ind. Ergon.* 38, 321–332. doi: 10.1016/j.ergon.2007.11.002

Michalski, R., Grobelny, J., and Karwowski, W. (2006). The effects of graphical interface design characteristics on human-computer interaction task efficiency. *Int. J. Ind. Ergon.* 36, 959–977. doi: 10.1016/j.ergon.2006.06.013

Murata, A., and Furukawa, N. (2005). Relationships among display features, eye movement characteristics, and reaction time in visual search. *Hum. Factors* 47, 598–612. doi: 10.1518/001872005774860032

Niemelä, M., and Saarinen, J. (2000). Visual search for grouped versus ungrouped icons in a computer interface. *Hum. Factors* 42, 630–635. doi: 10.1518/001872000779697999

Niu, Y.-f., Li, X., Yang, W.-j., Xue, C.-q., Peng, N.-y., and Jin, T. (2021). Smooth pursuit study on an eye-control system for continuous variable adjustment tasks. *Int. J. Hum. Comput. Interact.* 1–11. doi: 10.1080/10447318.2021.2012979

Niu, Y.-f., Liu, J., Cui, J-q., Yang, W-j., Zuo, H-r., and He, J-x. (2022). Research on visual representation of icon colour in eye-controlled systems. *Adv. Eng. Inform.* 52:101570.

Nowell, L T. (1997). *Graphical Encoding for Information Visualization: Using Icon Color, Shape, and Size to Convey Nominal and Quantitative Data.* Blacksburg, VA: Virginia Polytechnic Institute and State University.

Pearson, R., and Schaik, P. V. (2003). The effect of spatial layout of and link color in web pages on performance in a visual search task and an interactive search task [J]. *Int. J. Hum. Comput. Stud.* 59, 327–353. doi: 10.1016/S1071-5819(03)00045-4

Peng, Y. (2021). Research on APP interface layout and layer design based on visual search. *Ind. Design* 10, 75–76.

Rubin, J., and Chisnell, D. (2017). *Handbook of Usability Testing.* Beijing, China: Posts & Telecon Press.

Schaik, P. V., and Lin, J. (2001). The effects of frame layout and differential background contrast on visual search performance in web pages. *Interact. Comput.* 13, 513–525. doi: 10.1016/S0953-5438(00)00054-0

Steven, H. (2008). *The Resonant Interface HCI Foundations for Interaction Design* Beijing, China, Publishing House of Electronics Industry,5.

Susurratescape (n.d.). Interaction Design Principles and Theory 1——Nielsen Top 10 Usability [DB/OL]. Wiley.

Treisman, A., and Gelade, G. A. (1980). Feature-intergration theory of attention. *Cogn. Phychol.* 12, 97–136. doi: 10.1016/0010-0285(80)90005-5

Treisman, A., and Gormican, S. (1988). Feature analysis in early vision: evidence from search asymmetries. *Psychol. Rev.* 95, 15–48. doi: 10.1037/0033-295X.95.1.15

Wang, H., Huang, Y., Chen, M., and Xue, C. (2016). Analysis of cognitive model in icon search behavior based on ACT-R model. *J. Comput. Aided Des. Comput.* 28, 1740–1749.

Wolfe, J. M., and Horowitz, T. S. (2007). Five factors that guide attention in visual search. *Nat. Hum. Behav.* 1, 597–607. doi: 10.1038/s41562-017-0058

Wu, F.-G., and Chen, C.-Y. (2009). Effects of color display, color name, color formation and color alignment on the screen layout usability of customized product color combinations. *Int. J. Ind. Ergon.* 39, 655–666. doi: 10.1016/j.ergon.2009.04.004

Xiong, Z. (2019). *Research on the Interface Design of life Service APP Based on Ease of Use*. Wuhan, China: Wuhan Institute of Technology.

Zhang, Y. (2017). *Visual cognition research on APP interface navigation system design*. Jiangsu, China: Jiangnan University.

Zhang, Y., Zhu, Q., and Li, M. (2019). Construction of the evaluation index system of Mobile learning APP from the perspective of user experience based on D-S evidence theory. *J. Intelligence* 38, 187–194. doi: 10.3969/j.issn.1002-1965.2019.02.027

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Directing memory content to attentional templates: The finiteness effect of predictive information

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Visual search can be accelerated according to the properties of information stored in memory and prior knowledge of the upcoming work. This helps the searcher direct their attention to (or avoid) items that match these properties. Meanwhile, different functional areas where these properties exist become attentional templates. Compared with neutral conditions, the use of attentional templates significantly benefits reaction time (RT). However, previous studies might have confounded the memory-driven and cue-driven effects. Thus, it is less clear which factor influences the template benefits. Modeled on previous research, this study employed a new design to explore the independent effects of textual cues, thus finding an inverse effect. More specifically, positively cueing an item retained in memory did not improve behavioral performance, whereas negatively cueing an item did achieve such an enhancement. Moreover, positive cueing even resulted in some damage to attentional searching under some conditions, thus indicating that the advantages of positive cueing reported in previous studies may be driven by working memory, while the effects of negative cueing are driven by prior knowledge.

KEYWORDS

attention, working memory, predictive cue, short term memory, template

Introduction

Storing a specific feature of upcoming work before searching for its related target is an effective way to interact with the environment. Known as a 'target template', this type of information is maintained in the visual working memory (VWM). Thus, a subsequent attention search is biased toward representations in the list matching the target information (Duncan and Humphreys, 1989; Desimone and Duncan, 1995). To test how these template representations guide attention, most studies have employed the dual-task paradigm, in which before the relevant target can be detected from the list of distractors and the observer must remember a feature. In this context, many studies have found that if the cue matches the target when compared to a neutral baseline where the cue contains no information search, the performance will improve (Wolfe et al., 2004; Vickery et al., 2005; Töllner et al., 2010). In neurophysiology, sustained activity in the lateral parieto-occipital regions was found when subjects stored target-related representations during the delay period (Chelazzi et al., 1993; Carlisle et al., 2011), thereby indicating that such working memory content influences the upcoming search toward its related objects.

Attentional guidance can also be performed by inhibiting distractors as a supplement to facilitate visual search; more precisely, any distractor objects in the array are removed from the scanning process (Gaspelin and Luck, 2018). These results indicate that by excluding target irrelevant items from an attentional array, non-target information can also be used effectively to facilitate visual search in predictive environments. Recent evidence has shown that such attentional suppression is implemented by reducing the weights of distractor (no-target) features and not increasing the weights of target features (Moher et al., 2014; Nie et al., 2016). Furthermore, the creation of a negative (distractor) attentional template, which dictates information to be avoided, may constitute an underlying mechanism for distractor suppression in search guidance (Duncan and Humphreys, 1989; Humphreys and Müller, 1993). Compared with the positive (target) template, the negative template attenuated the activation of features associated with the distractors labeled as avoidance, thus reducing their potential for competitive selection. Hence, both positive (target) and negative (distractor) templates support the prediction of task-related goals in the generative environment (see Conci et al., 2012).

Both distractor suppression and target selection appear to modulate searches in predictive environments. Previous studies on setting negative (interference) or positive (target) cues before searching the array have shown that priming a set of non-target or target features in the upcoming search array improves task performance; the observer can set negative or positive templates to suppress unrelated items and accelerate the goal items, respectively. These studies have typically employed a condition-blocked design, in which one block contains one textual cue type (positive/negative) and prior knowledge (textual cue) is presented before each block starts. Thus, subjects know that the subsequent memory item is a distractor or target before a block starts, and accordingly, this prior information helps them speed up the attentional task (Arita et al., 2012; Kugler et al., 2015; Reeder et al., 2017; Conci et al., 2019).

Of note, most studies have reported that negative distractor cues tend to produce smaller benefits in comparison with positive target cues, thereby demonstrating that negative templates are relatively more difficult to utilize and that prior knowledge of the upcoming task plays a more important role in target selection than distractor suppression (Kugler et al., 2015). In this study, each trial of the cueing condition involved a memory item with predictive information and a memory-target-matched/non-target-matched visual search test, including a search for an unrelated color that was presented to be remembered in the neutral condition. However, such an approach may cause confusion because other studies have reported that representations are maintained in the memory automatic bias attention direction when searching for memory content-matched items (Anderson et al., 1997; Logan and Gordon, 2001; Soto et al., 2008). Thus, memory items and predictive cues produce a top-down effect (automatic guidance vs. search strategy), relative to the neutral condition. The results of these experiments may confound the memory-driven and predictive cue-driven effects rather than demonstrate the effects of the predictive cue itself.

To clarify this issue and further examine the role of VWM representations in cueing effect, we conducted two experiments in reference to the study conducted by Arita et al. (2012). In Experiment 1, we replaced the neutral condition with memory-item-target-match (MM) and memory-item-non-target-match (MN) conditions and then set the same color of stimulants in a fixed region (Arita et al., 2012; Exp. 1, 2, 3). To exclude the effect of the search strategy, we randomly altered the colors of the search display in Experiment 2. Moreover, in the present study, we mixed the conditions in a block and the textual cue (prior knowledge) about the WM content was set in each trial (Beck et al., 2018).

In sum, we found that when controlling for memory representation as an additional variable, the negative cue produced more benefits than the positive cue. Moreover, this effect remained even after increasing the search load and controlling the strategy. These results are completely contrary to those found in previous studies (Kugler et al., 2015). Surprisingly, the positive cue even caused some damage to the subsequent visual search. This implies that tactic cues play different roles in each of the two inversed channels that facilitate the transformation of initial memory contents into different attentional templates according to top-down predictive cues.

Materials and methods

Experiment 1

Experiment 1 employed a variant of the paradigm provided by Arita et al. (2012), with four implemented conditions, namely the memory-item-target-match (MM), memory-item-non-target-match (MN), cue-memory-item-target-match (C-MM), and cue-memory-item-non-target-match (C-MN). Here, we focused on any differences between the positive cue (target color) reaction time (RT) benefits (MM-CMM) and negative cue (non-target color) RT benefits (MN-CMN).

Experiment 1 methods

Participants

We recruited a total of 24 undergraduate students (3 males, 21 females; M age = 19.96; SD = 1.16) from Zhejiang Normal University in China. For study inclusion, these participants were required to have normal or corrected-to-normal color vision and sufficient visual acuity. None withdrew from the experiment due

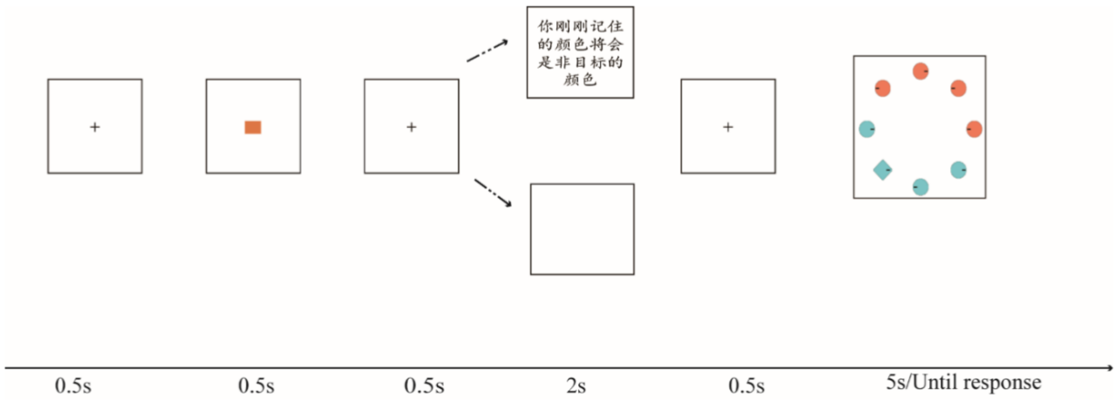

FIGURE 1
Experiment 1 task. The first portions of all trials were identical, beginning with a fixation dot (0.5s), followed by a memory item (0.5s), then a predictive cue (2s) presented to indicate the fate of the remembered item (target or non-target); next, a search test was presented until the response. Participants were required to search for a diamond in a set of circles, then make a judgment about the location of the line. In the no-cue condition, the remembered color was required to be presented in the search display as a target feature or distractor feature. The predictive cues were 100% valid.

to physical discomfort or subjective reasons. All data were included in the analysis. We determined the set size (n = 24) based on Arita et al. (2012), wherein the effect size ($\eta^2 = 0.23$) indicated that at least 18 participants were required to achieve 80% power.

Each participant provided informed consent, per the Declaration of Helsinki. The research plan was approved by the Behavioral and Social Sciences Institutional Review Board of Zhejiang Normal University. Each participant was given monetary compensation (30 RMB) after completing the experiment.

Visual stimuli and apparatus

We controlled the stimuli and response registration using Python scripts.[1] Participants were tested in a dim room with their chins positioned on a chinrest located 70 cm from a 17-in LCD monitor (resolution: 1024 /// 768; refresh rate: 85 Hz).

After remembering a color at the beginning of the search, 4/8/12 colored shapes (1° × 1°) were presented on an imaginary circle with a radius of 4° at the same angle deviation and centered at the fixation, against a gray background (Figure 1). The shapes were of two forms, namely 3/7/11 circles and one diamond, whereas two stimuli colors were randomly selected from 12 color values. The colors were selected from a set of 180 color values evenly distributed along with a color wheel in L*a*b* (L* = 70, a* = 20, b* = 38) color space at intervals of 30°.

Procedure

We used a 2*2*3 repeated-measures design with predictive cue type: cue/no cue, match type: target match/non-target match, and set size: 4/8/12 as three factors. Thus, each set size included four types of test conditions: cue-target match (positive cue), no-cue-target match, cue non-target match (negative cue), and no-cue non-target match. We set three blocks and each contained one search load of the mixed conditions. The order of conditions was also counterbalanced across the participants. Experiment 1 began with 20 practice trials, following the instructions regarding the cue color and its relationship to the target color.

The participants performed 420 trials. Each trial began with a black fixation at the center of the screen for 0.5 s, followed by a color they needed to remember for 0.5 s, also placed at the center of the screen. The remembered color had two conditions: target match or non-target match. At this time, one of three possible arrangements was presented at the center of the screen for 2 s, including two predictive cues written in Chinese: (1) "the color you have just remembered will be the target color"" (target match cue/positive cue); (2) "the color you have just remembered will be the non-target color" (non-target match cue/negative cue); and (3) empty screen. Finally, the participants were presented with a visual search task containing 4/8/12 items, wherein they were prompted to locate a diamond from a set of circles and then indicate the location of the embedded line (i.e., right or left). As in Arita et al. (2012), only two colors were presented in the search task, with half displayed in the color to be remembered, and all items always symmetrized in a fixed region of the screen. In each condition, the location of the target was pseudorandomized (Figure 1).

Experiment 1 results

The accuracy of each condition was on the ceiling (>98%); thus, we did not include it in the analysis. We excluded wrong response trials from the analysis and conducted a repeated-measures analysis of variance (ANOVA) on the RTs and related benefits. The ANOVA on RTs revealed a significant main effect for cue type [F (1,23) = 30.15, $p < 0.001$, $\eta^2_p = 0.57$], match type [F (1,23) = 96.16, $p < 0.001$, $\eta^2_p = 0.81$], and set size [F (2,46) =16.15, $p < 0.001$, $\eta^2_p = 0.41$]. Further comparisons indicated

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[1] https://www.python.org

that no-cued trials responses were longer than cued trials [$t(23) = -5.49$, $p < 0.001$, *Cohens'd* $= -1.12$]; target match trials responses outperformed non-target match trials [$t(23) = -9.81$, $p < 0.001$, *Cohens'd* $= -2$]; and set size 4 showed faster RT than set size 8 [$t(23) = -4.38$, $p < 0.001$, *Cohens'd* $= -0.89$] and set size 12 [$t(23) = -5.33$, $p < 0.001$, *Cohens'd* $= -1.09$].

Importantly, there was also a significant interaction between cue type and match type [$F\ (1,23) = 25.12$, $p < 0.001$, $\eta^2_p = 0.52$], with a longer RT of non-target match trials under no-cue condition than under cue condition [$t(23) = -7.43$, $p < 0.001$]. However, RT values of target-matching tests were similar between the cue and no-cue conditions [$t(23) = -0.53$, $p > 0.05$]. The results indicated that the effect of the cue was much larger for the non-target match (negative) than for the target match (positive). The interactions between set size and cue type were also significant [$F\ (2,46) = 4.84$, $p < 0.05$, $\eta^2_p = 0.17$]. However, match type and set size were not significant [$F\ (2,46) = 2.02$, $p > 0.05$, $\eta^2_p = 0.08$], nor was the three-way interaction [$F(2,46) = 0.24$, $p > 0.05$, $\eta^2_p = 0.01$; Figure 2A].

We also calculated RT benefits for the positive and negative cues and then stored this as a new analysis variable. Next, we conducted a 2*3 ANOVA with RT benefits and set size as the two levels. The statistical results showed a main effect for cue benefit [$F\ (1,23) = 25.12$, $p < 0.001$, $\eta^2_p = 0.52$], whereas the *post-hoc* test showed that the negative cue benefit was significantly higher than the positive cue benefit [$t\ (23) = -5.01$, $p < 0.001$, *Cohens'd* $= -1.02$; Figure 2B].

In Experiment 1, the negative textual cue thus produced more benefits than the positive cue. While prior knowledge of the distracting color enhanced performance, knowledge of the upcoming target color did not always lead to performance benefits.

Experiment 1 discussion

Participants responded better under positive (vs. negative) cues, which supports previous findings. However, the cueing effect of the positive cue failed to be observed in Experiment 1. This implies that the positive cue may not produce substantial benefits in the context of informing observers about the color of an upcoming visual search target. Meanwhile, the negative cue produced relative benefits. Taken together, these results provide evidence that the negative cue benefit is larger than the target cue benefit.

Experiment 2

In Experiment 1, we examined the effects of predictive cues after excluding the influence of the memory item. Our results were directly opposite to those reported in previous studies. However, our color symmetry settings might have led to a potential problem, as participants could have strategically used that information when giving their responses. In Experiment 2, we eliminated this possibility by randomly mixing colors in the search array.

Experiment 2 methods

While the Experiment 2 apparatus, stimuli, design, and procedure were similar to those in Experiment 1, we implemented some important changes. Specifically, we randomly shuffled colors' locations in the visual search display and increased the trial number to 560 across three blocks. The participants included 24 individuals who did not participate in Experiment 1 (four males, 20 females; M age = 20.75; SD = 1.91). All had normal or corrected-to-normal vision and were right-handed. All other details were the same as in Experiment 1.

Experiment 2 results

For the same reason, accuracy was not included in the statistical analysis in experiment 2. The ANOVA on RTs revealed a significant main effect for cue type [$F\ (1,23) = 7.36$, $p < 0.05$, $\eta^2_p = 0.24$], match type [$F\ (1,23) = 95.65$, $p < 0.001$, $\eta^2_p = 0.81$], and set size [$F\ (2,46) = 34.19$, $p < 0.001$, $\eta^2_p = 0.60$]. The comparisons of main effects indicated that no-cued trials responses took longer than cued trials [$t(23) = -2.71$, $p < 0.05$, *Cohens'd* $= -\ 0.55$] and target match trials responses outperformed those of target un-match trials [$t(23) = -9.78$, $p < 0.001$, *Cohens'd* $= -2$].

Notably, there was also a significant interaction between cue type and match type [$F\ (1,23) = 31.9$, $p < 0.001$, $\eta^2_p = 0.58$], with a longer RT of non-target match trials under no-cue condition than under cue condition [$t(23) = -5.08$, $p < 0.001$]. Consistent with Experiment 1, RT values of target-matching tests were similar between the cue and no-cue conditions [$t(23) = -0.31$, $p > 0.05$]. The interactions between set size and cue type were also significant [$F\ (2,46) = 0.61$, $p > 0.05$, $\eta^2_p = 0.01$]. However, match type and set size were significant [$F\ (2,46) = 11.41$, $p < 0.001$, $\eta^2_p = 0.33$], nor was the three-way interaction [$F\ (2,46) = 0.3$, $p > 0.05$, $\eta^2_p = 0.01$]. The results showed that predictive cues had a great benefit in the substance visual search task (Figure 3A).

We also calculated the RT benefits. Here, the ANOVA showed a significant main effect for cue benefit [$F\ (1,23) = 31.90$, $p < 0.001$, $\eta^2_p = 0.58$], whereas the *post-hoc* test showed that the negative cue benefit was significantly higher than the positive cue benefit [$t\ (23) = -5.65$, $p < 0.001$, *Cohens'd* $= -1.15$; Figure 3B].

Experiment 2 discussion

The mixed color presentation did not influence our results in Experiment 2. This further confirmed that the cueing effect of prior knowledge is limited in distractor suppression rather than in target selection. This finding was also consistent with our initial predictions, thus confirming that the construction of a different template may have independent and distinct components.

General discussion

In this study, we conducted two behavioral experiments to retest the influences of two types of predictive cues (positive and negative), finding directly opposite results from those reported in previous studies (Wolfe et al., 2004; Vickery et al., 2005; Töllner

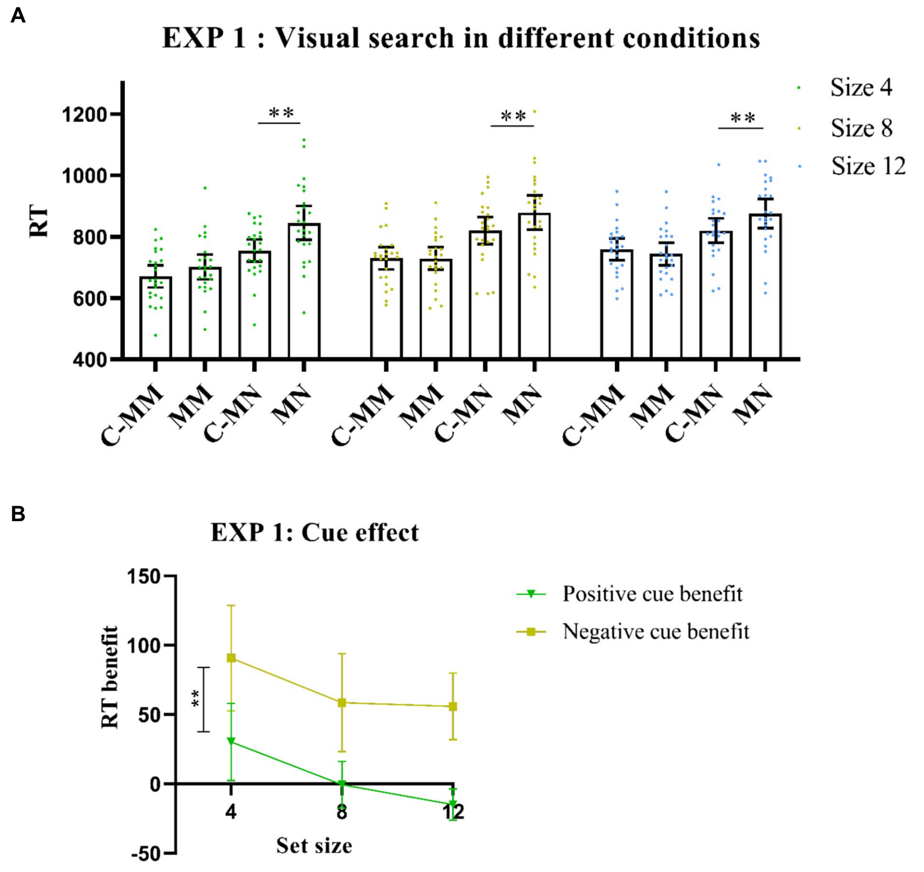

FIGURE 2
(A) Visual search performance in all Experiment 1 conditions. MM: memory-item-target-match; MN: memory-item-non-target-match; C-MM: cue-memory-item-target-match; CMN: cue-memory-item-non-target-match. **$p<0.001$. Error bars represent 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988). **(B)** Cue benefit in Experiment 1. **$p<0.001$. Error bars represent 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988). Positive cue benefit=MM-CMM(RT); Negative cue benefit=MN-CMN(RT).

et al., 2010; Kugler et al., 2015). Based on the methodology provided by Arita et al. (2012), Experiment 1 increased two conditions to manipulate the VWM matching effect. Here, the positive cue benefit was significantly smaller than the negative cue benefit and close to the baseline. Subsequently, Experiment 2 employed the same framework as Experiment 1, but with shuffled color symmetry. These results reinforced our initial conclusion. We also increased the set size to explore whether the observed effect was a function of attention load and confirm that the negative cue effect was stable. We believe that these results represent different components of the target and distractor templates.

To date, previous studies have produced mixed results; some have supported (Arita et al., 2012; Cunningham and Egeth, 2016; Reeder et al., 2017) and some have rejected (Beck and Hollingworth, 2015; Becker et al., 2016; Beck et al., 2018) the notion distractor inhibitory template. Our results support the basic findings reported by Arita et al. (2012) and thus provide new evidence reinforcing the existence of the template. As described in the introduction section, the completion of a visual search task after remembering an unrelated color may not work the same as at the baseline when compared to the positive or negative cue condition. At least two factors are involved in such an experiment, including (1) the relationship between the memory color and search color and (2) the predictive cue. The former represents an automatic driver linkage between memory and attention (Bundesen, 1990; Anderson et al., 1997; Logan and Gordon, 2001), whereas the latter represents a valid external strategy that modulates resource allocation (Wolfe et al., 2004; Vickery et al., 2005). These two completely different factors might have influenced the conclusions made in previous work.

The relatively small positive cue benefits can be attributed to a conflict between two distinct guiding factors. While we cannot currently provide sufficient evidence to prove this, we did find that the positive cue imposed significant damage to visual attention in some cases. Here, two top-down benefit strategies possibly competed for resources, as some researchers have reported that the representation obtaining the status of attentional template, whether at encoding or during maintenance, competes for the

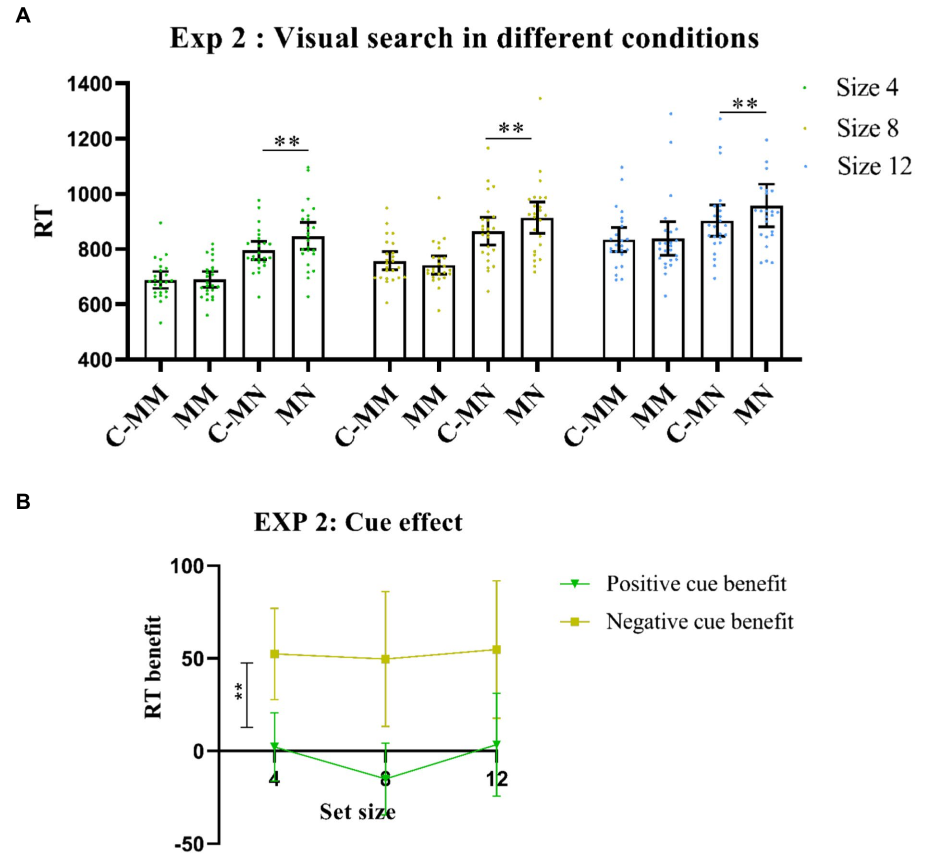

FIGURE 3
(A) Visual search performance in all Experiment 2 conditions. MM: memory-item-target-match; MN: memory-item-non-target-match; C-MM: cue-memory-item-target-match; CMN: cue-memory-item-non-target-match. $^{**}p<0.001$. Error bars represent 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988). **(B)** Cue benefit in Experiment 2. $^{**}p<0.001$. Error bars represent 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988). Positive cue benefit=MM-CMM (RT); Negative cue benefit=MN-CMN (RT).

amount of WM resources proportional to its relevance for visual search (Huynh Cong and Kerzel, 2021).

Consistent with previous studies, we also found a target selection advantage (Arita et al., 2012; Cunningham and Egeth, 2016; Reeder et al., 2017). Distractor suppression consists of at least two procedural stages: (1) selecting and inhabiting the distractor feature and then (2) searching for the target (Chang and Egeth, 2019). Thereafter, target selection can directly search for the target using the former information. The RT differences may be because of the additional stage. Given that the larger RT benefits in the positive template observed in other studies cannot affect the trend of the RT differences (Arita et al., 2012; Kugler et al., 2015), our results also show that the target template maintains a priority effect in visual searches. However, the problem is determining the source of the target template advantage; our results indicate that it is derived through the relationship between WM and the target, including implicit knowledge about the future attention task. In contrast, if WM contents mismatch the future task and participants are given prior information, then this may reshape WM representations to adapt to the environment, thus generating better benefits than the mismatch condition.

Based on the separation of the two templates, our research provides evidence that the positive template can be accommodated by a "memory-driven" model, positing that perceptual attention is biased toward features maintained in the working memory (Desimone and Duncan, 1995). More precisely, the binding between working memory content and visual attentional search is strong and automatic (Woodman and Luck, 2007). If prior knowledge matches the memory content, the advantage of working memory matching will cover the slight advantage of prior knowledge, leading to no significant difference of predictive cue in the target-match condition in the present results. Meanwhile, the negative template is best suited to a 'feature-based visual search' model (Treisman and Gelade, 1980; Wolfe et al., 1989; Wolfe, 1994; Wolfe and Gray, 2007), which posits that top-down information supports the generation of a stronger weight for the coding of target (distractor) related features. More specifically, top-down task goals drive the direction of our attention; in the present study, the informative cues successfully improved the task performance in the non-target match condition, indicating the colored feature was directed to the visual search task actively.

There is still no clear answer whether the internal modes of different templates rely on shared neural mechanisms (Cowan, 1999; Yamaguchi et al., 2004) or if they are unique and operate at different levels of cognitive or neural processing (Reeder et al., 2017, 2018). While WM may potentially work as a source of such functional areas, it is not the only factor because learning also plays a critical role in such psychological activities (Geng et al., 2019). Even for the representations held in WM space, each may have its specific characteristics (Oberauer, 2002). Besides, there are some limitations concerning the results of behavioral measurements. Thus, future studies can explore the differences in the mechanism of different attention templates from the perspective of neurophysiology. Moreover, although the set size was increased to 12, the search task seemed easy and static in our experiment. This rendering mode reduces its similarity to real-dynamic scene search. These questions should be addressed in future studies.

The idea that we can configure our attention to select certain objects is attractive. However, while our findings demonstrate that we can use prior information to avoid specific features, this information cannot be used when memory items have already been matched to the target. We also found evidence suggesting that the cueing effects observed for target templates in previous studies might have been memory-driven, while the negative cueing effects were due to prior useful information. This indicates that the two attention templates involve completely different mechanisms.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by the Behavioral and Social Sciences Institutional Review Board of Zhejiang Normal University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Anderson, J. R., Matessa, M., and Lebiere, C. (1997). ACT-R: a theory of higher level cognition and its relation to visual attention. *Human–Computer Interaction* 12, 439–462. doi: 10.1207/s15327051hci1204_5

Arita, J. T., Carlisle, N. B., and Woodman, G. F. (2012). Templates for rejection: configuring attention to ignore task-irrelevant features. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 580–584. doi: 10.1037/a0027885

Beck, V. M., and Hollingworth, A. (2015). Evidence for negative feature guidance in visual search is explained by spatial recoding. *J. Exp. Psychol. Hum. Percept. Perform.* 41, 1190–1196. doi: 10.1037/xhp0000109

Beck, V. M., Luck, S. J., and Hollingworth, A. (2018). Whatever you do, don't look at the...: evaluating guidance by an exclusionary attentional template. *J. Exp. Psychol. Hum. Percept. Perform.* 44, 645–662. doi: 10.1037/xhp0000485

Becker, M. W., Hemsteger, S., and Peltier, C. (2016). No templates for rejection: a failure to configure attention to ignore task-irrelevant features. *Vis. Cogn.* 23, 1150–1167. doi: 10.1080/13506285.2016.1149532

Bundesen, C. (1990). A theory of visual attention. *Psychol. Rev.* 97, 523–547.

Carlisle, N. B., Arita, J. T., Pardo, D., and Woodman, G. F. (2011). Attentional templates in visual working memory. *J. Neurosci.* 31, 9315–9322. doi: 10.1523/JNEUROSCI.1097-11.2011

Chang, S., and Egeth, H. E. (2019). Enhancement and suppression flexibly guide attention. *Psychol. Sci.* 30, 1724–1732. doi: 10.1177/095679761987881

Chelazzi, L., Miller, E. K., Duncan, J., and Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature* 363, 345–347. doi: 10.1038/363345a0

Conci, M., Deichsel, C., Müller, H. J., and Töllner, T. (2019). Feature guidance by negative attentional templates depends on search difficulty. *Vis. Cogn.* 27, 317–326. doi: 10.1080/13506285.2019.1581316

Conci, M., Zellin, M., and Müller, H. J. (2012). Whatever after next? Adaptive predictions based on short- and long-term memory in visual search. *Front. Psychol.* 3:409. doi: 10.3389/fpsyg.2012.00409

Cowan, N. (1999). "An embedded-process model of working memory," in *Models of working memory: Mechanisms of active maintenance and executive control*. eds. A. Miyake and P. Shah (Cambridge: Cambridge University Press).

Cunningham, C. A., and Egeth, H. E. (2016). Taming the white bear: initial costs and eventual benefits of distractor inhibition. *Psychol. Sci.* 27, 476–485. doi: 10.1177/0956797615626564

Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222. doi: 10.1146/annurev.ne.18.030195.001205

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458. doi: 10.1037/0033-295x.96.3.433

Gaspelin, N., and Luck, S. J. (2018). The role of inhibition in avoiding distraction by salient stimuli. *Trends Cogn. Sci.* 22, 79–92. doi: 10.1016/j.tics.2017.11.001

Geng, J. J., Won, B. Y., and Carlisle, N. B. (2019). Distractor ignoring: strategies, learning, and passive filtering. *Curr. Dir. Psychol. Sci.* 28, 600–606. doi: 10.1177/0963721419867099

Humphreys, G. W., and Müller, H. J. (1993). SEarch via recursive rejection (SERR): a connectionist model of visual search. *Cogn. Psychol.* 25, 43–110. doi: 10.1006/cogp.1993.1002

Huynh Cong, S., and Kerzel, D. (2021). Allocation of resources in working memory: theoretical and empirical implications for visual search. *Psychon. Bull. Rev.* 28, 1093–1111. doi: 10.3758/s13423-021-01881-5

Kugler, G., Hart, B. M., Kohlbecher, S., Einhäuser, W., and Schneider, E. (2015). Gaze in visual search is guided more efficiently by positive cues than by negative cues. *PLoS One* 10:e0145910. doi: 10.1371/journal.pone.0145910

Loftus, G. R., and Loftus, E. F. (1988). *Essence of statistics*. New York: Alfred A Knopf.

Logan, G. D., and Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychol. Rev.* 108, 393–434. doi: 10.1037/0033-

Moher, J., Lakshmanan, B. M., Egeth, H. E., and Ewen, J. B. (2014). Inhibition drives early feature-based attention. *Psychol. Sci.* 25, 315–324. doi: 10.1177/0956797613511257

Nie, Q.-Y., Maurer, M., Müller, H. J., and Conci, M. (2016). Inhibition drives configural superiority of illusory gestalt: combined behavioral and drift-diffusion model evidence. *Cognition* 150, 150–162. doi: 10.1016/j.cognition.2016.02.007

Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *J. Exp. Psychol. Learn. Mem. Cogn.* 28, 411–421. doi: 10.1037/0278-7393.28.3.411

Reeder, R. R., Olivers, C. N., Hanke, M., and Pollmann, S. (2018). No evidence for enhanced distractor template representation in early visual cortex. *Cortex; a journal devoted to the study of the nervous system and behavior* 108, 279–282. doi: 10.1016/j.cortex.2018.08.005

Reeder, R. R., Olivers, C. N. L., and Pollmann, S. (2017). Cortical evidence for negative search templates. *Vis. Cogn.* 25, 278–290. doi: 10.1080/13506285.2017.1339755

Soto, D., Hodsoll, J., Rotshtein, P., and Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends Cogn. Sci.* 12, 342–348. doi: 10.1016/j.tics.2008.05.007

Töllner, T., Zehetleitner, M., Gramann, K., and Müller, H. J. (2010). Top-down weighting of visual dimensions: behavioral and electrophysiological evidence. *Vis. Res.* 50, 1372–1381. doi: 10.1016/j.visres.2009.11.009

Treisman, A. M., and Gelade, G. (1980). A feature-integration theory of attention. *Cogn. Psychol.* 12, 97–136. doi: 10.1016/0010-0285(80)90005-5

Vickery, T. J., King, L.-W., and Jiang, Y. V. (2005). Setting up the target template in visual search. *J. Vis.* 5, 8–92. doi: 10.1167/5.1.8

Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychon. Bull. Rev.* 1, 202–238. doi: 10.3758/BF03200774

Wolfe, J. M., Cave, K. R., and Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *J. Exp. Psychol. Hum. Percept. Perform.* 15, 419–433. doi: 10.1037/0096-1523.15.3.419

Wolfe, J. M., and Gray, W. (2007). "Guided search 4.0: current progress with a model of visual search," in *Integrated models of cognitive systems*. ed. W. Gray (New York, NY: Oxford University Press), 99–119.

Wolfe, J. M., Horowitz, T. S., Kenner, N. M., Hyle, M., and Vasan, N. (2004). How fast can you change your mind? The speed of top-down guidance in visual search. *Vis. Res.* 44, 1411–1426. doi: 10.1016/j.visres.2003.11.024

Woodman, G. F., and Luck, S. J. (2007). Do the contents of visual working memory automatically influence attentional selection during visual search? *J. Exp. Psychol. Hum. Percept. Perform.* 33, 363–377. doi: 10.1037/0096-1523.33.2.363

Yamaguchi, S., Hale, L. A., D'Esposito, M., and Knight, R. T. (2004). Rapid prefrontal-hippocampal habituation to novel events. *J. Neurosci.* 24, 5356–5363. doi: 10.1523/JNEUROSCI.4587-03.2004

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The facilitating effect of identical objects in visual working memory

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According to the associative network of memory representations proposed by embedded processes models, the links between related memory representations were automatically established, which rendered these representations more easily activated. The present study adopted color recall tasks to explore whether the memory performance of identical objects was enhanced *via* the strengthening links between them, producing facilitating effect of identical objects. In Experiment 1, the number of identical items was manipulated. The results evidenced the facilitating effect, which was positively related to the number of identical objects. Experiment 2 modulated the spatial location of identical objects, which suggested that the facilitating effect was absent when two pairs of identical objects were located diagonally. Furthermore, Experiment 3 suggested that the facilitating effect was observed for the identical items which were presented in the second and fourth quadrants, rather than the first and third quadrants. Together, these results evidenced the facilitating effect of identical objects, which, however, was affected by spatial bias.

KEYWORDS

visual working memory, identical objects, facilitating effect, spatial bias, recall task

1. Introduction

The visual working memory (VWM) system is widely regarded as the cornerstone of cognitive functions, which bridge the external environment and mind (Baddeley, 1992; Cowan, 1999). Previous studies show that participants can only remember 3–4 simple items in a VWM task (Luck and Vogel, 1997). Although individuals can improve the precision of VWM representation by sacrificing the amount number of stored representations (Gao et al., 2011; Machizawa et al., 2012; Ye et al., 2017, 2019; Long et al., 2020), the view that VWM is limited in its storage capacity is widely accepted (Vogel et al., 2001; Alvarez and Cavanagh, 2004). In the face of the dynamically presented visual information, the memory representations were conferred with different priorities according to the task demands during the highly complex tasks (Ericsson and Kintsch, 1995; Rose, 2020; Stokes et al., 2020). In light of embedded processes models of working memory (Cowan, 1999; Oberauer, 2002, 2005), the memory items greatly attended were retained in the region of direct access

(RDA) serving for the current processing, one of which was represented in the focus of attention (FOA); that was termed as the active state. Those items that were less relevant to the immediate task were maintained in the activation region of long-term memory (aLTM), and got accessed when needed later; they were regarded to be held in the passive state (LaRocque et al., 2014; Peters et al., 2019; Li et al., 2020, 2021; Zhang et al., 2022). Regarding the associative network of memory representations, the memory representations were deemed to be retained in distinct states according to the relevance to the current task, with the "state" signaling the accessibility of a representation for ongoing cognitive processing (Olivers et al., 2011; Stokes et al., 2020; Zhang et al., 2022). The memories in the active state are characterized by most privilege and direct accessibility, while the passive memories are accessed indirectly through links to the active representation (Oberauer, 2001; Oberauer and Lange, 2009; Peters et al., 2019).

During the memory task with multiple items, individuals widely adopted the chunking strategy, which rendered the memory functioning more efficient. Chunking means the links between items are generated (Ericsson and Kintsch, 1995; Oberauer, 2002). Notably, the working memory system was primarily responsible for the links of item–item and item–context, while the strength of links relied on the relation between items (Oberauer, 2002; Oberauer and Lange, 2009; Kaiser et al., 2015; Liu et al., 2022). Accordingly, we might suppose that these items with identical information tended to build up strengthening links relative to the unidentical items. When one item was activated, its linked item could be automatically activated *via* the associative links (Oberauer, 2005).

According to the embedded process models, it was proposed that the memory items were automatically bound to their positions in RDA, and the links between related memory items were spontaneously established (Oberauer and Lange, 2009). Given that the memory items with identical information were more likely to be chunked together with the strong associative links, it was assumed that the memory representations could be readily activated by means of the associative links when the other representations that were linked to it were activated. Thus, we could reasonably reckon that these memory representations that were possessed with the same feature were conferred with a low activation threshold of achieving the activation state relative to those memory items, which greatly differed. Accordingly, activation of memory representations with the same feature could require less resources due to the low activation threshold, thereby the spared resources preferably being used to enhance the memory performance. If it was the case, we predicted that the memory precision should be enhanced when presenting more identical items, while the spatial information of memory items might play a role. Thus, that opened up the question of whether the strong associative links between identical items could contribute to better memory performance, that is, the facilitating effect of identical objects.

In this study, we attempted to explore the facilitating effect of identical objects by measuring the precision and quantity of memory representations in color recall tasks. Based on the definition of an identical object, we defined the two bars with the same orientation as the identical objects. The bar's orientation should be remembered precisely during the encoding and retention period and retrieved later when probed. The size of the memory set did never exceed the memory capacity (no more than four items), which ensured the successful encoding of all memory items (Luck and Vogel, 1997; Cowan, 2001).

2. Experiment 1

We manipulated the number of identical objects to assess the facilitating effect of identical objects in Experiment 1, generating three conditions, two pairs of identical objects (2-pair), one pair of identical objects (1-pair), and no identical objects (0-pair). Considering that the size of the memory set was less than four, the memory quantity was comparable across the three conditions. We predicted that, if the facilitating effect of identical objects existed, the memory precision in the 2-pair and 1-pair conditions would be better than that of the 0-pair condition; if not, the memory precision in the three conditions did not differ.

2.1. Method

2.1.1. Participants

There were 12 participants (six female participants; mean age: 23.67 ± 3.06 years) from the Liaoning Normal University. Each of them signed the written informed consent before the experiment and received 15 CNY after participation for compensation. They all reported right-handedness and normal color vision, as well as normal and corrected-to-normal sight. The research was authorized by the Research Ethics Committee of Liaoning Normal University.

2.1.2. Stimuli

Each sample array contained four black-oriented bars (1.1° × 0.2°). The four bars were located at the four quadrants on a gray (RGB value, 120, 120, 120) screen. Each bar was in the center of each quadrant. The orientation of each bar changes between 0° and 179° at a 1° distance, producing 180 directions. All orientations of bars were randomly selected from them. The orientations of any two bars in the memory array were either identical or different. The orientations of the two different bars differed by at least 30°. The procedure was run by E-Prime 1.1 software. Visual stimuli were displayed on the 19-inch screen (60-Hz refresh rate, 1,024 × 768 pixels). Participants' responses were recorded from the computer mouse and keyboard. There was a fixation cross (0.2°) in the middle and consistently visible until finishing the experiment.

2.1.3. Procedure

Experiment 1 was conducted by a within-subject design. The memory array consistently presented four objects. The objects were bilaterally presented because previous studies suggest that, due to the allocation of more attentional resources, VWM performance is better when visual items are allocated in both left and right visual fields than within only one hemifield (Umemoto et al., 2010; Zhang et al., 2018). There were three conditions: two pairs of identical bars (2-pair), one pair of identical bars (1-pair), and no identical bars (0-pair; see Figure 1A). The 2-pair condition meant that the orientation of two bars which might be horizontally or vertically arranged in the memory array was the same, and the directions of the other two arranged horizontally or vertically were also the same, but the orientations of the first two were different from the latter two. The 1-pair condition indicated that the orientations of two objects were identical, but the orientations of the other two were different; the orientations of the first two were different from the latter two. The 0-pair condition indicated that the four bars had completely different orientations, so there was no pair of identical objects.

Before the appearance of the memory array lasting for 300 ms, only the fixation cross was presented for 500 ms. Then the screen was blank, lasting for 800 ms, and a test display appeared. In the probe array, a horizontal bar appeared centrally, and a white square outline which indicated to recall the orientation of the bar which previously appeared at that cued location. The test display did not disappear until making a response (see Figure 1B). The horizontal bar needs to be rotated to reproduce an orientation the same as the original at that square-cued location. Participants adjusted the orientation of the bars by clicking the two mouse buttons: a button used for rotating the bar at a free angle and the other used for fine adjustment by increasing or decreasing 1° per click. When participants were satisfied with their response, the probe array disappeared, and the next trial began.

We provided participants with instructions before starting formal trials. They were informed to make a response as accurately and quickly as possible, meanwhile the accuracy was emphasized. Three conditions were mixed randomly. Each condition contained 160 trials, creating 480 trials a total. Before starting, a practice of 20 trials was carried out by participants. The whole experiment lasted approximately 1 h.

2.2. Result

The Mem toolbox was used for the data analysis (Suchow et al., 2013). Individuals' data were fitted with the mixture model (Zhang and Luck, 2008). The standard deviation (*SD*) indexed the width of the distribution of memory errors, and its reciprocal could reflect the memory precision. The guess rate (*g*) indicated the height of uniform distribution, reflecting the storage probability, that is, memory quantity. Then, *SD* and *g* of all participants were averaged under the three conditions (Figures 2A–E).

The guess rate (*g*) and *SD* were subject to one-way ANOVA separately. η_p^2 was reported as effect size. We used Greenhouse–Geisser adjustment to correct p. There was no main effect of guess rate, $F(2, 22) = 1.06$, $p > 0.05$, $\eta_p^2 = 0.09$, while the significant main effect of memory precision was observed, $F(2, 22) = 10.75$, $p < 0.05$, $\eta_p^2 = 0.49$. *Post hoc* test suggested that the memory precision in the 2-pair condition was high, and the precision of the 1-pair was better than the 0-pair (all $p < 0.05$). These results suggested that the

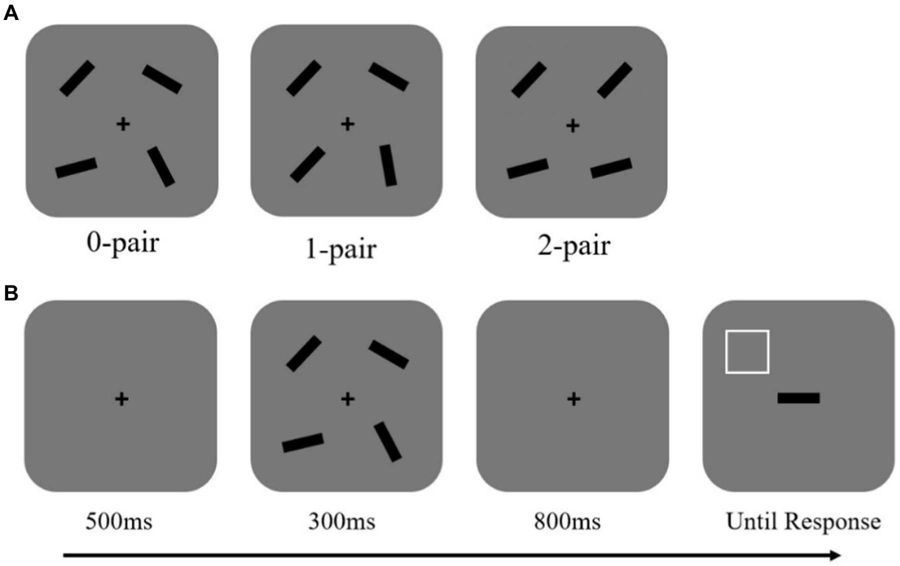

FIGURE 1
(A) Spatial configuration of memory items in Experiment 1. There were three conditions: 0-pair condition, 1-pair condition, and 2-pair condition. **(B)** The schematic of the experimental procedure. The white square outline was used as a cue to instruct participants to recall the orientation of the bar, which previously appeared at that cued location.

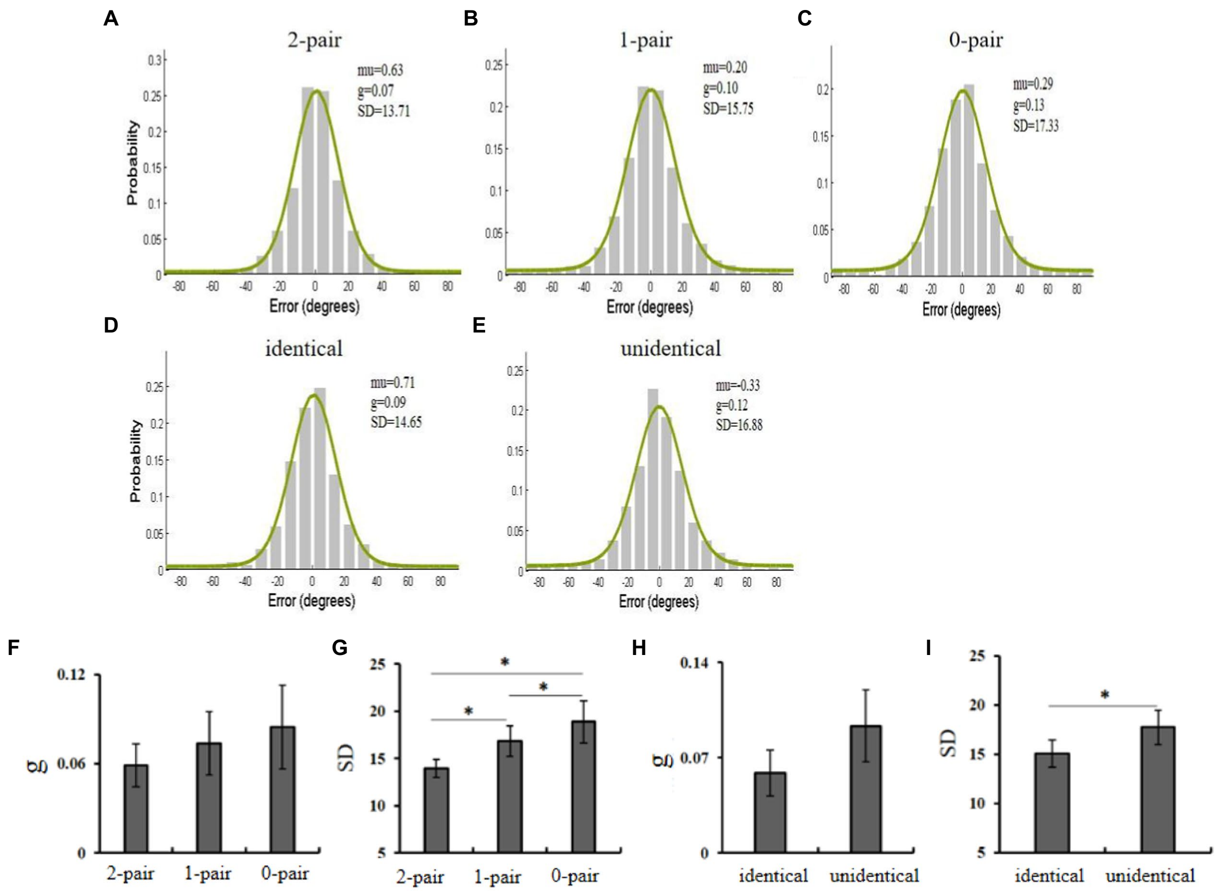

FIGURE 2
(A–C) Distributions of response errors with the fit of standard mixture model in the condition with two pairs of identical objects (2-pair), one pair of identical objects (1-pair), and no pair of identical objects (0-pair). **(D,E)** The distributions of response errors for the identical items and unidentical items in the 1-pair condition. **(F,G)** The guess rate and *SD* in the three conditions. **(H,I)** The guess rate and *SD* for the identical items and unidentical items in the 1-pair condition. The black bars represent the standard error.

guess rate was independent of the number of identical objects, while the memory precision increased as more pairs of identical objects were presented, revealing the facilitating effect of identical objects (Figures 2F,G).

If the enhancement of memory precision resulted from the sameness of objects, we then expected that, in the 1-pair condition, the memory precision of identical objects was better than that of the other two objects. As we expected, the results of the paired-sample *t*-test showed that the guess rate did not differ between the identical and unidentical objects, $t(11) = 3.98$, $p > 0.05$, Cohen's $d = 0.27$, whereas the memory precision of identical objects was greatly higher than unidentical objects, $t(11) = 8.01$, $p < 0.05$, Cohen's $d = 0.42$ (Figures 2H,I).

2.3. Discussion

The earlier results indicated that the memory precision of the identical objects was better than that of the unidentical, which reflected the facilitating effect of identical objects. That is, the memory precision improved as more pairs of identical objects were remembered. For the external visual environment, the visual information could be perceptually structuralized even for the discrete items. According to the Gestalt principles, the discrete items can be encoded as an integrated object, which specifically guides attentional resources and then impacts the cognitive process (Palmer and Rock, 1994; Treisman and Zhang, 2006). According to the binding mechanisms in the RDA, the item was bound to its context automatically (Oberauer and Lange, 2009). That seemed to imply that the link strength between items might be affected by their spatial distance. In other words, the links of identical items might be weak when they are presented at a relatively far distance, while the links are relatively strong at a close distance. Considering that the facilitating effect of identical objects was observed for the memory items located horizontally or vertically in Experiment 1, that leaves up the question of whether the facilitating effect still occurred when locating the identical items diagonally. That question was explored in Experiment 2.

3. Experiment 2

In this part, we aimed to explore the effect of location information on the facilitating effect of identical objects. The locations of identical objects were manipulated. Based on the experimental conditions in Experiment 1, we designed the horizontal condition (2-pair-horizontal), vertical condition (2-pair-vertical), diagonal condition (2-pair-diagonal), and four unidentical conditions (4-object). There were two pairs of identical objects in each condition. In addition, there was a condition of presenting two unidentical items as baseline (2-object).

3.1. Method

3.1.1. Participants

Recruitment of 12 undergraduates (seven female participants, mean age: 23.67 ± 1.89 years) who came from the Liaoning Normal University; they received 15 CNY for compensation for their participation. Written informed consents were signed by each participant. They reported normal color vision and normal or corrected-to-normal sight.

3.1.2. Stimuli and procedure

The stimuli and procedure in this experiment were similar to the previous experiment (see Figure 3B) but involved some modification. The memory arrays consisted of two unidentical objects (2-object), four unidentical objects (4-object), two pairs of identical objects arranged horizontally (2-pair-horizontal), two pairs of identical objects arranged vertically (2-pair-vertical), and two pairs of identical objects arranged diagonally (2-pair-diagonal; see Figure 3A). Participants need to perform all the conditions. The five conditions were mixed randomly with each condition containing 80 trials. There were 400 trials across five blocks. Before the formal experiment started, participants needed to perform 20 trials for practice. That experiment lasted approximately 1 h.

3.2. Result

The offsets between the response and original values were fitted using mixture models, generating the guess rate (*g*) and *SD* (Figures 4A–E). The guess rate and *SD* were separately analyzed by one-way ANOVA. The results showed no main effect of guess rate, $F(4, 44) = 1.57$, $p > 0.05$, $\eta_p^2 = 0.13$, while the main effect of *SD* was significant, $F(2.5, 28) = 8.58$, $p < 0.05$, $\eta_p^2 = 0.44$ (Figures 4F,G). *Post hoc* analysis suggested that the precision of 2-pair-diagonal items was greatly lower than 2-object, 2-pair-horizontal, and 2-pair-vertical (all $p < 0.05$), while comparable to the 4-object ($p > 0.05$). The precision did not differ between the 2-pair-horizontal and the 2-pair-vertical conditions ($p > 0.05$). The 2-object had statistically better precision than the 4-object ($p < 0.05$). These results are depicted in Figures 4F,G, demonstrating that the spatial position of identical objects had an effect on the facilitating effect.

3.3. Discussion

These results suggested that the identical objects were conferred with higher memory precision compared to the unidentical objects when the identical items were located horizontally and vertically, manifesting the facilitating effect again. Importantly, the facilitating effect was absent when the identical items were presented in a diagonal manner. The absence of facilitating effect might be explained by the fact that the associative links between the two pairs of identical items intersected due to

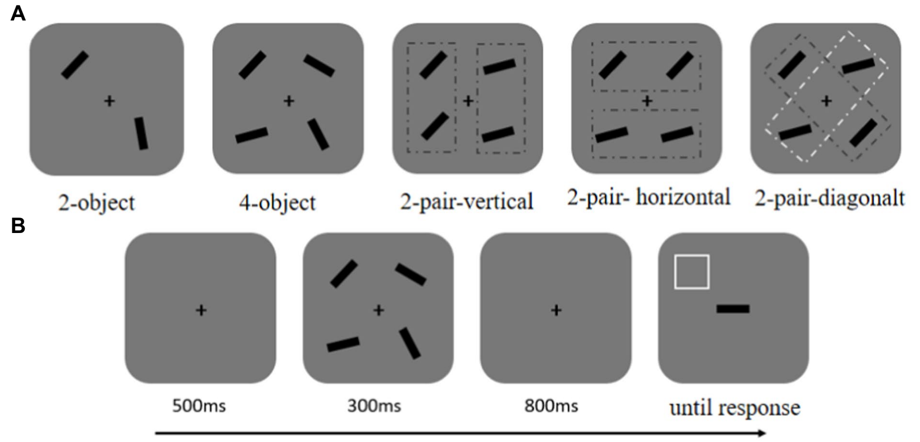

FIGURE 3
(A) Spatial configuration of memory items in Experiment 2. The memory arrays consisted of two unidentical objects (2-object), four unidentical objects (4-object), two pairs of identical objects arranged vertically (2-pair-vertical), two pairs of identical objects arranged horizontally (2-pair-horizontal), and two pairs of identical objects arranged diagonally (2-pair-diagonal). **(B)** The schematic of a trial.

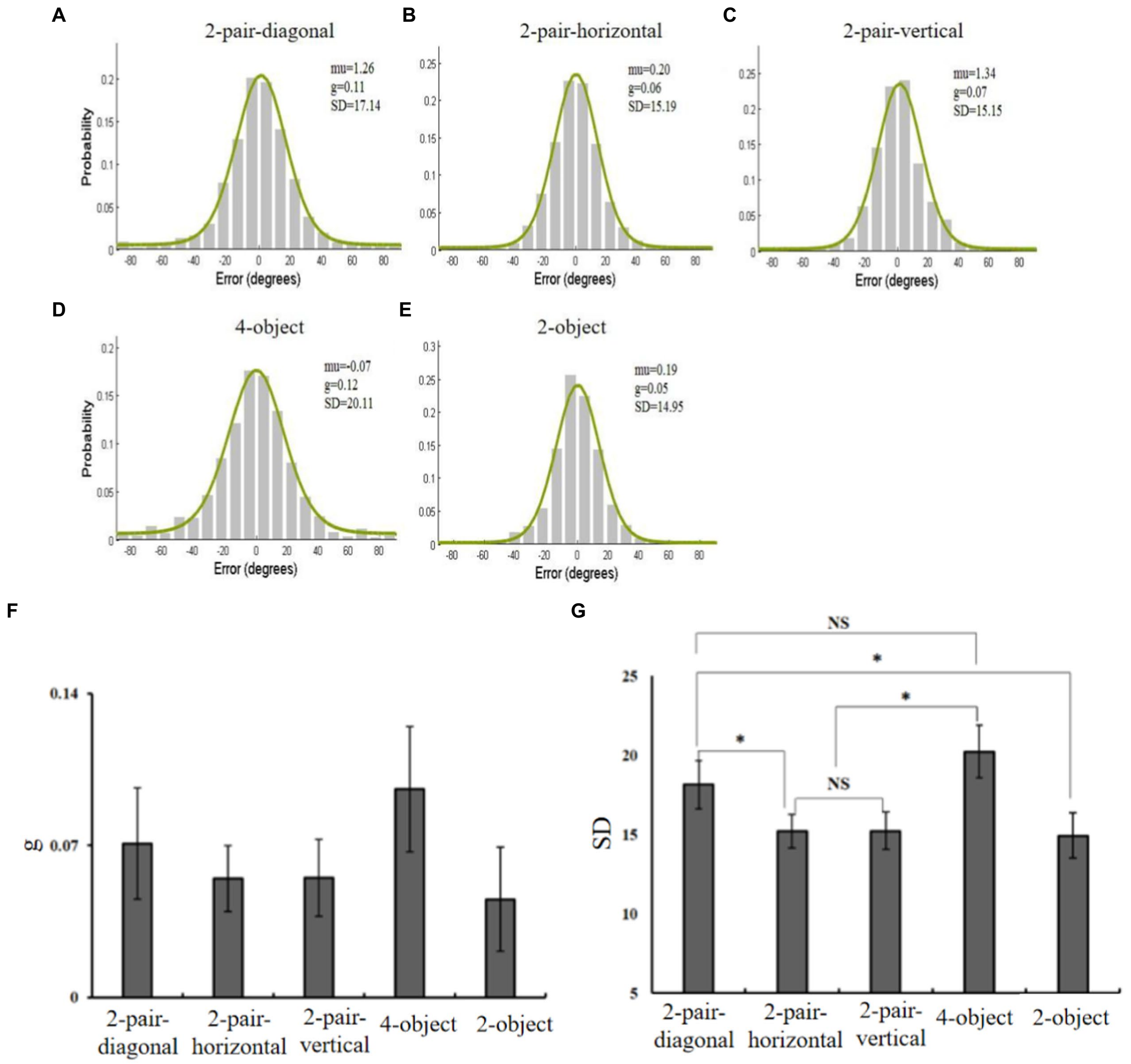

FIGURE 4
(A–E) Distributions of response errors with the fit of standard mixture model in the 2-pair-diagonal, 2-pair-horizontal, 2-pair-vertical, 2-object, and 4-object conditions. **(F,G)** The guess rate and *SD* in the five conditions. The black bars represent the standard error.

the diagonal position of the two pairs, which thus caused the interference and then overrode the facilitating effect. If this was the case, it should be expected a facilitating effect when a pair of identical objects was presented diagonally, which was explored in the following part.

4. Experiment 3

4.1. Method

4.1.1. Participants

Notably, 14 undergraduates (13 female participants, mean age: 21.43 ± 2.13 years) took part in Experiment 3 and received 15 CNY after the completion of the experiment. Participants provided written informed consent when they arrived at the lab. All reported right-handedness and normal color vision, as well as the normal or corrected-to-normal sight.

4.1.2. Stimuli and procedure

We adopted similar stimuli and procedure to the Experiment 1 in this part, excepting the following (see Figure 5B). The color recall task was conducted in a within-subject design. There were constantly four items in each condition, and the identical objects were always presented in diagonal. That generated three conditions, one pair in the first and third quadrants (1-3-quadrant condition), one pair in the second and fourth quadrants (2-4-quadrant condition), and two pairs in diagonal (2-pair condition;

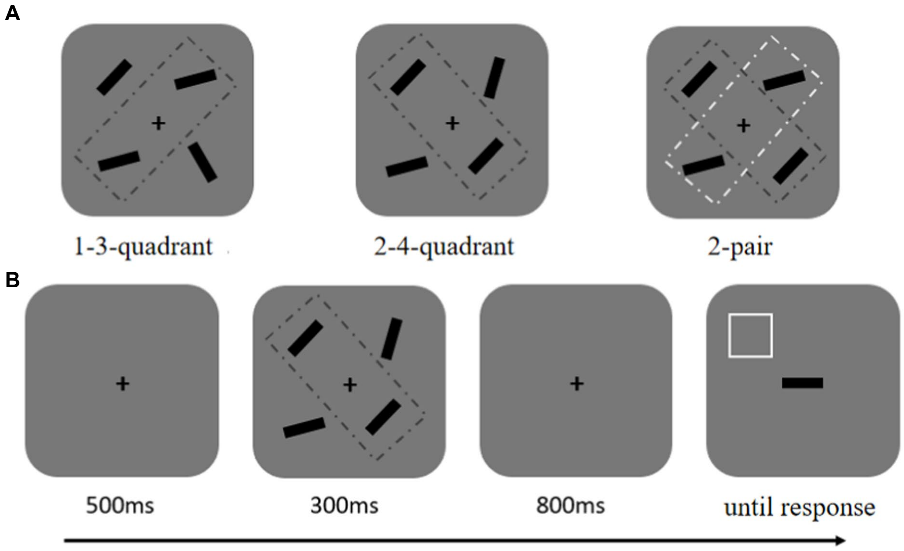

FIGURE 5
(A) Spatial configuration of memory items in Experiment 3. **(B)** The schematic of a trial.

see Figure 5A). The three conditions were mixed randomly; each condition contained 80 trials with five blocks. At least 1 min was inserted between blocks for a rest. Before the formal trials, participants received 20 trials for practice, ensuring that to be well familiar with the experimental procedure.

4.2. Results

The offset between response and original values was fitted using the mixture model (Figures 6A–C), producing *SD* and guess rate (*g*). We run a one-way ANOVA on them separately. The results showed that the main effect of guess rate was not significant, $F(2, 26) = 2.26$, $p > 0.05$, $\eta_p^2 = 0.15$, but a significant main effect of memory precision was observed, $F(2, 26) = 8.28$, $p < 0.05$, $\eta_p^2 = 0.39$. A subsequent simple effect test showed that the precision in the 2-pair condition was higher than the 1-3-quadrant condition ($p < 0.05$), and the precision in the 2-4-quadrant was also better than the 1-3-quadrant condition ($p < 0.05$). The precision of the 2-pair matched the precision of the 2-4-quadrant ($p > 0.05$).

To explore the effect of diagonal location on the facilitating effect, we then conducted a 2 (quadrant:1–3 vs. 2–4) × 3 (location of identical items: 2-pair vs. 1-3-quadrant vs. 2-4-quadrant) ANOVA on *SD* and *g* (Figures 6D,E). For the guess rate, there was no main effect of the location of identical items, $F(2, 26) = 1.03$, $p > 0.05$, $\eta_p^2 = 0.07$, neither nor the main effect of the quadrant, $F(1, 13) = 0.11$, $p > 0.05$, $\eta_p^2 = 0.01$. The two factors did not significantly interact, $F(2, 26) = 0.14$, $p > 0.05$, $\eta_p^2 = 0.01$. For the memory precision, the main effect of quadrant was not significant, $F(1, 13) = 4.13$, $p > 0.05$, $\eta_p^2 = 0.24$, neither was the main effect of the location of identical items, $F(2, 26) = 2.62$, $p > 0.05$, $\eta_p^2 = 0.17$. Importantly, the interaction was significant, $F(2, 26) = 7.00$, $p < 0.05$, $\eta_p^2 = 0.35$. The subsequent analysis showed that, for the items in the first and third quadrants, the memory precision was comparable across the three conditions. Whereas for the items in the second and fourth quadrants, the memory precision in the 1-3-quadrant condition was significantly lower than the 2-4-quadrant and 2-pair conditions ($p < 0.05$), and the latter two matched with each other ($p > 0.05$). In the 2-pair condition, the memory precision of objects in the second and fourth quadrants was higher than the other two ($p < 0.05$); in the 2-4-quadrant condition, the precision of objects in the second and fourth quadrants was higher than others ($p < 0.05$); in the 1-3-quadrant condition, the four objects have comparable precision ($p > 0.05$). These results showed that the objects in the second and fourth quadrants have an advantage in behavioral performance over those in the first and third quadrants. These results are depicted in Figures 6F,G.

4.3. Discussion

These results showed that the identical items that were located in the first and third quadrants were not endowed with facilitating effects, whereas the facilitating effect still occurred when they were located in the second and fourth quadrants. Therefore, these results revealed that the facilitating effect of identical items was greatly related to the quadrant information when they were located diagonally, which might be interpreted by spatial bias.

5. General discussion

This current study attempted to explore whether the memory performance of identical objects could be enhanced due to the

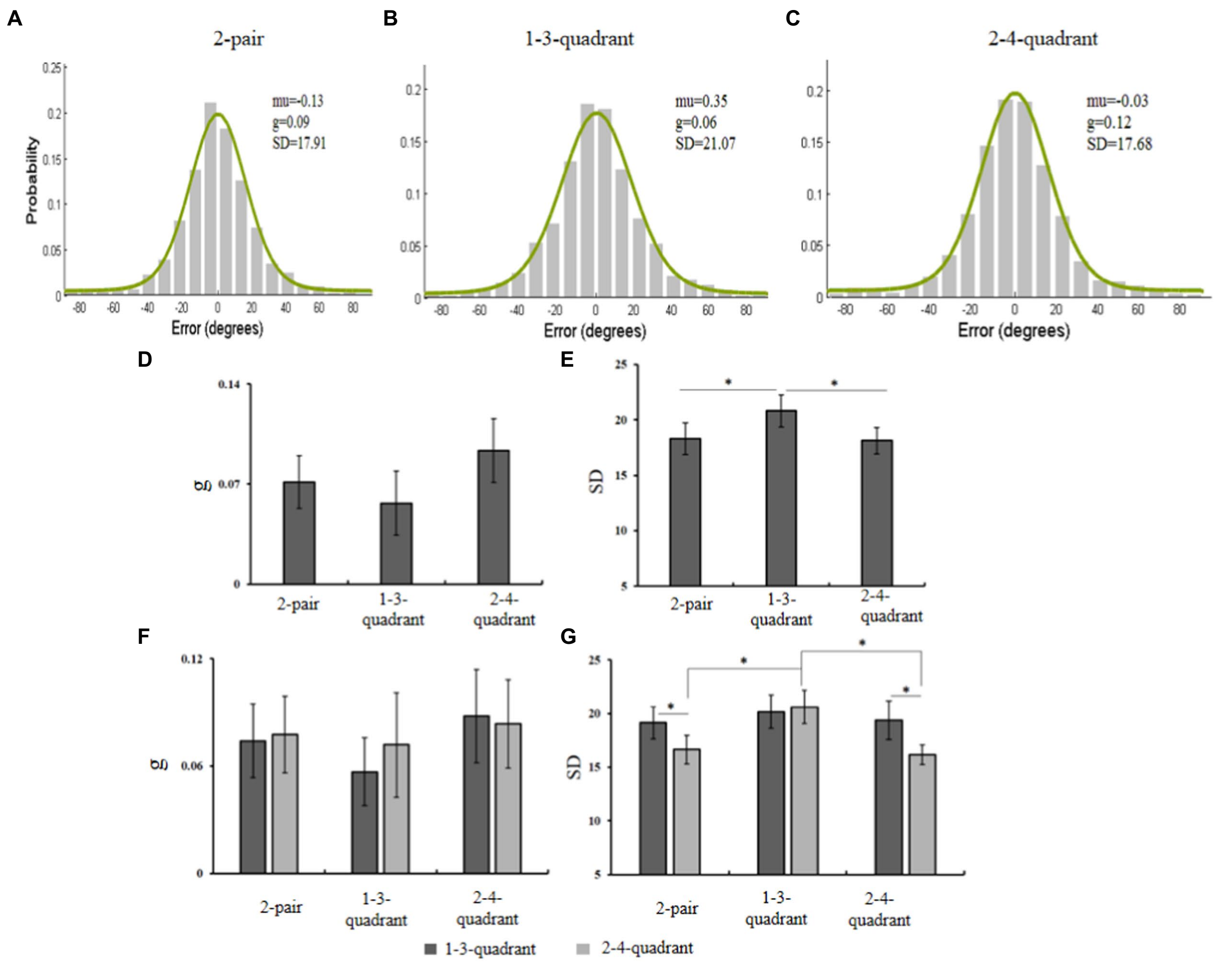

FIGURE 6
(A–C) Distributions of response errors with the fit of standard mixture model in the 2-pair, 1-3-quadrant, and 2-4-quadrant conditions. **(D,E)** The guess rate and SD in the three conditions. **(F,G)** The guess rate and SD of items in the 1-3-quadrant and 2-4-quadrant under the three conditions. The black bars represent the standard error.

strengthening links between them across three experiments. We varied the number of identical items in Experiment 1, and these results showed that the memory precision was higher when more identical items were presented, indicating the facilitating effect of identical objects. Given that the memory items were automatically bound with spatial context according to the binding mechanisms (Oberauer, 2002; Oberauer and Lange, 2009), the location information of memory items should be taken into account. In addition to the horizontal and vertical conditions, two pairs of identical items were located diagonally in Experiment 2. We observed the absence of facilitating effect of identical items. However, it was premature to consider that the facilitating effect completely relied on space proximity (Shepard, 1962). Furthermore, Experiment 3 examined what the effect the spatial location on the facilitating effect. In this part, the identical items were always presented diagonally and differed in the quadrant. It was found that the identical items in the second and fourth quadrants still conferred with facilitating effect, but rather in the first and third quadrants. Overall, we concluded that the object sameness contributed to better memory performance, evidencing the facilitating effect of identical objects; that facilitating effect was conditioned by the spatial context, thus not extended to the identical objects that were presented in any random positions.

In terms of the memory system, the associative network of memory representations was established *via* the abundant links between related representations. The high relevance between the representations preferentially contributed to strengthening links. In the current study, the memory precision acted as the behavioral indicator of the linking strength of memory representations, which to some certain revealed that physically identical objects produced relatively stronger links than unidentical objects. Notably, the linking strength was conditioned by location information, which at least complied with the proximity of the Gestalt principle (Peterson and Berryhill, 2013; Shen et al., 2014).

Moreover, it has previously been proposed that spatial information plays an important role. When visual stimuli appeared within the field of vision, individuals would involuntarily focus on a specific visual field, which resulted in the preferable processing of the stimuli in the focused visual field over other unfocused visual fields. That was referred to as spatial bias (Ossandon et al., 2014). The facilitating effect from the identical objects located in the second and fourth quadrants might be accounted for by the spatial bias that was thought to derive from the interaction between sensory attention and motor intentional (Schwartz et al., 1997). For example, a previous study has found that the left visual field bias worked during the early perception of face stimuli. That bias was presumed to be accounted for by the hemisphere lateralization or the product of control by high-lever brain areas. In addition, the social culture might also have an effect on spatial bias. Brady et al. (2005) found that, for example, people tended to depend on the expressions of the left face for making a response when the left and right faces wore different expressions during a face discrimination task; however, the left bias was absent for those people who habitually wrote and read from right to left.

The research on spatial bias previously suggested that participants showed a leftward bias in the early period of visual research, independent of the stimuli category (Ossandon et al., 2014). In addition, a study on the gaze bias had revealed that individuals tended to gaze at the upper-left location in the initial gaze movement when they performed a visual search; in addition, the upper-left and lower-right parts were thought as favored locations, though depending on conditions (Durgin et al., 2008). That is, we are more likely to focus on the top part when the attention shifted to the left visual field, while the focus was put on the down part when attending to the right visual field. Intriguingly, this research on the spatial bias convergingly pointed to the second or/and fourth quadrants, which was compatible with the findings of the current study. Though there was no agreement on the quadrant edge, it seemed to presume that the second quadrant was widely regarded to be the most prioritized.

The sameness of memory items should be regarded as the extremity of the similarity of memory items. There were two theoretical interpretations that might underpin the facilitating effect of similarity. First, it has been pointed out that the enhanced memory performance resulted from the simplification of the memory array due to the similarity of memory items, thus indirectly reducing the memory load and lowering the need for cognitive resources (Mate and Baques, 2009). However, Lin and Luck (2009) argued that better memory performance of similar items was attributed to reciprocal facilitation (Lin and Luck, 2009). The current results pattern suggested that the guess rate was low and comparable across different conditions, indicating that the number of memory items successfully encoded in VWM did not differ. That thus denied the reducing memory load account. In addition, considering that the memory precision should reach an asymptote when the load reached four, intriguingly, the memory precision was modulated by the number of identical items through which four items were remembered, which implied the reciprocal facilitation between the identical items *via* strengthening links. That seemed to be consistent with Lin's proposal.

6. Conclusion

Overall, the current study evidenced the facilitating effect of identical objects, while the facilitating effect was affected by location information (i.e., spatial bias). In further research, it was necessary to investigate what the role of spatial distance and configuration in the facilitating effect of identical objects. Given that the facilitating effect was observed from two identical objects in the current study, the present findings paved the way for further exploration of whether the facilitating effect was larger if the number of identical objects was more than two, and whether the facilitating effect had a similar level when increasing the overall memory load. Future research on these questions would benefit from a complete understanding of the maintenance mechanisms of identical items.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Research Ethics Committee of Liaoning Normal University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

GR and NM developed the study concept and designed the experiment, performed the data analysis, and provided critical revision. NM performed testing and data collection. GR, NM, and ML interpreted the data. ML drafted the manuscript and refined the language. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Alvarez, G. A., and Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychol. Sci.* 15, 106–111. doi: 10.1111/j.0963-7214.2004.01502006.x

Baddeley, A. (1992). Working memory. *Science* 255, 556–559. doi: 10.1126/science.1736359

Brady, N., Mark, C., and Mary, F. (2005). Perceptual asymmetries are preserved in memory for highly familiar faces of self and friend. *Brain Cogn.* 58, 334–342. doi: 10.1016/j.bandc.2005.01.001

Cowan, N. (1999). "An embedded-processes model of working memory" in *Models of working memory: Mechanisms of active maintenance and executive control*. eds. A. Miyake and P. Shah (Cambridge: Cambridge University Press), 62–101.

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behav. Brain Sci.* 24, 87–114. doi: 10.1017/S0140525X01003922

Durgin, F. H., Doyle, E., and Egan, L. (2008). Upper-left gaze bias reveals competing search strategies in a reverse Stroop task. *Acta Psychol.* 127, 428–448. doi: 10.1016/j.actpsy.2007.08.007

Ericsson, K. A., and Kintsch, W. (1995). Long-term working memory. *Psychol. Rev.* 102, 211–245. doi: 10.1037/0033-295X.102.2.211

Gao, Z., Yin, J., Xu, H., Shui, R., and Shen, M. (2011). Tracking object number or information load in visual working memory: revisiting the cognitive implication of contralateral delay activity. *Biol. Psychol.* 87, 296–302. doi: 10.1016/j.biopsycho.2011.03.013

Kaiser, D., Stein, T., and Peelen, M. V. (2015). Real-world spatial regularities affect visual working memory for objects. *Psychon. Bull. Rev.* 22, 1784–1790. doi: 10.3758/s13423-015-0833-4

LaRocque, J. J., Lewis-Peacock, J. A., and Postle, B. R. (2014). Multiple neural states of representation in short-term memory? It's a matter of attention. *Front. Hum. Neurosci.* 8, 8, 1–14. doi: 10.3389/fnhum.2014.00005

Li, Z., Liang, T., and Liu, Q. (2021). The storage resources of the active and passive states are independent in visual working memory. *Cognition* 217:104911. doi: 10.1016/j.cognition.2021.104911

Li, Z., Zhang, J., Liang, T., Ye, C., and Liu, Q. (2020). Interval between two sequential arrays determines their storage state in visual working memory. *Sci. Rep.* 10:7706. doi: 10.1038/s41598-020-64825-4

Lin, P. H., and Luck, S. J. (2009). The influence of similarity on visual working memory representations. *Vis. Cogn.* 17, 356–372. doi: 10.1080/13506280701766313

Liu, X., Liu, R., Guo, L., Astikainen, P., and Ye, C. (2022). Encoding specificity instead of online integration of real-world spatial regularities for objects in working memory. *J. Vis.* 22:8. doi: 10.1167/jov.22.9.8

Long, F., Ye, C., Li, Z., Tian, Y., and Liu, Q. (2020). Negative emotional state modulates visual working memory in the late consolidation phase. *Cognit. Emot.* 34, 1646–1663. doi: 10.1080/02699931.2020.1795626

Luck, S. J., and Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature* 390, 279–281. doi: 10.1038/36846

Machizawa, M. G., Goh, C. C., and Driver, J. (2012). Human visual short-term memory precision can be varied at will when the number of retained items is low. *Psychol. Sci.* 23, 554–559. doi: 10.1177/0956797611431988

Mate, J., and Baques, J. (2009). Visual similarity at encoding and retrieval in an item recognition task. *Q. J. Exp. Psychol.* 62, 1277–1284. doi: 10.1080/17470210802680769

Oberauer, K. (2001). Removing irrelevant information from working memory: a cognitive aging study with the modified Sternberg task. *J. Exp. Psychol. Learn. Mem. Cogn.* 27, 948–957. doi: 10.1037/0278-7393.27.4.948

Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *J. Exp. Psychol. Learn. Mem. Cogn.* 28, 411–421. doi: 10.1037/0278-7393.28.3.411

Oberauer, K. (2005). Binding and inhibition in working memory: individual and age differences in short-term recognition. *J. Exp. Psychol. Gen.* 134, 368–387. doi: 10.1037/0096-3445.134.3.368

Oberauer, K., and Lange, E. B. (2009). Activation and binding in verbal working memory: a dual-process model for the recognition of nonwords. *Cogn. Psychol.* 58, 102–136. doi: 10.1016/j.cogpsych.2008.05.003

Olivers, C. N. L., Peters, J., Houtkamp, R., and Roelfsema, P. R. (2011). Different states in visual working memory: when it guides attention and when it does not. *Trends Cogn. Sci.* 15, 327–334. doi: 10.1016/j.tics.2011.05.004

Ossandon, J. P., Onat, S., and Konig, P. (2014). Spatial biases in viewing behavior. *J. Vis.* 14:20. doi: 10.1167/14.2.20

Palmer, S., and Rock, I. (1994). Rethinking perceptual organization: the role of uniform connectedness. *Psychon. Bull. Rev.* 1, 29–55. doi: 10.3758/BF03196566

Peters, B., Rahm, B., Kaiser, J., and Bledowski, C. (2019). Differential trajectories of memory quality and guessing across sequential reports from working memory. *J. Vis.* 19:3. doi: 10.1167/19.7.3

Peterson, D. J., and Berryhill, M. E. (2013). The gestalt principle of similarity benefits visual working memory. *Psychon. Bull. Rev.* 20, 1282–1289. doi: 10.3758/s13423-013-0460-x

Rose, N. S. (2020). The dynamic-processing model of working memory. *Curr. Dir. Psychol. Sci.* 29, 378–387. doi: 10.1177/0963721420922185

Schwartz, R. L., Adair, J. C., Na, D., Williamson, D. J. G., and Heilman, K. M. (1997). Spatial Bias:Attentional and Intentional Influence in Normal Subjects. *Neurology* 48, 234–242. doi: 10.1212/wnl.48.1.234

Shen, M., Gao, Q., Tang, N., Shui, R., Chen, S., and Gao, Z. (2014). Constructing gestalt in visual working memory. *J. Vis.* 14:34. doi: 10.1167/14.10.34

Shepard, R. N. (1962). The analysis of proximities: multidimensional scaling with an unknown distance function. Part I. *Psychometrika* 27, 125–140. doi: 10.1007/BF02289630

Stokes, M. G., Muhle-Karbe, P. S., and Myers, N. E. (2020). Theoretical distinction between functional states in working memory and their corresponding neural states. *Vis. Cogn.* 28, 420–432. doi: 10.1080/13506285.2020.1825141

Suchow, J. W., Brady, T. F., Fougnie, D., and Alvarez, G. A. (2013). Modeling visual working memory with the MemToolbox. *J. Vis.* 13:9. doi: 10.1167/13.10.9

Treisman, A., and Zhang, W. (2006). Location and binding in visual working memory. *Mem. Cogn.* 34, 1704–1719. doi: 10.3758/BF03195932

Umemoto, A., Drew, T., Ester, E. F., and Awh, E. (2010). A bilateral advantage for storage in visual working memory. *Cognition* 117, 69–79. doi: 10.1016/j.cognition.2010.07.001

Vogel, E. K., Woodman, G. F., and Luck, S. J. (2001). Storage of features, conjunctions and objects in visual working memory. *J. Exp. Psychol. Hum. Percept. Perform.* 27, 92–114. doi: 10.1037/0096-1523.27.1.92

Ye, C., Hu, Z., Li, H., Ristaniemi, T., Liu, Q., and Liu, T. (2017). A two-phase model of resource allocation in visual working memory. *J. Exp. Psychol. Learn. Mem. Cogn.* 43, 1557–1566. doi: 10.1037/xlm0000376

Ye, C., Sun, H. J., Xu, Q., Liang, T., Zhang, Y., and Liu, Q. (2019). Working memory capacity affects trade-off between quality and quantity only when stimulus exposure duration is sufficient: evidence for the two-phase model. *Sci. Rep.* 9:8727. doi: 10.1038/s41598-019-44998-3

Zhang, W., and Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature* 453, 233–235. doi: 10.1038/nature06860

Zhang, Y., Ye, C., Roberson, D., Zhao, G., Xue, C., and Liu, Q. (2018). The bilateral field advantage effect in memory precision. *Q. J. Exp. Psychol.* 71, 749–758. doi: 10.1080/17470218.2016.1276943

Zhang, J., Ye, C., Sun, H.-J., Zhou, J., Liang, T., Li, Y., et al. (2022). The passive state: a protective mechanism for information in working memory tasks. *J. Exp. Psychol. Learn. Mem. Cogn.* 48, 1235–1248. doi: 10.1037/xlm0001092

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Dynamic and static angry faces influence time perception differently—Evidence from ERPs

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The dynamic characteristics of facial expressions might affect time perception. Compared with static emotional faces, dynamic emotional faces are more intense, have higher ecological validity, and contain time series information, which may lead to time overestimation. In the present study, we aimed at investigating how dynamic characteristics of angry facial expressions affect time perception, as measured using event-related potentials (ERPs). Dynamic and static angry and neutral faces with different durations (400, 600, 800, 1000, 1200, 1400, and 1600 ms) were presented in the classical temporal bisection paradigm. Participants were asked to judge whether the duration of the presented face was closer to 400 or 1600 ms. The behavioral results showed a significant overestimation effect for dynamic angry faces compared with static faces, both in terms of proportion of long and Bisection Point. The ERP results indicated that the processing mechanisms are significantly different between judging the duration of dynamic and static angry faces. Dynamic angry faces evoked a larger N2 and Late Positive Potential than did static faces, while the static angry faces evoked a larger P2 and Early Posterior Negativity. The Contingent Negative Variation showed a complex change pattern over time. Our results indicate that dynamic angry facial expressions influence time perception differently than do static faces. Static angry faces were processed earlier and were considered to cause an overestimation of time through early emotional arousal and attentional bias, while dynamic angry faces may have caused the overestimation of time through response inhibition and late sustained attention.

KEYWORDS

time perception, dynamic characteristic, angry face, event-related potentials, dynamic facial expression

1. Introduction

Time is the basic dimension of life. Rapid and accurate time perception greatly influences one's daily life, especially in the context of social interaction. Failure to accurately perceive others' facial expressions and responses that are too late or too early may result in social failure. According to previous studies, time perception can be greatly influenced by the emotional state of the social counterpart (Buhusi and Meck, 2005; Droit-Volet and Gil, 2009; Tamm et al., 2014). Perceived emotion may bias an individual's time perception. In general, negative emotional events are perceived as longer than neutral or positive emotional events (known as the subjective lengthening effect), while happy emotions make people feel like "time is flying" (known as the subjective shortening effect) (Gil and Droit-Volet, 2011; Droit-Volet et al., 2016; Tian et al., 2018). Moreover, distinct negative emotions may exert different effects on time perception. Gil and Droit-Volet (2011) reported that anger, fear, and sadness have a lengthening effect, while shame has a shortening effect or no effect on time perception, depending on whether participants correctly recognized this emotion. The level of arousal induced by facial expression can also affect time perception; for instance, angry expressions have been found to result in a larger lengthening effect than sad expressions (Fayolle and Droit-Volet, 2014).

Another factor that can influence time perception is the dynamic (movement) feature of a stimulus. Static photographs and pictures are the most frequently used stimuli in previous studies (Gil and Droit-Volet, 2011; Li and Yuen, 2015). However, compared with static facial materials, dynamic faces are more natural, more common in daily life, and better reflect individuals' genuine emotional states (Sato and Yoshikawa, 2007; Li and Yuen, 2015). Several studies have also shown that subjects judge the emotion of moving faces as more intense and realistic than that of static faces, and recognition accuracy is also reportedly enhanced for dynamic stimuli (Wehrle et al., 2000; Biele and Grakowska, 2006; Sato and Yoshikawa, 2007). Therefore, dynamic emotional stimuli may have a different effect on time perception than do static stimuli. According to the scalar timing theory, dynamic faces attract more attention than static faces, and thus lead to a more robust lengthening or overestimation effect (Gibbon, 1977; Gibbon et al., 1984). More recently, empirical research from Fayolle and Droit-Volet (2014) examined the effects of dynamic facial expression displays on time perception in a temporal bisection task. The participants were firstly trained to respond "short" or "long" after presented the short (0.4 s) and the long (1.6 s) standard duration in the form of an oval. They were then presented with seven different comparison durations and asked to respond whether the comparison duration was more similar to the "short" or "long" standard duration. In the formal test, the oval was replaced with different arousing emotional facial expressions (anger vs. sadness) in either a dynamic or a static form with different comparison durations. Their results suggested that facial movements amplified the effect of emotion on time perception, whereby dynamic angry emotional expressions were perceived as being longer than static sad expressions.

The specific effect of facial dynamic features on time perception might have different neural underpinnings to the effect of static features. Previous work on the neural mechanisms underlying facial emotion processing has shown that dynamic emotional face processing is mainly associated with activity in brain areas related to social treatment (the superior temporal sulcus) and to emotion processing (the amygdala) (Alves, 2013). Previous studies have also tested the electrophysiological indicators of time perception during the presentation of static faces (Dan et al., 2009; Gan et al., 2009; Tamm et al., 2014; Recio et al., 2017). However, to the best of our knowledge, no studies have yet investigated the neural correlates of the potentially distinct mechanisms underlying the effect of dynamic and static stimuli on time perception. Our study is therefore the first to examine this question using an event-related potential (ERP) methodology.

In accordance with previous studies on the neural mechanisms underlying the effect of emotion on time perception (Dan et al., 2009; Gan et al., 2009; Kei et al., 2011; Tamm et al., 2014; Recio et al., 2017; Wang et al., 2019), we focused our analyses on four ERP components, as follows: the P2, Early Posterior Negativity (EPN), Late Positive Potential (LPP), and Contingent Negative Variation (CNV). As an important early visual component, the P2 (100–200 ms) reflects a person's sensitivity to emotional expression, and is affected by the interaction between emotional stimulation and task-related factors (Foti et al., 2009). In addition to these early visual components, the EPN and LPP are also often found and discussed in the context of emotional expression processing tasks. The EPN component reflects attentional processing of emotional information, but also is associated with the rapid detection of facial information. Previous studies have shown that threatening angry faces induce a larger EPN component in the early stage of expression recognition (Recio et al., 2011, 2017). The late LPP component has been shown to be associated with arousal estimation of upcoming emotional stimuli. LPPs induced by high-arousal faces are significantly greater in amplitude than those elicited by low-arousal faces, which indicates that high-arousal faces attract more attention and receive more processing resources. Compared with static faces, dynamic faces attract more attention, and once the dynamic characteristics are noticed, it is difficult to get rid of it, so this results in greater LPP volatility (Zhu and Liu, 2014). The CNV is considered to be a marker of time accumulation, target duration, and electrophysiological correlates of the perceived target duration. Some studies have demonstrated there to be a positive correlation between the average CNV amplitude and the estimated stimulus duration (Macar and Vidal, 2004; Gan et al., 2009; Tarantino et al., 2010; Kei et al., 2011). However, the evidence for this is inconsistent, with some work reporting there to be no direct relationship between them (Kononowicz and Hedderik, 2011; Tamm et al., 2014). This question needs to be further explored. Furthermore, the CNV amplitude has been found to be significantly correlated with different attentional resources recruited by different emotions. Compared with neutral faces, the CNV amplitude is smaller in response to faces exhibiting happiness and anger, because emotional processing lessens the cognitive resources allocated to time perception (Gan et al., 2009; Zhang et al., 2014).

Based on the above evidence, we investigated the temporal mechanisms underlying the effect of dynamic features of facial expression on time perception by employing the temporal bisection paradigm. Facial stimuli (angry vs. neutral) with different dynamic characteristic (dynamic vs. static) and durations (400, 600, 800, 1000, 1200, 1400, and 1600 ms) were presented and participants' behavior performance and event-related potential (ERP) responses were recorded. We expected that the dynamic facial expression would be judged longer than static facial expression in behavior result, as previously evidenced as overestimation effect. Besides, the effect of facial dynamic features on time perception would also reflect on different EPR components evoked when processing dynamic angry faces compared with static angry or neutral faces. Based on previous literatures of the psychological meaning associated with different ERP components, we speculate that the amplitude of the timing sensitive CNV would display separated waveforms in different duration and dynamic facial expression conditions. Furthermore, compared with neutral and angry static faces, we predicted that dynamic angry faces would evoke larger amplitudes of the P2, EPN, LPP, and CNV components, indicating the presence of distinct neural mechanisms underlying the attention effects of different dynamic features of emotional expressions on time perception.

2. Materials and methods

2.1. Participants

Participants were 15 college students from a university in Beijing (*M* = 22.6 years old, *SD* = 1.61 years, 11 female). Participants were right-handed, had normal or corrected-to-normal vision, were not colorblind, and had no history of mental illness. The Research Ethics Committee of College of Preschool Education, Capital Normal University approved this study. Participants signed an informed consent form before the experiment, and were given an appropriate remuneration after the experiment.

2.2. Stimulus materials

We selected 20 photographs of neutral and static angry face from 20 models from the Nimstim database (Tottenham et al., 2009), and asked 20 college students (10 men, 10 women) to rate each for their emotion type and arousal on a Likert scale ranging from 1 to 9. Finally, the neutral and corresponding angry photos of 6 models were selected. The dynamic anger face was generated using fantamorph software, as in previous research (Fayolle and Droit-Volet, 2014). Each dynamic face was morphed from the neutral to the angry face of the same model. Each dynamic facial sequence consisted of 6 frames, with the duration of each frame depending on the total duration of the dynamic face (400, 600, 800, 1000, 1200, 1400, and 1600 ms) based on previous studies (Droit-Volet and Wearden, 2002; Gil and Droit-Volet, 2012; Fayolle and Droit-Volet, 2014). For instance, a dynamic facial sequence of 400 ms would consist six frames (each frame last for 66.6 ms), changing from a neutral face (the first frame) gradually to the last and most intense angry face frame (the sixth frame). Another 20 college students (10 men, 10 women) rated the emotion type and arousal of all three groups of stimuli (static neutral faces, static angry faces, and dynamic angry faces). The dynamic angry face stimuli were had one of three durations (400, 1000, and 1600 ms).

Recognition and arousal ratings for the three facial stimuli groups are shown in **Table 1**. There was no significant difference in recognition rate between the three groups, $F(2, 357) = 0.08$, $p > 0.05$. However, there was a significant between-group difference in arousal ratings, $F(2, 357) = 155.14$, $p < 0.001$, whereby the static and dynamic angry faces were rated as more arousing than neutral faces. No significant difference in arousal was found between static and dynamic angry faces.

We analyzed the recognition rate and arousal level of dynamic angry faces at different durations (400, 1000, and 1600 ms). There was no significant difference in recognition between the three durations [M ± SD, 400 ms: 0.87 ± 0.034; 1000 ms: 0.84 ± 0.37; 1600 ms: 0.83 ± 0.38, $F(2, 357) = 0.4$, $p > 0.05$]. The ratings for arousal were also not significantly different between the three durations [400 ms: 7.04 ± 1.25; 1000 ms: 6.97 ± 1.23; 1600 ms: 7.00 ± 1.37; $F(2, 357) = 0.10$, $p > 0.05$].

TABLE 1 Description of ratings of different facial stimuli (*M* ± *SD*).

	Neutral face (NF)	Static angry face (SA)	Dynamic angry face (DA)
Recognition rate	0.84 ± 0.37	0.83 ± 0.38	0.84 ± 0.37
Arousal	3.33 ± 2.14	6.80 ± 1.93	6.97 ± 1.23

2.3. Procedure

Participants were seated in front of a monitor showing experimental stimuli through Eprime-2.0 software (Psychology Software Tools Inc., Pittsburgh, USA). Each participant went through three experimental stages: the initial learning stage, the practice stage, and the last formal test.

In the initial learning phase, participants were randomly presented with a 12 cm × 16 cm pink oval that lasted for one of two different durations—400 ms as the standard short duration and 1600 ms as the standard long duration.

In the second practice phase, participants were presented with a 12 cm × 16 cm pink oval for 400 or 600 ms and asked to judge whether this oval was closer to the short duration or long duration. Feedback was provided as either "correct" or "wrong." Participants were only able to proceed to the next formal test after their accuracy rate reached 80% or above.

In the formal test, the oval was replaced with a facial expression of a different emotion type and facial dynamic combinations (static neutral, static anger, and dynamic anger), each last for six different durations (400, 600, 800, 1000, 1200, 1400, and 1600 ms). The procedure of a single trial is depicted in **Figure 1**. A fixation cross was first shown for 500 ms and then followed by a 610–650 ms inter-stimulus interval, then the facial expression was presented with random duration of 400, 600, 800, 1000, 1200, 1400, or 1600 ms. Participants were asked whether the duration of this expression was closer to the standard short or long duration, and responses were made by pressing "d" (short condition) or "f" (long condition). The button-press assignment was counterbalanced across different participants. No feedback was shown in the formal test. Each participant completed 630 trials in five blocks, each block consisted of 18 facial expression (six pictures for each of the three facial stimuli: static neutral, static anger, and dynamic anger) with seven different durations. The test lasted about 30 min.

2.4. EEG recording and analysis

EEG recordings were obtained with NeuroScan system (NeuroScan, Inc., Herndon, VA, USA) from 32 electrodes positioned according to the 10/20 system and referenced to the bilateral mastoid with a bandpass filter of 0.05–30 Hz. An electrooculogram was recorded from electrodes placed below and lateral to the eyes. Curry 7 software was used for offline data processing (Compumedics, Abbotsford, Australia). The time window was chosen from –200 ms before stimulus onset (pre-stimulus 200 ms was used as the baseline) and 1800 ms after the stimulus. Blinks and other eye movement artifacts were removed using independent-component analyses. Six ERP components were separately analyzed based on previous research and our hypotheses. For the N1 and P2 components, the mean amplitudes were separately averaged at three centro-frontal electrodes (Fz, FCz, and Cz) in the 70–140 ms and 150–190 ms time windows, respectively; the same was applied for the EPN at two posterior electrodes (O1 and O2) in the 250–350 ms time window, and for the LPP at two centro-parietal electrodes (CPz and Pz) in the 320–800 ms interval, as well as for the CNV at the centro-frontal electrodes (Fz and FCz) from 250 ms to the end of the stimulus presentation.

2.5. Statistical methods

The psychophysical function with the proportion of long responses [*p*(long)] was plotted against the seven different duration in the three different facial dynamic groups. We also computed two temporal parameters to better account for the variations of time perception according to previous studies (Fayolle and Droit-Volet, 2014); namely, the Bisection Point (BP) and the Weber Ratio (WR).

The BP is the subjective point of equality, which is the duration of time the subjects responded with long as often as they did short, $p(\text{long}) = 0.5$. The smaller the BP value, the more overvalued the time.

The WR indicates the time sensitivity, and was computed as the result of differential threshold $\{D[p(\text{long}) = 0.75] - D[p(\text{long}) = 0.25]\}/2$ divided by BP [time duration corresponding to 75% *p*(long)-time duration of 25% *p*(long)]. The lower the WR, the steeper the psychophysical function and the higher the temporal sensitivity.

The *p*(long) was computed as the subjects' response as "long" divided by the total number of trials. Behaviors were analyzed using the *p*(long) as a dependent variable, and the facial dynamic condition (static neutral, static anger, and dynamic anger) and duration as independent variables.

For the ERP results, a repeated-measures ANOVA was applied to assess differences in the peak and latency of the N1, P2, and N2, and the average amplitude (volatility) of the EPN, LPP, and CNV as the dependent variables, and the facial dynamic condition and electrode position as independent variables.

3. Results

3.1. Behavioral results

3.1.1. Analysis of the proportion of "long" responses

Figure 2 presents the psychophysical functions of the proportion of long responses [*p*(long)] plotted against the seven duration conditions in the three facial dynamic groups. This revealed an important effect of dynamic features on time perception. As shown in this figure, the psychophysical functions shifted more toward the left for dynamic angry faces, compared with the static anger and static neutral faces. An ANOVA was run on the *p*(long) with the duration and dynamic features as within-subjects factors. The results showed a significant main effect of duration, $F(6, 252) = 380.98$, $p < 0.001$, $\eta^2_p = 0.90$. *Post hoc* analysis suggested that the differences of *p*(long) between different durations were all significant [$M_{400\ ms} = 0.03 \pm 0.05$, $M_{600\ ms} = 0.11 \pm 0.15$, $M_{800\ ms} = 0.35 \pm 0.22$, $M_{1000\ ms} = 0.61 \pm 0.20$, $M_{1200\ ms} = 0.81 \pm 0.14$, $M1_{400\ ms} = 0.90 \pm 0.10$, $M_{1600\ ms} = 0.94 \pm 010$]. The main effect of dynamic features was also significant, $F(2, 42) = 11.48$, $p < 0.001$, $\eta^2_p = 0.35$, with a *p*(long) that was much higher in the dynamic anger condition than in the static anger and neutral conditions. The *p*(long) in the static anger condition was also significantly higher than that in the static neutral condition ($M_{DA} = 0.63 \pm 0.13$, $M_{SA} = 0.53 \pm 0.18$, $M_{NF} = 0.45 \pm 0.11$). The interaction between duration and facial dynamic features was also significant, $F(12, 252) = 4.83$, $p < 0.001$, $\eta^2_p = 0.19$. Simple effect analysis revealed that the *p*(long) of the dynamic angry face was significantly longer than that of the static anger and neutral faces in the 800, 100, and 1200 ms conditions (800 ms: $M_{DA} = 0.53 \pm 0.27$, $M_{SA} = 0.33 \pm 0.27$, $M_{NF} = 0.19 \pm 0.11$; 1000 ms: $M_{DA} = 0.82 \pm 0.14$, $M_{SA} = 0.59 \pm 0.29$, $M_{NF} = 0.41 \pm 0.18$; 1200 ms: $M_{DA} = 0.91 \pm 0.08$, $M_{SA} = 0.81 \pm 0.18$, $M_{NF} = 0.72 \pm 0.17$).

3.1.2. Bisection point and weber ratio in the different facial dynamic conditions

An ANOVA revealed a significant main effect of facial dynamic features on the BP, $F(2, 28) = 9.38$, $p < 0.01$, $\eta^2_p = 0.40$. The BP was lower for the dynamic angry face condition than for the static angry and neutral face conditions, and the BP was significantly lower in the static angry face condition than in the neutral face condition ($M_{DA} = 847.11 \pm 135.01$, $M_{SA} = 947.30 \pm 173.67$, $M_{NF} = 1035.06 \pm 176.24$). The comparison between static angry and neutral faces confirmed a lengthening effect of high-arousing facial expressions (anger in the present experiment). The comparison between dynamic anger and static anger further suggested a lengthening effect when facial expressions were presented dynamically.

In contrast, the ANOVA on the WR did not show any significant results [$F(2, 34) = 0.33$, $p > 0.05$, $\eta^2_p = 0.02$; **Table 2**], thus suggesting that time sensitivity was not different between the three facial conditions (dynamic angry, static angry, and static neutral faces).

3.1.3. Reaction time of different emotion types and facial dynamics

An ANOVA was conducted on the reaction time (RT), with duration and facial expression features as within-subject factors. There was a significant main effect of duration on RT, $F(6, 252) = 25.70$, $p < 0.001$, $\eta^2_p = 0.38$, whereby the RT was significantly longer in the 800 and 1000 ms duration conditions than in the rest conditions (400, 600, 1200, 1400, and 1600 ms). The RT in the 1600 ms condition was significantly longer than in the rest (400, 600, 800, 1000, 1200, and 1400 ms) ($M_{400\ ms} = 601.27 \pm 155.15$, $M_{600\ ms} = 634.90 \pm 147.12$, $M_{800\ ms} = 748.70 \pm 165.51$, $M_{1000\ ms} = 701.34 \pm 185.49$, $M_{1200\ ms} = 615.48 \pm 167.43$, $M1_{400\ ms} = 538.51 \pm 173.62$, $M_{1600\ ms} = 474.10 \pm 121.51$). The main effect of facial dynamic feature on RT was also significant, $F(1, 42) = 4.11$, $p < 0.05$, $\eta^2_p = 0.16$, whereby the RTs in response to dynamic and static angry faces were significantly shorter than those in the neutral face condition ($M_{DA} = 570.48 \pm 148.49$, $M_{SA} = 590.75 \pm 131.27$, $M_{NF} = 687.76 \pm 198.47$; **Figure 3**).

3.2. ERP results

3.2.1. P2

A 3 (dynamic feature: dynamic anger, static anger, neutral) × 2 (hemisphere: left, right) repeated-measures ANOVA was conducted on the average amplitudes of the P2 component. The main effect of facial dynamic feature was significant, $F(2, 84) = 13.89$, $p < 0.001$, $\eta^2_p = 0.25$. P2 amplitude evoked by static anger faces was significantly higher than dynamic anger and neutral ($M_{DA} = 3.18 \pm 2.53\ \mu V$; $M_{SA} = 4.75 \pm 2.46\ \mu V$; $M_{NF} = 3.17 \pm 2.82\ \mu V$). The interaction between these two factors was not significant ($p > 0.05$).

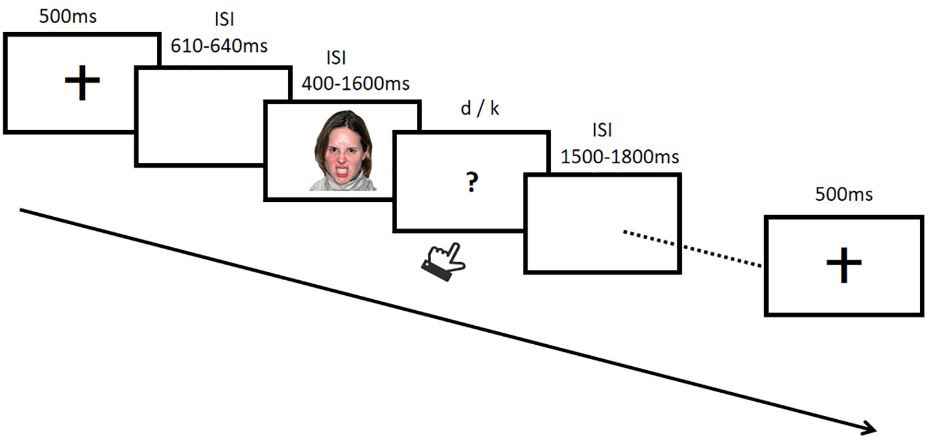

FIGURE 1
Example of the procedure for a formal test trial.

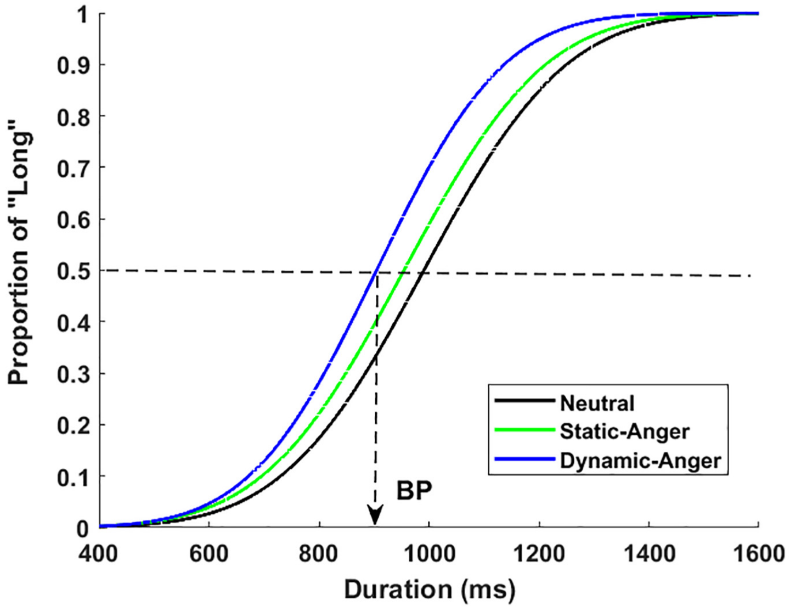

FIGURE 2
Proportion of long responses plotted against the different durations for dynamic angry, static angry, and neutral faces.

3.2.2. N2

A 3 (dynamic feature: dynamic anger, static anger, neutral) × 2 (hemisphere: left, right) repeated-measures ANOVA analysis was also conducted on the average N2 amplitude. There was a significant main effect of a facial dynamic feature on N2 amplitude, $F(2, 84) = 9.71$, $p < 0.001$, $\eta^2_p = 0.19$, whereby the N2 amplitude evoked by dynamic anger faces was significantly larger than that elicited in the static anger and neutral conditions ($M_{DA} = -2.17 \pm 3.08$ μV; $M_{SA} = -1.25 \pm 3.55$ μV; $M_{NF} = -0.84 \pm 2.85$ μV; Figure 4). There was no main effect of the hemisphere and no interaction between these two factors ($p > 0.05$).

3.2.3. EPN

The same ANOVA analysis was conducted on the average EPN amplitude in the 250–300 ms time window. There was a significant main effect of facial dynamic feature on EPN amplitude, $F(2, 56) = 15.56$, $p < 0.001$, $\eta^2_p = 0.36$, whereby the EPN amplitude evoked by dynamic anger was significantly smaller than that evoked by neutral faces and static anger ($M_{DA} = 5.60 \pm 3.30$ μV, $M_{NF} = 6.97 \pm 4.08$ μV, $M_{SA} = 7.40 \pm 3.66$ μV). The other main effect and interaction effect was not significant ($p > 0.05$). In the 300–350 ms time window, the amplitude induced by dynamic anger,

TABLE 2 Bisection point and weber ratio for the three different facial expression conditions.

	Bisection point			Weber ration		
	Neutral	Static anger	Dynamic anger	Neutral	Static anger	Dynamic anger
M	1035.06	947.3	847.11	0.10	0.11	0.10
SD	176.24	173.67	135.01	0.05	0.04	0.04

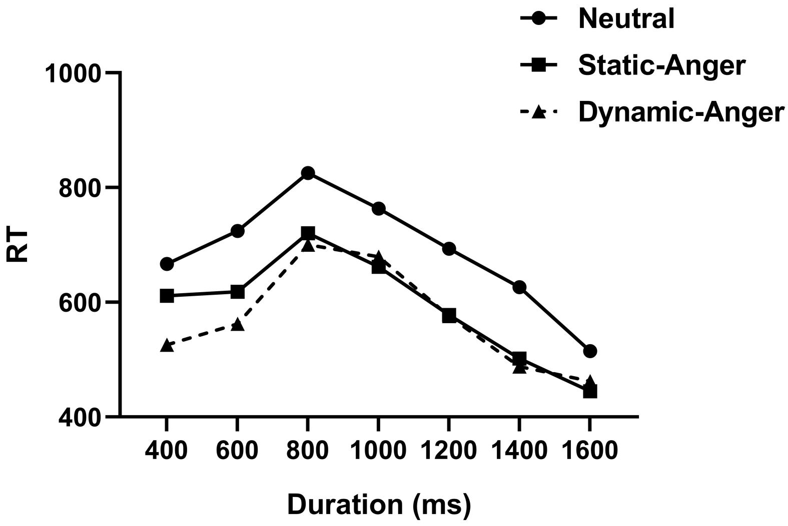

FIGURE 3
Reaction times in the different facial expression conditions.

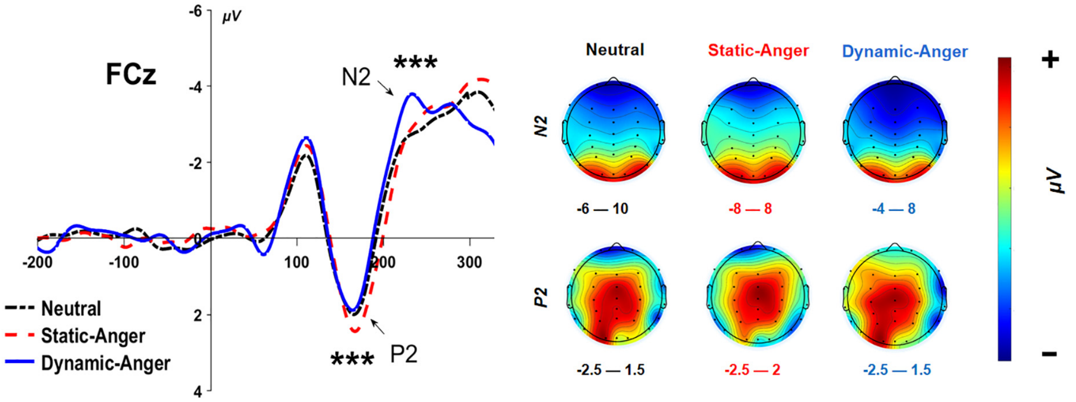

FIGURE 4
The grand-mean ERP waveforms of the N2 and P2 components at FCz. ***$P < 0.001$.

neutral faces, and static anger gradually increased significantly, with dynamic angry faces evoking significantly larger amplitude than neutral faces, neutral faces also induced significantly larger amplitude than static angry faces ($M_{DA} = 3.96 \pm 2.42$ μV; $M_{SA} = 4.84 \pm 3.30$ μV; $M_{NF} = 6.07 \pm 3.70$ μV; **Figure 5**).

3.2.4. LPP

An ANOVA analysis on the average LPP amplitude in two different time windows (320–450 ms and 450–800 ms) revealed there to be a significant main effect of facial dynamic feature, 320–450 ms: $F(2, 56) = 24.61$, $p < 0.001$, $\eta^2_p = 0.47$; 450–800 ms: $F(2, 56) = 47.26$, $p < 0.001$, $\eta^2_p = 0.63$. In the 320–450 ms time window, the amplitude evoked in the dynamic anger condition was significantly higher than that evoked in the static anger and neutral face conditions; the amplitude in the static condition was also significantly larger than that in the neutral face condition ($M_{DA} = 2.82 \pm 3.37$ μV; $M_{SA} = 1.14 \pm 3.68$ μV; $M_{NF} = 0.39 \pm 2.74$ μV). In the 450–800 ms time window, the amplitude induced by dynamic anger was also significantly larger than that elicited in the static anger and neutral face conditions, but there was no significant difference between the static anger and neutral face conditions ($M_{DA} = 4.49 \pm 3.27$ μV; $M_{SA} = 1.54 \pm 3.32$ μV; $M_{NF} = 1.27 \pm 2.50$ μV). The other main effect and interaction effect were not significant ($p > 0.05$; **Figure 6**).

3.2.5. CNV

According to the behavioral results, the p(long) was significantly different between the duration conditions of 800, 1000, and 1200 ms. We conducted three ANOVA analyses separately to assess the CNV amplitude under these three duration conditions, using the average amplitude of the CNV from 250 ms to the end of the stimuli presentation. In the 800 ms duration condition, there was a significant main effect of a facial dynamic feature on CNV amplitude, $F(2, 56) = 18.88$, $p < 0.001$, $\eta^2_p = 0.24$. The CNV amplitude evoked by static anger was significantly larger than that evoked in the dynamic anger and neutral conditions ($M_{DA} = -0.53 \pm 5.08$ μV; $M_{SA} = -4.88 \pm 5.06$ μV; $M_{NF} = -1.12 \pm 5.46$ μV). In the 1000 and 1200 ms duration conditions, there was a significant main effect of a facial dynamic feature on CNV amplitude [1000 ms: $F(2, 56) = 6.84$, $p < 0.01$, $\eta^2_p = 0.2$; 1200 ms: $F(2, 56) = 19.09$, $p < 0.001$, $\eta^2_p = 0.41$]. The CNV amplitude in the static anger and neutral face conditions

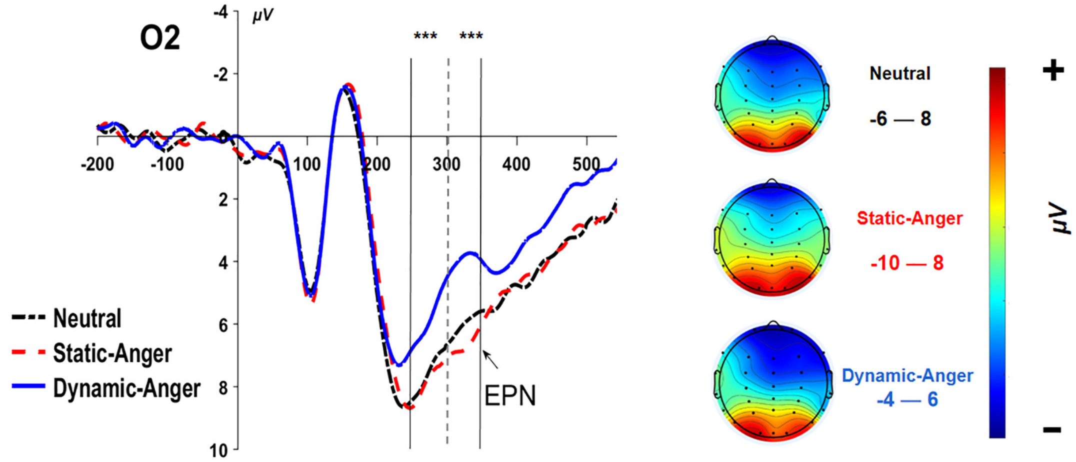

FIGURE 5
The grand-mean ERP waveforms of the EPN component at O2. ***$P < 0.001$.

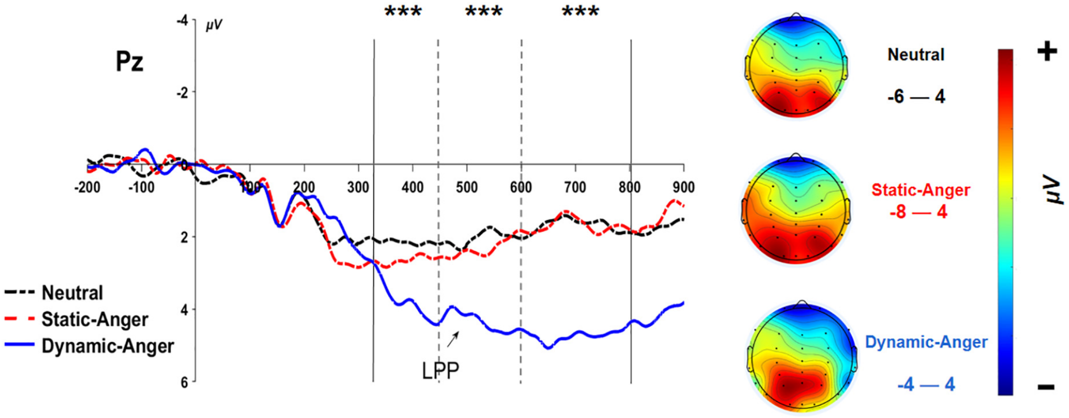

FIGURE 6
The grand-mean ERP waveforms of the LPP component at Pz. ***$P < 0.001$.

was significantly larger than that in the dynamic anger condition (1000 ms: M_{DA} = −0.67 ± 4.36 µV, M_{SA} = −2.30 ± 4.21 µV, M_{NF} = −1.97 ± 4.21 µV; 1200 ms: M_{DA} = 1.33 ± 5.03 µV, M_{SA} = −2.65 ± 3.51 µV, M_{NF} = −2.83 ± 3.05 µV). No other significant effects were found ($ps > 0.05$; **Figure 7**).

4. Discussion

The central aim of the present study was to investigate the effect of facial dynamic features on time perception using ERP methods. The behavioral results revealed a significant overestimation effect when judging the duration of dynamic angry faces compared with static angry and static neutral faces. Several ERP components were assessed to objectively characterize the states generated by the dynamic features of the facial expression. All five components predicted to be involved (the N2, P2, EPN, LPP, and CNV) showed a significant dynamic effect, but with different amplitude patterns. Taken together, these results confirm our hypothesis that the dynamic feature of facial expression can influence individuals' time perception both at behavioral and electrophysiological levels.

In terms of behavioral performance, we observed a steady and significant decrease in the *p*(long) judgment from dynamic anger to static anger and neutral faces, which supports previous findings (Fayolle and Droit-Volet, 2014; Li and Yuen, 2015; Xu et al., 2021). According to the scalar timing theory, attention to attractive or arousing stimuli results in the activation of a switch that alters the number of pulses emitted from a pacemaker, which are subsequently collected in an accumulator, and this causes the perceived duration to be prolonged (Gibbon, 1977; Lake, 2016). Second, from the perspective of facial movement, dynamic faces attract more attention due to motion characteristics, which leads to a longer perceived duration than of static faces (Fayolle and Droit-Volet, 2014; Li and Yuen, 2015). Finally, the RT for both dynamic angry and static angry faces was significantly shorter than the RT for neutral faces. This further confirms the arousal effect caused by high-arousing expression (anger) rather than low-arousing expression (neutral) (Gil and Droit-Volet, 2011; Tipples et al., 2015; Uusberg et al., 2018; Benau and Atchley, 2020).

The ERP results suggested that there is an early processing advantage for static angry faces *via* emotional arousal and attentional bias, while dynamic angry faces are mainly processed in a later

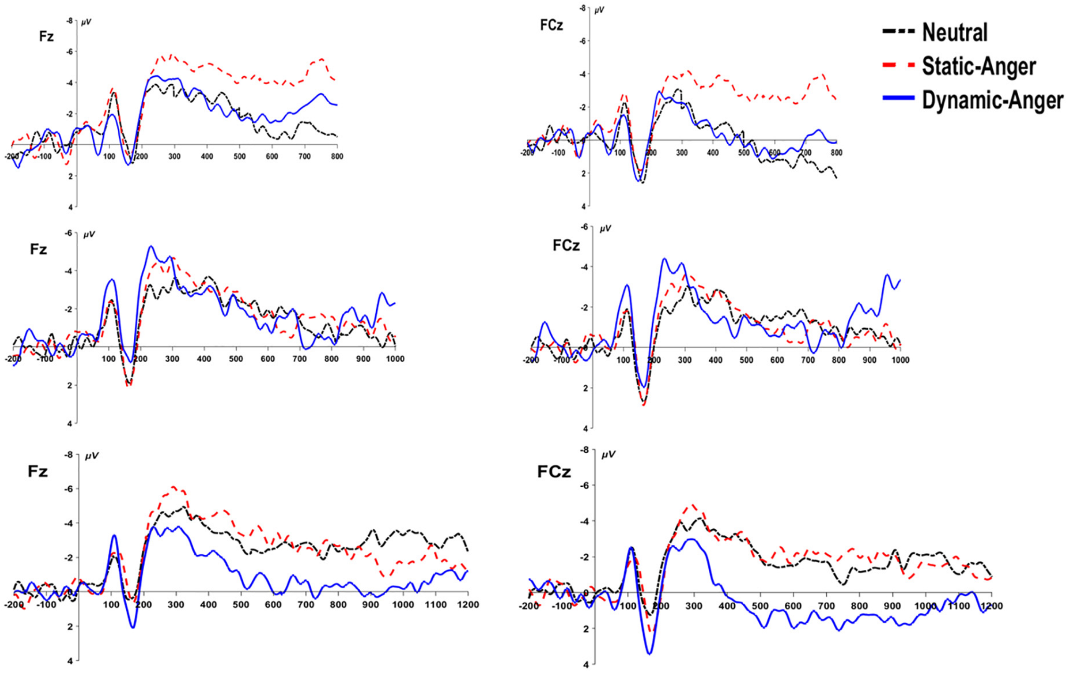

FIGURE 7
The grand-mean ERP waveforms of the CNV component at Fz and FCz under the three different duration conditions (800, 1000, and 1200 ms).

temporal stage *via* response inhibition and attracting attention. Specially, we found that the P2 amplitude was larger for static angry faces than for dynamic angry and neutral faces, while no significant difference was found between dynamic angry and neutral faces. Previous studies have reported that the P2 might reflect conscious access to sensory information and that it can be modulated by alternative attention. High-arousing and negative angry facial expressions have been proposed to attract more attentional resources, which results in a larger P2 amplitude (Hillyard et al., 1973; Cui and Luo, 2009). Given that the dynamic anger material was morphed from a neutral expression to an increasingly intense angry face with six facial sequences (frames), the earlier time window of 150–190 ms (P2) for dynamic anger was more inclined to a neutral rather than an angry expression. Take the dynamic angry face with duration of 400 ms as example, it consists 6 frames changing gradually from neutral face (the first frame) to the most intense angry face (the sixty frame). While the first half of this dynamic angry face (0 ms–200 ms) was more inclined to be the neutral face. This may account for the reason why no difference in amplitude was found between dynamic anger and neutral face condition.

Similarly, the N2 amplitude was significantly greater for dynamic anger than static and neutral face conditions. Previous studies have found that the frontal located N2 component was more related with odd stimuli and response inhibition (Folstein and Petten, 2008). According to one study employing go/no-go paradigm, the no-go condition evoked a larger N2 amplitude (Folstein and Petten, 2008; Wang et al., 2020). Compared with static faces, dynamic faces have been found to have a greater effect on individuals' attentional processes. Subjects need to inhibit dynamic information to accomplish a task (Li and Yuen, 2015). In this regard, this larger N2 amplitude in the dynamic anger condition may reflect the inhibition processes (Gan et al., 2009).

The EPN amplitude became significantly larger from the dynamic angry face to neutral and static anger face conditions. As an early posterior negativity, the EPN reflects an increase in the amount of sensory processing resources, which is modulated by brain systems in which visual representations are evaluated in terms of their meaning, such as the amygdala and prefrontal cortex (Pourtois et al., 2012). The EPN amplitude has been found to be significantly different in response to emotional and neutral stimuli (Recio et al., 2011). Furthermore, the emotional effect on EPN is reportedly modulated by the amount of cognitive resources (Perry et al., 2019; Wang et al., 2019). In one previous study, the EPN was not affected by negative facial stimuli and showed a pattern of automatic processing in a rich cognitive resource condition; the emotional effect was only present in the low cognitive resource demanding condition, whereby presentation of a high-arousing picture evoked a larger EPN amplitude (Zhu and Liu, 2014). This result further demonstrated that the emotional effect on EPN was not influenced by attentional control, but an automatic process (Schindler and Kissler, 2016). Furthermore, as explained, in the early time window of 250–300 ms, the dynamic stimuli may be still more inclined to be perceived as neutral face among the six facial sequences (frames) consisting the dynamic stimuli, which may further explain why the dynamic angry face had no effect on time perception.

We also found a significantly larger LPP amplitude in response to dynamic and static anger faces compared with neutral faces (320–450 ms). This result is in line with evidence from previous studies showing that the emotional effect in response to high-arousing stimuli (angry faces) induces a larger LPP amplitude than does low-arousing stimuli (neutral faces) (Schupp et al., 2004; Weinberg and Hajcak, 2010). The LPP component has been identified as a key indicator of the arousal effect on attentional processes, and attention is captured more by negative arousing stimuli than by arousing stimuli of another valence

(Ye et al., 2018; Long et al., 2020; Xie et al., 2022). However, in the later 450–800 ms time window, there was no significant difference in LPP amplitude, as a measure of time perception, between the static angry and neutral face conditions, while time perception on dynamic angry faces still evoked a significantly larger amplitude than static angry and neutral faces. This result can be interpreted according to a negative processing advantage that occurs at the early processing stage (320–450 ms), whereby more attentional resources are attracted to angry faces than to neutral faces, which results in the emotion effect (anger vs. neutral faces). In the later processing stage (450–800 ms), the negative processing advantage could have been replaced by the motion characteristics of the dynamic faces. The LPP is a later component that is indicative of a higher analysis level and evaluation of emotion stimuli, which require more cognitive resources. This could be why there was no significant difference in the LPP amplitude caused by time perception of static angry and neutral faces. Another possible explanation is related to the cognitive resources required to perform the present temporal bisection task. Compared with other temporal judgment paradigms, such as the reproduction paradigm, the current study employed the temporal bisection paradigm, which has been shown to be a low cognitively demanding task (Qu et al., 2021). Enough cognitive resources seemed to be allocated to both the temporal judgment task and implicit emotion perception task. In the dynamic anger condition, individuals' attention was more easily attracted by the motion characteristics of the dynamic angry faces, which may result in more attentional resources available for the implicit emotion perception and evaluation task. More empirical evidence is still needed to verify this possibility.

The CNV amplitude has been interpreted as a marker of temporal accumulation, with longer subjective durations associated with larger amplitudes, and to be related to processes such as arousal level, expectation, and attention (Macar et al., 1999; Macar and Vidal, 2004). In the present study, after analyzing the CNV amplitude under three duration conditions (800, 1000, and 1200 ms) separately, the data consistently suggested that the CNV amplitude induced by static angry faces was larger than that elicited in response to dynamic anger, and did not accumulate with the increase in duration. Given that the arousal level between dynamic and static angry faces was not significantly different based on pre- and post-experiment rating results, the difference in CNV amplitude may reflect different mechanisms underlying the processing of dynamic and static facial stimuli during the temporal bisection task. However, some researchers have also suggested that the complex pattern of CNV was not solely accounted for by emotion arousal and attentional processes, and other studies found no direct relationship between the CNV amplitude and time processing (Kononowicz and Hedderik, 2011; Tamm et al., 2014). Future studies are needed to further investigate the underlying mechanisms and possibilities.

This study has some limitations that should be noted. First, we employed the temporal bisection paradigm to investigate dynamic and emotional effects on time perception. However, previous studies have found that the temporal task used may influence the effect of emotion on time perception (Gil and Droit-Volet, 2011), and different tasks may exert different cognitive demands, which may lead to different results. Further comparisons should be made using different temporal judgment paradigms simultaneously. Second, the psychological meaning of the ERP components found in the present study still requires further evidence. For instance, it is not entirely clear whether the larger N2 amplitude by time perception in response to dynamic angry faces is an indicator of response inhibition or a response to odd stimuli. Finally, the sample size in the present study was relatively small and future research should recruit more subject to further evidence the dynamic effect found in the present study.

5. Conclusion

To summarize, using a classical temporal bisection task with different comparison durations and dynamic emotional expressions (dynamic angry, static angry, and static neutral faces), we revealed a significantly different effect of dynamic versus static expressions on time perception. The analysis on the proportion of long responses, BP, and RT results suggested that the duration of dynamic facial expression was overestimated compared with static and neutral expressions. The ERP results indicated that dynamic features evoked different ERP responses. The static angry faces mainly induced larger P2 and EPN components, while the dynamic angry faces evoked larger-amplitude N2 and LPP components. These results indicate that different neural mechanisms may underlying the overestimation effect of time perception between facial expressions with different dynamic features.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Research Ethics Committee of College of Preschool Education, Capital Normal University. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

FQ and XS contributed to designing the experiments and analyzing the data. XS, JD, TG, and HW contributed to collecting the data. FQ and CG contributed to writing the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Alves, N. T. (2013). Recognition of static and dynamic facial expressions: a study review. *Estudos Psicologia* 18, 125–130. doi: 10.1590/S1413-294X2013000100020

Benau, E. M., and Atchley, R. A. (2020). Time flies faster when you're feeling blue: sad mood induction accelerates the perception of time in a temporal judgment task. *Cogn. Process.* 21, 479–491. doi: 10.1007/s10339-020-00966-8

Biele, C., and Grakowska, A. (2006). Sex differences in perception of emotion intensity in dynamic and static facial expressions. *Exp. Brain Res.* 26, 1–6.

Buhusi, C. V., and Meck, W. H. (2005). What makes us tick? functional and neural mechanisms of interval timing. *Nat. Rev. Neurosci.* 6, 755–765. doi: 10.1038/nrn1764

Cui, F., and Luo, Y. J. (2009). Facial expression processing of people with different empathic abilities:an erp study. *Chin. J. Clin. Psychol.* 17, 390–393.

Dan, F., Hajcak, G., and Dien, J. (2009). Differentiating neural responses to emotional pictures: evidence from temporal-spatial PCA. *Psychophysiology* 46, 521–530.

Droit-Volet, S., and Gil, S. (2009). The time–emotion paradox. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 1943–1953. doi: 10.1098/rstb.2009.0013

Droit-Volet, S., and Wearden, J. (2002). Speeding up an internal clock in children? Effects of visual flicker on subjective duration. *Q. J. Exp. Psychol.* 55, 193–211.

Droit-Volet, S., Fayolle, S. L., and Gil, S. (2016). Emotion and time perception in children and adults: the effect of task difficulty. *Timing Time Percept.* 4, 7–29. doi: 10.1163/22134468-03002055

Fayolle, S. L., and Droit-Volet, S. (2014). Time perception and dynamics of facial expressions of emotions. *PLoS One* 9:e97944. doi: 10.1371/journal.pone.0097944

Folstein, J. R., and Petten, C. V. (2008). Influence of cognitive control and mismatch on the n2 component of the erp: a review. *Psychophysiology* 45, 152–170.

Foti, D., Hajcak, G., and Dien, J. (2009). Differentiating neural responses to emotional pictures: evidence from temporal-spatial PCA. *Psychophysiology* 46, 521–530.

Gan, T., Wang, N., Zhang, Z., Li, H., and Luo, Y. J. (2009). Emotional influences on time perception: evidence from event-related potentials. *Neuroreport* 20, 839–843. doi: 10.1097/WNR.0b013e32832be7dc

Gibbon, J. (1977). Scalar expectancy theory and weber's law in animal timing. *Psychol. Rev.* 84, 278–325. doi: 10.1037/0033-295X.84.3.279

Gibbon, J., Morrell, M., and Silver, R. (1984). Two kinds of timing in circadian incubation rhythm of ring doves. *Am. J. Physiol.* 247, R1083–R1087. doi: 10.1152/ajpregu.1984.247.6.R1083

Gil, S., and Droit-Volet, S. (2011). "time flies in the presence of angry faces"… depending on the temporal task used! *Acta Psychol.* 136, 354–362. doi: 10.1016/j.actpsy.2010.12.010

Gil, S., and Droit-Volet, S. (2012). Emotional time distortions: the fundamental role of arousal. *Cogn. Emot.* 26, 847–862. doi: 10.1080/02699931.2011.625401

Hillyard, S. A., Hink, R. F., Schwent, V. L., and Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science* 182, 177–180. doi: 10.1126/science.182.4108.177

Kei, N. K., Simon, T., and Penney, T. B. (2011). Temporal accumulation and decision processes in the duration bisection task revealed by contingent negative variation. *Front. Integr. Neurosci.* 5:77. doi: 10.3389/fnint.2011.00077

Kononowicz, T. W., and Hedderik, V. R. (2011). Slow potentials in time estimation: the role of temporal accumulation and habituation. *Front. Integr. Neurosci.* 5:48. doi: 10.3389/fnint.2011.00048

Lake, J. I. (2016). Recent advances in understanding emotion-driven temporal distortions. *Curr. Opin. Behav. Sci.* 8, 214–219. doi: 10.1016/j.cobeha.2016.02.009

Li, W. O., and Yuen, K. (2015). The perception of time while perceiving dynamic emotional faces. *Front. Psychol.* 6:1248. doi: 10.3389/fpsyg.2015.01248

Long, F., Ye, C., Li, Z., Tian, Y., and Liu, Q. (2020). Negative emotional state modulates visual working memory in the late consolidation phase. *Cogn. Emot.* 34, 1646–1663. doi: 10.1080/02699931.2020.1795626

Macar, F., and Vidal, F. (2004). Eventrelated potentials as indices of time processing: a review. *J. Psychophysiol.* 18, 89–104. doi: 10.1027/0269-8803.18.23.89

Macar, F., Vidal, F., and Casini, L. (1999). The supplementary motor area in motor and sensory timing: evidence from slow brain potential changes. *Exp. Brain Res.* 125, 271–280. doi: 10.1007/s002210050683

Perry, C., Willison, A. T., Walker, M. K., Nankivell, M. C., Lawrence, L. M., and Alexander, T. (2019). Working memory load affects early affective responses to concrete and abstract words differently : evidence from ERPs. *Cogn. Affect. Behav. Neurosci.* 19, 377–391. doi: 10.3758/s13415-018-00686-9

Pourtois, G., Schettino, A., and Vuilleumier, P. (2012). Brain mechanisms for emotional influences on perception and attention: what is magic and what is not. *Biol. Psychol.* 92, 492–512. doi: 10.1016/j.biopsycho.2012.02.007

Qu, F., Shi, X., Zhang, A., and Gu, C. (2021). Development of young children's time perception: effect of age and emotional localization. *Front. Psychol.* 12:688165. doi: 10.3389/fpsyg.2021.688165

Recio, G., Sommer, W., and Schacht, A. (2011). Electrophysiological correlates of perceiving and evaluating static and dynamic facial emotional expressions. *Brain Res.* 1376, 66–75. doi: 10.1016/j.brainres.2010.12.041

Recio, G., Wilhelm, O., Sommer, W., and Hildebrandt, A. (2017). Are event-related potentials to dynamic facial expressions of emotion related to individual differences in the accuracy of processing facial expressions and identity? *Cogn. Affect. Behav. Neurosci.* 17, 364–380. doi: 10.3758/s13415-016-0484-6

Sato, W., and Yoshikawa, S. (2007). Spontaneous facial mimicry in response to dynamic facial expressions. *Cognition* 104, 1–18. doi: 10.1016/j.cognition.2006.05.001

Schindler, S., and Kissler, J. (2016). Selective visual attention to emotional words: early parallel frontal and visual activations followed by interactive effects in visual cortex. *Hum. Brain Mapp.* 37, 3575–3587. doi: 10.1002/hbm.23261

Schupp, H. T., Junghöfer, M., Weike, A. I., and Hamm, A. O. (2004). The selective processing of briefly presented affective pictures: an ERP analysis. *Psychophysiology* 41, 441–449. doi: 10.1111/j.1469-8986.2004.00174.x

Tamm, M., Uusberg, A., Allik, J., and Kreegipuu, K. (2014). Emotional modulation of attention affects time perception: evidence from event-related potentials. *Acta Psychol.* 149, 148–156. doi: 10.1016/j.actpsy.2014.02.008

Tarantino, V., Ehlis, A. C., Baehne, C., Boreatti-Huemmer, A., Jacob, C., Bisiacchi, P., et al. (2010). The time course of temporal discrimination: an erp study. *Clin. Neurophysiol.* 121, 43–52. doi: 10.1016/j.clinph.2009.09.014

Tian, Y., Liu, P., and Huang, X. (2018). The role of emotion regulation in reducing emotional distortions of duration perception. *Front. Psychol.* 9:347. doi: 10.3389/fpsyg.2018.00347

Tipples, J., Brattan, V., and Johnston, P. (2015). Facial emotion modulates the neural mechanisms responsible for short interval time perception. *Brain Topogr.* 28, 104–112.

Tottenham, N., Tanaka, J. W., Leon, A. C., McCarry, T., Nurse, M., Hare, T. A., et al. (2009). The NimStim set of facial expressions: judgments from untrained research participants. *Psychiatry Res.* 168, 242–249. doi: 10.1016/j.psychres.2008.05.006

Uusberg, A., Naar, R., Tamm, M., Kreegipuu, K., and Gross, J. J. (2018). Bending time: the role of affective appraisal in time perception. *Emotion* 18, 1174–1188. doi: 10.1037/emo0000397

Wang, J. M., Liu, Y., Zhou, Y. Z., Zhang, L., Yin, M., Yang, R., et al. (2020). Inhibitory control in spicy food cravers: a behavioral and ERP study. *J Psychol Sci.* 2020, 150–157.

Wang, X., Lu, J., and Chen, W. (2019). The processing of emotional words and its emotional effect characteristics: evidence from ERP studies. *Adv. Psychol. Sci.* 27, 1842–1852. doi: 10.3724/SP.J.1042.2019.01842

Wehrle, T., Kaiser, S., Schmidt, S., and Scherer, K. R. (2000). Studying the dynamics of emotional expression using synthesized facial muscle movements. *J. Personal. Soc. Psychol.* 78:105. doi: 10.1037/0022-3514.78.1.105

Weinberg, A., and Hajcak, G. (2010). Beyond good and evil: the time-course of neural activity elicited by specific picture content. *Emotion* 10, 767–782. doi: 10.1037/a0020242

Xie, W., Ye, C., and Zhang, W. (2022). Negative emotion reduces visual working memory recall variability: a meta-analytical review. *Emotion* 2021, 8851066.

Xu, Q., Ye, C., Gu, S., Hu, Z., Lei, Y., Li, X., et al. (2021). Negative and positive bias for emotional faces: evidence from the attention and working memory paradigms. *Neural Plast.* 2021:8851066. doi: 10.1155/2021/8851066

Ye, C., Xu, Q., Liu, Q., Cong, F., Saariluoma, P., Ristaniemi, T., et al. (2018). The impact of visual working memory capacity on the filtering efficiency of emotional face distractors. *Biol. Psychol.* 138, 63–72. doi: 10.1016/j.biopsycho.2018.08.009

Zhang, D., Liu, Y., Wang, X., Chen, Y., and Luo, Y. (2014). The duration of disgusted and fearful faces is judged longer and shorter than that of neutral faces: the attention-related time distortions as revealed by behavioral and electrophysiological measurements. *Front. Behav. Neurosci.* 8:293. doi: 10.3389/fnbeh.2014.00293

Zhu, Y. Y., and Liu, Z. Y. (2014). An ERP study of dynamic facial emotional expressions under different attentional conditions. *Chin. J. Appl. Psychol.* 20, 375–384.

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Effects of physical activity on visuospatial working memory in healthy individuals: A systematic review and meta-analysis

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Introduction: Physical activity interventions improve cognitive performance, especially visuospatial working memory (VSWM). However, evidence on the effects of these interventions in children, adolescents, and older adults remains scant. This meta-analysis aimed to identify the effects of physical activity on VSWM improvement in healthy individuals and the best exercise intervention program to improve VSWM capacity.

Methods: We searched for randomized controlled trials (RCTs) of exercise interventions targeting VSWM in healthy individuals from Web of Science, MEDLINE, BIOSIS Previews, PubMed, China National Knowledge Infrastructure, and Wanfang Data (Chinese) databases, from inception to August 20, 2022.

Results: Among 21 articles (1,595 healthy participants), the heterogeneity test statistic was I2 = 32.3%, p = 0.053. The mean quality scores of the included articles were 6.9 points (reaction time [RT] studies) and 7.5 points (Score studies). Moreover, 28 RCTs were included (10 RT studies and 18 Score studies), and the subgroup analysis found significant effects for elderly participants, children, interventions involving a higher level of cognitive engagement, low and moderate exercise intensity, chronic exercise, exercise duration ≥60 min, and exercise period ≥90 days. Physical activity had a small but significant positive impact on VSWM in healthy individuals. Current evidence confirms the effects of physical activity on VSWM capacity only in children and seniors but not in young adults. Other age groups, including adolescents and middle-aged adults, have not been studied. Prescription of interventions involving high-level cognitive engagement, low and moderate exercise intensity, chronic exercise, exercise for >30 min per session, and exercise for more than 3 months is recommended for children and seniors.

Discussion: Future RCTs would be to fill the gap in studies on adolescents and middle-aged adults, and report detailed exercise intervention programs about different age groups.

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KEYWORDS

physical activity, visuospatial working memory, healthy individuals, children, seniors

1. Introduction

The concept of working memory (WM) evolved in 1974 from the concept of short-term memory; the former emphasizes the ability to manipulate short-term information, whereas the latter emphasizes storage of messages (Baddeley and Hitch, 1974). WM is conceptualized as the ability to mentally retain and manipulate information (Mesulam, 2000). The multi-component model (Baddeley, 2003) clearly explains the composition and specific meaning of WM; it emphasizes storage and manipulation of information and comprises four mutually independent modules. The phonological loop is primarily responsible for storing and processing auditory and linguistic representations. The visuospatial sketchpad is primarily responsible for storing and processing visual and spatial representations. The central executive is responsible for the operation of the entire WM system and supports the interaction between other modules, as well as the interaction between WM and long-term memory. The episodic buffer is responsible for storing the binding representations between various types of information, both internal and external to the module.

Visuospatial WM (VSWM) is a relatively common name for the visuospatial sketchpad, consisting of visual WM (VWM) and spatial WM (SWM), with the two WM components being both independent and interconnected (Baddeley, 2001). Although VWM and SWM emphasize the non-semantic information of the "what" and "where" of the identified object, respectively, they are still complementary in many cases (Baddeley, 2003). Individuals cannot live, learn, or work efficiently without using VSWM. Its deficiency or impairment can prevent people from living a normal life, and its degeneration can lead to inefficiency in learning and work. Therefore, VSWM has been the subject of research since the 1970s.

Visuospatial WM in children and adolescents is of particular importance in academic performance and mental health. Children's VSWM is associated with school success. For example, the reading process involves encoding of visual and spatial information (Fletcher-Flinn and Thompson, 2007), and a positive correlation exists between visual processing efficiency and reading accuracy (Ferretti et al., 2008). Mathematics learning involves visuospatial and visual perceptual abilities, and deficits in these abilities are likely to contribute to children's mathematical difficulties (Rasmussen and Bisanz, 2005). Furthermore, handwriting has an important influence on academic performance, and children's visual information processing and visuomotor integration abilities are related to their handwriting abilities, particularly visual non-motor processing (visual sequential memory and visual closure) and visuomotor integration (Feder et al., 2005; Feder and Majnemer, 2007). In addition, one study confirmed that VSWM is strongly correlated with performance in subjects such as mathematics, English, and science (St Clair-Thompson and Gathercole, 2006). However, deficits in VSWM can affect children's social interaction processes and even lead to social dysfunction (Kofler et al., 2018), which can negatively affect mental health (Mueller et al., 2015).

Both children's and adults' academic performance is linked to VSWM measures, especially in mathematics (Furst and Hitch, 2000) and reading comprehension (Pham and Hasson, 2014). Basic skills related to mathematics and reading comprehension are required in many occupations, and more so in fields such as architecture and engineering (Verstijnen et al., 1998). Hence, adults' VSWM competencies are tied to their career development.

Visuospatial WM is vital for older people to enjoy a normal old age; however, it has a definite tendency to degenerate with age, with a progressively increased risk for developing dementia, Alzheimer's disease (AD), and other neurodegenerative diseases closely related to WM (Bo et al., 2009; Leung et al., 2015). Fortunately, exercise seems to slow down this degenerative process (Tsai et al., 2019). Many studies confirm the preventive effect of physical activity on the development of AD—either sporadic AD (Maliszewska-Cyna et al., 2017) or genetically influenced AD (Smith et al., 2011)—in older people and that even light exercise can reduce the risk for the disease. Physical activity is negatively associated with the risk for developing AD. The fact that physically active healthy older adults are less likely to develop AD than those who are sedentary or less physically active is widely accepted; specifically, they have better executive functions, such as WM.

Previous studies have explored various neurophysiological mechanisms *via* which exercise can improve WM and thus prevent AD in older adults. For example, exercise promotes an increase in gray matter in the hippocampus and other brain structures, and this increase is positively correlated with the amount of exercise (Erickson et al., 2010); furthermore, exercise increases the amount of *N*-acetylaspartate, a marker of neuronal activity that decreases with age, thereby increasing neuronal activity (Erickson et al., 2012) and improving WM (Xi et al., 2011). More importantly, brain-derived neurotrophic factor (BDNF) is associated with WM as a neurotrophin involved in regulating dendritic and synaptic plasticity in the hippocampus, and interestingly, it can be induced by doing exercise. Experimental studies in rats have shown that exercise can significantly increase BDNF expression in hippocampus compared to control groups (Sable et al., 2021). Activity-regulated cytoskeleton-associated protein (ARC) plays a vital role in the AMPARs trafficking, which is another crucial biochemical marker that can also be induced through exercise (Garcia et al., 2017).

The improvement effect of exercise on VSWM has been confirmed by many studies, especially the significant positive effects on patients with mild cognitive impairment (Law et al., 2013), dementia (Cheng et al., 2014), schizophrenia (Fujii et al., 2020), and depression (Greer et al., 2015; Brondino et al., 2017), as well as on children with attention deficit hyperactivity disorder (ADHD) (Bustamante et al., 2016; Benzing et al., 2018). Correspondingly, positive effects have been found for exercise programs such as aerobic exercise (Tsai et al., 2014), tai chi (Liao et al., 2021), and open-skill exercise (Guo et al., 2016). However, improvement of VSWM ability is also necessary for healthy people. More importantly, whether these exercise programs can be transferred or extended to healthy individuals, and whether there are exercise programs suitable for healthy people of different ages and sexes, needs to be further analyzed.

A previous meta-analysis explored the effects of exercise in three main areas: (1) non-healthy populations experiencing various cognitive-related disorders or impairments (AD, depression, ADHD, etc.); (2) exercise programs such as aerobic exercise, mind–body exercise (combination of slow physical activity, abdominal breathing, and meditation; for example, tai chi, yoga, and Qigong; Wei et al., 2020; Xiong et al., 2021), open-skill exercise (Zhu et al., 2020), coordinative exercise (Ludyga et al., 2022), artistic gymnastics (Serra et al., 2021), and acute moderate-intensity exercise (McMorris et al., 2011); and (3) studies on the superordinate concepts of VSWM: WM, cognitive function, executive function, and other concepts. However, for cognitively healthy people, few studies exist on the intervention effect of exercise on VSWM, and no consistent results have been obtained. If an individual needs to increase exercise to improve VSWM or delay VSWM decline with age in the absence of impairment or abnormal decline in cognitive ability (unlike decline with age), most effective exercise program, the optimal duration of each exercise, and the shortest effective period of exercise need to be further explored. Furthermore, whether the program is available for healthy people of all ages and sexes also needs to be further discussed. Therefore, a necessity has arisen to conduct a systematic, comprehensive, objective, and quantitative review to further summarize and refine a specific exercise prescription for healthy people and explore whether the improvement and enhancement effects on VSWM are significant.

Thus, this meta-analysis makes innovative contributions to the improvement of VSWM through exercise concerning individual characteristics, qualitative characteristics of exercise, and quantitative characteristics of exercise. Results of this meta-analysis will help the development of more targeted exercise prescriptions, identify the knowledge gap between researchers and practitioners, and provide evidence-based recommendations to clinicians to refine prescriptions for the prevention of VSWM capabilities degradation.

2. Methods

The protocol for this systematic review was registered on PROSPERO (CRD42022354737) and INPLASY (INPLASY202280053) and is available in full on inplasy.com (10.37766/inplasy2022.8.0053). The meta-analysis process covered the requirements of the 27-item checklist of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (Liberati et al., 2009). The analysis methods and inclusion criteria were specified in advance and documented in the protocol.

2.1. Eligibility criteria

Studies were selected by two authors (QZ and JD) according to the following inclusion criteria: (1) participants were of any age and sex and identified as cognitively and physically healthy *via* validated diagnostic tools; (2) participants had normal or corrected visual acuity; (3) intervention measures were all kinds of physical activities (two conditions must be met: skeletal muscle movement and energy expenditure); (4) all outcomes were quantified by validated VSWM measuring tools; and (5) the study was a randomized controlled trial (RCT) as RCTs have the highest quality of evidence in meta-analysis. Studies meeting the following criteria were excluded: (1) control measures include physical activity; (2) participants had concussions or other brain injuries; or (3) participants had contraindications to exercise or were taking medication. Reports meeting the following criteria were also excluded: (1) language of publication was not English or Chinese and (2) full text or important data (i.e., mean and standard deviation) were not available.

2.2. Information sources

We searched six electronic databases [Web of Science, MEDLINE, BIOSIS Previews, PubMed, China National Knowledge Infrastructure, and Wanfang Data (Chinese)] from inception to August 20, 2022. These databases contained almost all the potential RCTs we needed. Because of the limited human resources available for this review, only these six databases were selected.

2.3. Search strategy

A systematic search strategy was applied using MeSH word search. For example, the following retrieval strategy was used: "Exercise" [MeSH] (e.g., "Exercises" OR "Physical Activity" OR "Activities, Physical" OR "Activity, Physical" OR "Physical Activities" OR "Exercise, Physical" OR "Exercises, Physical" OR "Physical Exercise" OR "Physical Exercises" OR "Acute Exercise" OR "Acute Exercises" OR "Exercise, Acute OR Exercises, Acute" OR "Exercise, Isometric" OR "Exercises, Isometric" OR "Isometric Exercises" OR "Isometric Exercise" OR "Exercise, Aerobic" OR "Aerobic Exercise" OR "Aerobic Exercises" OR "Exercises, Aerobic" OR "Exercise Training" OR "Exercise Trainings" OR "Training, Exercise" OR "Trainings, Exercise") AND "Memory, Short-Term" [MeSH] (e.g., "Memories, Short-Term" OR "Memory, Short Term" OR "Short-Term Memories" OR "Short-Term Memory" OR "Memory, Short term" OR "Memories, Short term" OR "Short term Memories" OR "Short term Memory" OR "Working Memory" OR "Working Memories" OR "Memory, Immediate" OR "Immediate Memories" OR "Immediate Memory" OR "Memories, Immediate" OR "Immediate Recall" OR "Immediate Recalls" OR "Recall, Immediate" OR "Recalls, Immediate").

2.4. Data extraction and coding

All documents obtained through the search strategy were imported into EndNote document management software to eliminate duplicates. The eligibility assessment was performed independently in an unblinded standardized manner by two authors (QZ and JD). Disagreements between reviewers were resolved by consensus. Information was extracted using a pre-designed data extraction form that included (1) basic information: author and year of publication; (2) participant characteristics: average age or age range in the experimental and control groups separately, and sample size; (3) experimental characteristics: study design, intervention type, control type, intervention information (intervention duration, intervention session time, intervention frequency, intervention intensity), measurement tools, and outcome indicators. One author (QZ) extracted the following data from the included studies, and the second author (JD) checked the extracted data. Disagreements were resolved through consensus. If agreement could not be reached, the third author (YZ) decided.

2.5. Study risk of bias assessment

Two authors (QZ and JD) independently assessed the risk for bias of the included studies according to the Physiotherapy Evidence Database (PEDro) scale (Maher et al., 2003), which comprises the following 11 items: eligibility criteria, randomization, concealed allocation, similar baseline, blinding of participants, blinding of therapists, blinding of assessors, more than 85% retention, intent-to-treat analysis, between-group comparison, and point measures and measures of variability. The total score of the quality evaluation was calculated from the scores of 10 items, excluding the first item (eligibility criteria). The range of the total score was 0–10; a score ≥ 6 indicated high quality of the assessed studies, and a score < 6 indicated low quality (Maher et al., 2003). Any disagreements between the reviewers were resolved through consultation with another reviewer (YZ).

2.6. Statistical syntheses and analysis

The meta-analyses were performed by computing standardized mean differences (SMDs) using a random-effects model in Stata 15.1 software. SMDs and 95% confidence intervals (CI) for each study were calculated. The primary outcome measure was the standardized mean difference in the VSWM-related tests or scale results of the exercise intervention and control groups. Heterogeneity was calculated using I^2 statistic with 95% CI, with 0, 25, 50, and 75% as the thresholds for none, low, medium, and high ratios of the included studies, respectively. Sources of heterogeneity were analyzed through subgroup analysis, meta-regression analysis, or re-run meta-analysis, by excluding studies with abnormal results.

Studies that met the inclusion and exclusion criteria were critically reviewed, and intervention characteristics were extracted for tabulation. VSWM scores and RT were the main outcome indicators. SMD was used for the combined effect sizes separately and was calculated using Hedges' *g*. The resulting effect sizes were transformed to bias-corrected Hedges' *g*, with values of 0.2, 0.5, and 0.8, which served as thresholds for small, medium, and large effects, respectively. Forest plots of the pooled effect sizes were drawn separately from the Score and RT data. The size of heterogeneity was tested using forest plots, and I^2 and its 95% CI were reported. If I^2 was >50% ($p < 0.1$), the source of heterogeneity was further analyzed using subgroup analysis and meta-regression analysis. If no source of heterogeneity was found, the random-effects model was selected directly for statistical analysis. If no heterogeneity was detected, a fixed-effects or random-effects model was directly selected for statistical analysis.

Subgroup analyses were conducted concerning six moderators: (1) Age was divided into three subgroups: children, young adults, and seniors; improvements in VSWM may vary with age and may be more significant during childhood and old age, which are two periods of rapid change—development and aging (Kupis et al., 2021). (2) Level of cognitive engagement was divided into two subgroups: high level and low level; exercise interventions with different cognitive requirements may have different improvement effects on VSWM (Formenti et al., 2021). (3) Exercise intensity was divided into two subgroups: low and moderate intensity and vigorous intensity; whether the intensity of exercise intervention will affect the improvement effect of exercise on VSWM is of significance for the clinical improvement of healthy people (Loprinzi et al., 2022). (4) Intervention time was divided into two subgroups: acute exercise and chronic exercise; acute exercise is defined as one-off exercise of relatively short duration, while chronic exercise is defined as exercise that lasts for a long time, several times a week, for weeks or years; a review showed that both acute and chronic exercise can improve the performance of memory systems (Loprinzi et al., 2021); however, the two may have different improvement effects on VSWM; therefore, further discussion is needed. (5) Intervention period was divided into three subgroups: <30, 30–89, and ≥90 days. Does a longer exercise cycle have a better effect on VSWM? Is there a peak for effect size? These questions require further subgroup analysis. (6) Intervention duration was divided into three subgroups: <30, 30–59, and ≥60 min; previous experiments in rats showed that increased exercise duration affects the level of WM enhancement (Sinaei et al., 2021), but whether the same results apply to healthy humans is open to further discussion.

2.7. Risk for publication bias assessment

We created a funnel plot to assess publication bias using the standard error and its inverse for each included study. The symmetry of the funnel plot indicated no risk for publication bias, both visually and formally, using the Egger's test. Because graphical evaluation can be subjective, we also conducted an adjusted rank correlation test (Begg test) as another formal statistical test to confirm whether publication bias exists.

3. Results

3.1. Literature search results

Initially, 2,808 articles were searched from six databases. All articles were imported into EndNote X9, and 926 duplicates were removed. In the preliminary review phase, 1,326 articles were excluded after reading the titles and abstracts; reasons for exclusion were having non-healthy participants ($n = 568$), being reviews or meta-analyses ($n = 264$), being non-RCT ($n = 292$), being unrelated to subject content ($n = 167$), and being non-Chinese or non-English ($n = 35$). Another 535 articles were excluded after reading the full text, and reasons for exclusion included non-full text ($n = 182$), lack of original data ($n = 154$), inappropriate measuring tools ($n = 102$), exercise intervention in the control group ($n = 58$), and phonological WM ($n = 39$). Finally, 21 articles were included in the review (Figure 1).

3.2. Eligible research characteristics

After review, 21 articles, including 28 RCTs, were included. The average intervention period was 10.9 weeks, the average intervention duration was 41.3 min, and the main intervention was aerobic exercise. RT and Score were the main outcome indicators in these articles. Among them, the visual N-back task and N-back (1-back, 2-back) measurement tools were mainly used in RT studies. In addition, measurement tools such as Digit Span Backwards (DSB), Digit Span Forward (DSF), Digit Span (DS), Visual Paired Associates (VISPA), VSWM, and spatial attention tasks were used in Score studies. The sample size comprised 1,595 healthy participants, who were divided into three age groups: children (4–11 years), young adults (18–35 years), and seniors (58–88 years). Except for one study that did not report sex proportion, 27 studies reported a female participation rate of 80.9% (Table 1).

3.3. Methodological quality evaluation

The quality of the 21 included articles was evaluated using the PEDro Scale (Table 2). The mean score for the quality of the RT articles was 6.9 points and that for the Score articles was 7.6 points. In addition, all articles reported "statistical analyses between groups" and "point measures and measures of variance" and used random allocation for experimental grouping. Moreover, 12 articles described the process of random allocation, 18 reported on baseline levels of participants, and 18 provided key outcome measures for over 85% of participants. Eighteen articles reported a retention rate of ≥85% and completeness of the measurement results.

3.4. Meta-analysis results

3.4.1. Heterogeneity test

A meta-analysis was conducted on 28 experiments, which were included in 21 articles on exercise interventions in VSWM. Among these, 10 were RT studies and 18 were Score studies. According to the heterogeneity test, the meta-analysis results of the 21 combined articles were as follows: $I^2 = 32.3\%$, $p = 0.053$; mild heterogeneity was observed. The heterogeneity of the RT-related studies was $I^2 = 0$, $p = 0.677$ and that of the Score studies was $I^2 = 0$, $p = 0.897$. Heterogeneity results show that the selection of outcome indicators may be the source of heterogeneity; therefore, the two types of indicators were analyzed separately (Table 3).

3.4.2. Overall effect size

Twenty-eight studies investigated the effects of exercise interventions on VSWM (Figure 2). According to the heterogeneity test, the choice of the outcome index would affect the statistical results. Therefore, RT and Score

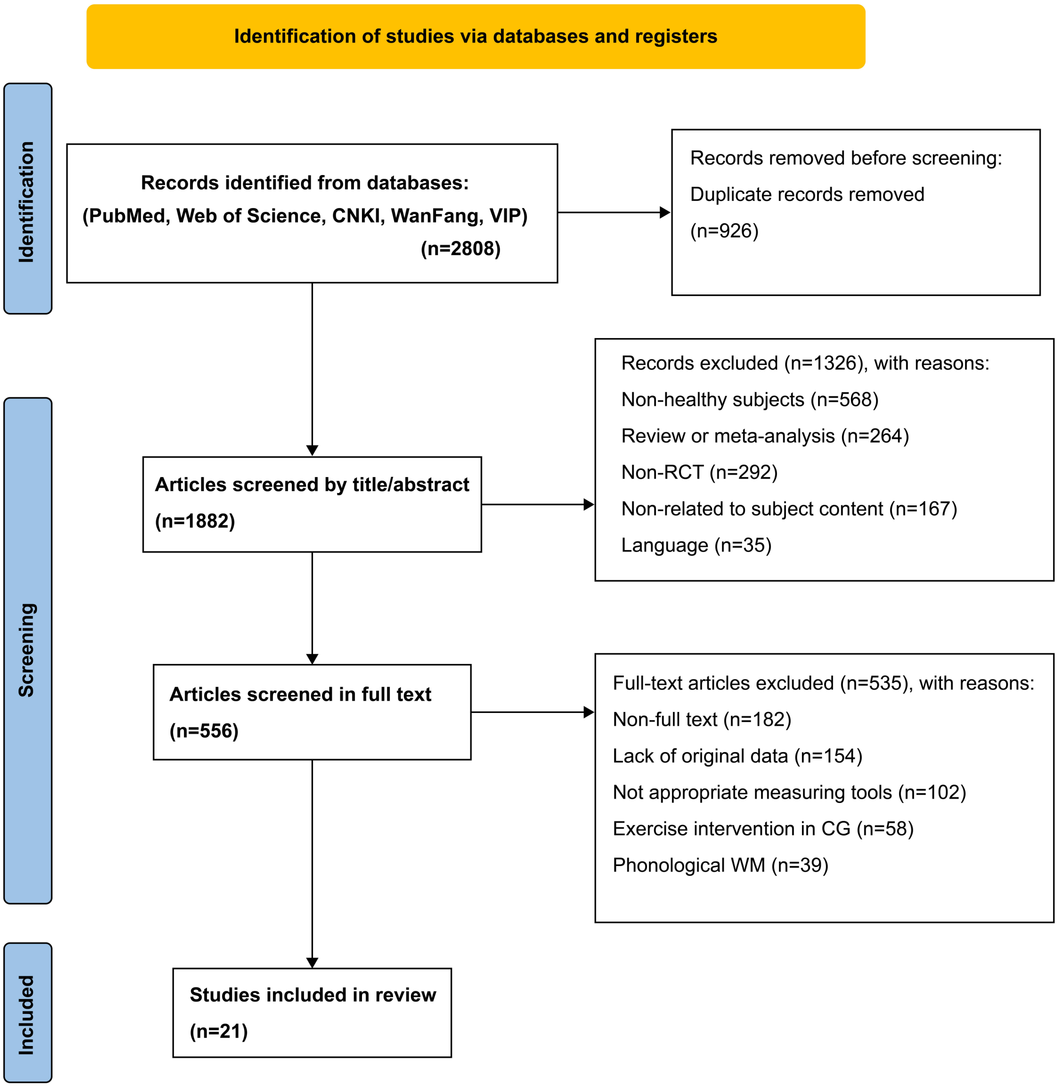

FIGURE 1
Flow of the study selection method.

are discussed separately in these studies, and the effect size was calculated separately for the RT and Score studies. The effect size of Score studies was SMD = 0.342, $p = 0.000$, which was significant. The effect size of RT studies was SMD = −0.202, $p = 0.037$, which was also significant (Table 3).

3.4.3. Publication bias results

We tested the included articles for publication bias, and the results showed that the RT (Figure 3A) and Score (Figure 3B) studies were evenly distributed in the funnel and approximately symmetrically distributed. Therefore, we preliminarily determined that these studies had no publication bias. To confirm the reliability of the results, Begg and Egger's tests were used to further evaluate publication bias objectively, which showed that RT ($p = 0.954$, 95% CI: −4.300–4.085) and Score ($p = 0.264$, 95% CI: −0.400–0.117) studies were free of publication bias.

3.5. Results of subgroup analysis

The overall forest map shows that physical exercise can effectively improve the VSWM ability of healthy individuals. The reasons for not using RT studies for subgroup analysis are as follows: the quality of RT studies is low and the weight is small. For the exercise interventions, variables (age, level of cognitive engagement, exercise intensity, intervention times, intervention period, and intervention duration) were likely to be influencing factors for healthy participants on VSWM. Consequently, subgroup analysis was used to help identify more appropriate exercise programs.

Participants were divided into three age subgroups: children, young adults, and seniors; the effect of the exercise interventions on VSWM was affected by the participants' age. Exercise had the best improvement effect on VSWM in senior participants (SMD = 0.361, $p = 0.000$), followed by that in children (SMD = 0.343, $p = 0.001$).

The types of exercise intervention included three groups of factors: level of cognitive engagement, exercise intensity, and intervention times. First, the effect size of the exercise intervention on VSWM was affected by the level of cognitive engagement: exercise interventions with a higher level of cognitive engagement had the best improvement effect on VSWM (SMD = 0.336, $p = 0.000$). Moreover, exercise interventions with low levels of cognitive engagement also partly improved VSWM (SMD = 0.254, $p = 0.027$). Second, the effect size of the exercise

TABLE 1 Characteristics of the studies included in the meta-analysis.

Reference (year)	Study design	Individual characteristic	Group	Intervention type	Control type	Intervention characteristic	Measuring tool	Outcomes measurement
Li (2019)	RCT	Community seniors, $n = 74$ EG age: 66.66 ± 4.89 CG age: 65.97 ± 4.13	EG: $n = 38$ CG: $n = 36$	Five mimic-animal exercises	NM	40 weeks 1 session/week 60 min/session	③⑤⑥	RT
Peng and Zhou (2016)	RCT	Female university students, $n = 59$ EG age: 21.33 ± 1.49 CG age: 21.0 ± 0.78	EG: $n = 31$ CG: $n = 28$	Acute aerobic exercise (Power cycling)	R	30 min	③	RT
Yang et al. (2019)	RCT	Women seniors, $n = 52$ EG-a age: 64.5 ± 3.9 EG-b age: 62.6 ± 4.6 CG age: 63.2 ± 5.3	EG-a: $n = 16$ EG-b: $n = 19$ CG: $n = 17$	Taijiquan; Square dance	W	6 months ≥5 sessions/week 75 min/session	③	RT
Zhang H. (2021)	RCT	University students, $n = 56$ EG age: 18.53 ± 0.57 CG age: 18.46 ± 0.71	EG: $n = 30$ CG: $n = 26$	Medium-intensity aerobic exercise	NM	9 weeks 4 sessions/week 60 min/session	⑦	RT
Lindheimer et al. (2017)	RCT	Healthy adults, $n = 60$	EG-a: $n = 15$ EG-b: $n = 15$ CG-a: $n = 15$ CG-b: $n = 15$	Cycling	PC	30 min/session	⑧	RT
Nishiguchi et al. (2015)	RCT	Community-dwelling older adults, $n = 48$ EG age: 73.0 ± 4.8 CG age: 73.5 ± 5.6	EG: $n = 24$ CG: $n = 24$	Dual task–based multimodel exercise; Walking exercise	NM	12 weeks 90 min/session	③	RT
Li et al. (2020)	RCT	Female university students, $n = 60$ EG-a age: 18.44 ± 0.51 EG-b age: 18.43 ± 0.51 CG age: 18.58 ± 0.51	EG-a: $n = 18$ EG-b: $n = 21$ CG: $n = 19$	Aerobic exercise; Resistance exercise	NM	8 weeks 3 sessions/week 60 min/session	③	RT
Wu (2021)	RCT	Children, $n = 40$ Range age: 4–5	EG: $n = 20$ CG: $n = 20$	Aerobic gymnastics	DR	8 weeks 2 sessions/week 60 min/session	⑫	RT
Brown et al. (2009)	RCT	Seniors, $n = 154$ EG-a age: 79.5 ± 5.9 EG-b age: 81.5 ± 6.9 CG age: 78.1 ± 6.4	EG-a: $n = 66$ EG-b: $n = 26$ CG: $n = 34$	Flexibility and relaxation; Specific resistance training; Balance (both static and dynamic) training	NM	6 months 2 sessions/week 60 min/session	①②④⑨	Score
Elkana et al. (2018)	RCT	Adults, $n = 69$ EG age: 25.43 (range: 19–34) CG age: 26.39 (range: 22–35)	EG: $n = 35$ CG: $n = 34$	Acute physical exercise	NM	15 min	⑩	Score

(Continued)

TABLE 1 (Continued)

Reference (year)	Study design	Individual characteristic	Group	Intervention type	Control type	Intervention characteristic	Measuring tool	Outcomes measurement
Moreau et al. (2017)	RCT	Children, age: NR	EG: *n* = 152 CG: *n* = 153	HIIT	NM	6 weeks	①	Score
Wilke (2020)	RCT	College students with exercise background, *n* = 35 EG-a age: 26.5 ± 4.4 EG-b age: 26.4 ± 2.6 CG age: 27.3 ± 3.8	EG-a: *n* = 12 EG-b: *n* = 11 CG: *n* = 12	HIIT; Aerobic walking	R	15 min	①②④	Score
Kramer et al. (2002)	RCT	Sedentary older adults, *n* = 125 EG age: 67.3 ± 5.2 CG age: 66 ± 5.3	EG: *n* = 66 CG: *n* = 58	Aerobic exercise	S	6 months 3 sessions/ week 40 min/session	①②⑪	Score
Nouchi et al. (2014)	RCT	Seniors, *n* = 64 EG age: 66.75 ± 7.61 CG age: 67.06 ± 2.82	EG: *n* = 32 CG: *n* = 32	Aerobic; Strength; Stretching	NM	4 weeks 3 sessions/ week	①②	Score
Tottori et al. (2019)	RCT	Children, *n* = 56 EG age: 10.0 ± 1.0 CG age: 10.4 ± 1.1	EG: *n* = 27 CG: *n* = 29	HIIT	NM	4 weeks 3 sessions/ week 8–10 min/ session	①②	Score
Kalbe et al. (2018)	RCT	Seniors, *n* = 55 EG-a age: 68.22 ± 7.96 EG-b age: 68.75 ± 6.62 CG age: 67.53 ± 5.89	EG-a: *n* = 18 EG-b: *n* = 20 CG: *n* = 17	Cognitive and physical training	CT	7 weeks 2 sessions/ week 90 min/session	①	Score
Hong et al. (2018)	RCT	Seniors, *n* = 25 EG age: 76.50 + ±6.36 CG age: 73.50 ± 5.57	EG: *n* = 12 CG: *n* = 13	Resistance exercises	NM	12 weeks 2 sessions/ week 60 min/session	①②	Score
Hariprasad et al. (2013)	RCT	Seniors, *n* = 120 EG age: 75.74 ± 6.46 CG age: 74.78 ± 7.35	EG: *n* = 62 CG: *n* = 58	Yoga	NM	6 months 3–4 sessions/week 60 min/session	①②⑬⑭	Score
Fabre et al. (2002)	RCT	Seniors, *n* = 24 EG-a age: 65.4 ± 2.2 EG-b age: 64.9 ± 1.4 CG age: 65.7 ± 1.5	EG-a: *n* = 8 EG-b: *n* = 8 CG: *n* = 8	Aerobic exercise; Mental training	NM	2 months 2 sessions/ week 60 min/session	②	Score
Li (2016)	RCT	Seniors, *n* = 66 EG-a age: 67.35 ± 4.29 EG-b age: 66.59 ± 4.02 CG age: 65.93 ± 5.13	EG-a: *n* = 22 EG-b: *n* = 25 CG: *n* = 19	Aerobic walk; Baduanjin	NM	6 months 3 sessions/ week 60 min/session	⑮	Score
Zhang B. (2021)	RCT	Children, *n* = 48 EG age: 11.167 ± 0.38 CG age: 11.208 ± 0.41	EG: *n* = 24 CG: *n* = 24	Rhythmic exercise	DR	18 weeks 3 sessions/ week 40 min/session	⑯	Score

NR, not reported; EG-a, Experimental group a; EG-b, Experimental group b; CG-a, Control group a; CG-b, Control group b; RCT, randomized controlled trial; NM, no movement; CT, cognitive training; DR, daily routine; S, stretching; R, reading; PC, passive cycling; W, Walk; ① DSB, Digits Span Backward; ② DSF, Digits Span Forward; ③ N-back; ④ DS, Digits span; ⑤ Stroop; ⑥ ANT, Attention Network Test; ⑦ 2-back; ⑧ Visual N-back Task; ⑨ VISPA, Visual Paired Associates; ⑩ VS-WM, Visuospatial Working Memory; ⑪ SAT, Spatial Attention Task; ⑫ 1-back; ⑬ SSB, Spatial Span Backward; ⑭ SSF, Spatial Span Forward; ⑮ WMS, Wechsler Memory Scale; ⑯ SWMs, Spatial Working Memory score.

TABLE 2 Physiotherapy evidence database (PEDro) scores and sum of the included studies.

Articles	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Sum (Items 2–11)
Reaction time (RT)												
Li (2019)	1	1	0	1	1	1	0	1	1	1	1	8
Peng and Zhou (2016)	1	1	0	1	0	0	0	1	1	1	1	6
Yang et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6
Zhang H. (2021)	1	1	0	1	0	0	0	1	1	1	1	6
Lindheimer et al. (2017)	1	1	0	1	1	0	0	1	1	1	1	7
Nishiguchi et al. (2015)	1	1	1	1	1	1	0	1	1	1	1	9
Li et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	6
Wu (2021)	1	1	1	1	0	0	0	1	1	1	1	7
Mean (RT)												6.9
Scores												
Brown et al. (2009)	1	1	1	1	1	0	0	1	1	1	1	8
Elkana et al. (2018)	1	1	1	1	0	0	0	0	1	1	1	6
Moreau et al. (2017)	1	1	1	1	1	0	1	1	1	1	1	9
Wilke (2020)	1	1	1	1	1	0	0	1	1	1	1	8
Kramer et al. (2002)	1	1	1	1	1	0	0	1	1	1	1	8
Nouchi et al. (2014)	1	1	1	1	0	0	1	1	1	1	1	8
Tottori et al. (2019)	1	1	0	1	0	0	0	1	1	1	1	6
Kalbe et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	6
Hong et al. (2018)	1	1	0	1	1	0	0	1	1	1	1	7
Hariprasad et al. (2013)	1	1	1	1	1	0	0	1	1	1	1	8
Fabre et al. (2002)	1	1	1	1	1	0	0	1	1	1	1	8
Li (2016)	1	1	1	1	1	1	1	1	1	1	1	10
Zhang B. (2021)	1	1	1	0	0	0	0	1	1	1	1	6
Mean (Score)												7.5

Item 1: eligibility criteria; Item 2: randomization; Item 3: concealed allocation; Item 4: similar baseline; Item 5: blinding of participants; Item 6: blinding of therapists; Item 7: blinding of assessors; Item 8: more than 85% retention; Item 9: intent-to-treat analysis; Item 10: between-group comparison; Item 11: point measures and measures of variability.

TABLE 3 Heterogeneity analysis of exercise effects of included studies.

	Heterogeneity		Effect size			
	I^2 (%)	*P*	SMD	95% CI	Z	*P*
RT	0	0.677	−0.202	[−0.393, −0.012]	2.08	0.037
Score	0	0.897	0.342	[0.228, 0.457]	5.86	0.000
Total	32.3	0.053	0.198	[0.100,0.296]	3.95	0.000

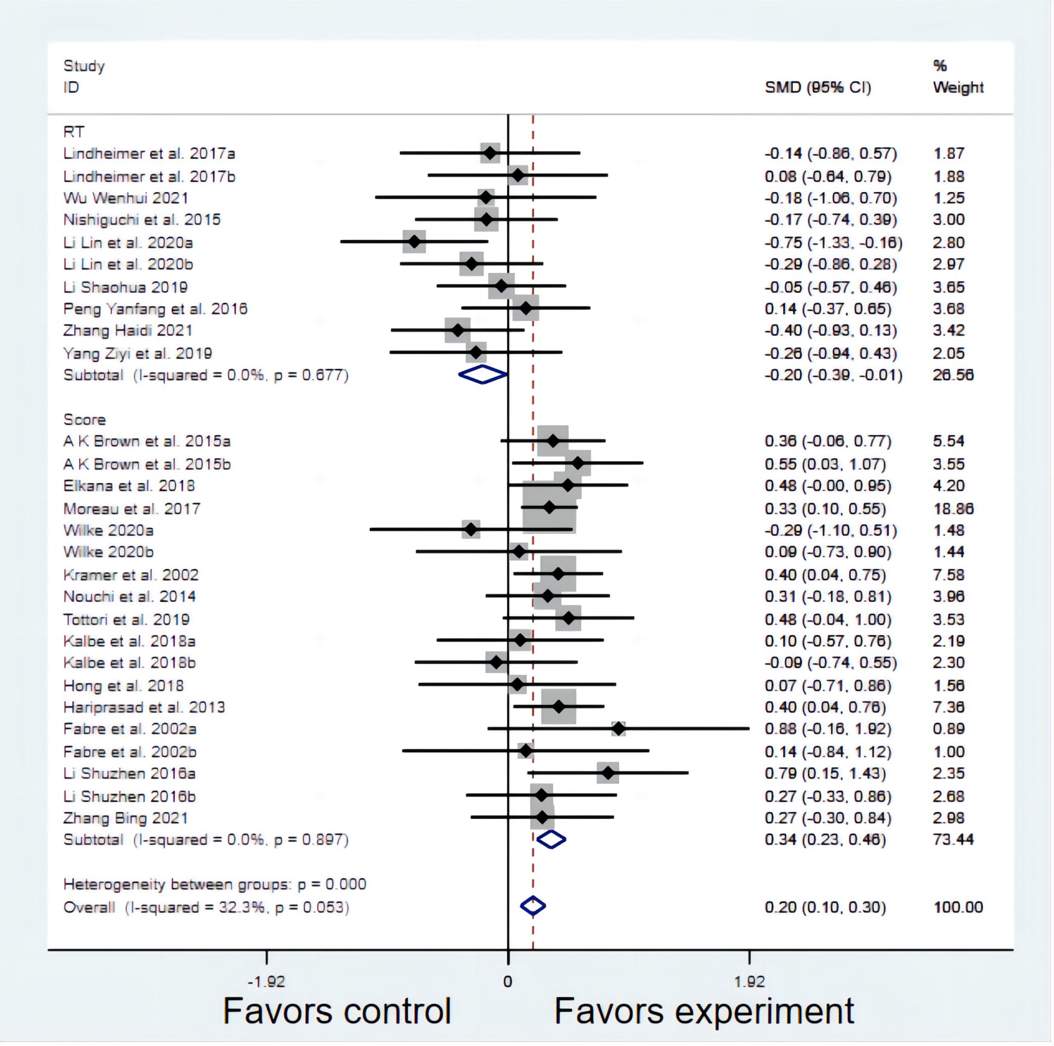

FIGURE 2
The effect of reaction time (RT) and score.

intervention on VSWM was affected by exercise intensity, and the effect of low-and moderate-intensity interventions (SMD = 0.366, $p = 0.000$) was better than that of vigorous interventions (SMD = 0.299, $p = 0.003$). Finally, chronic exercise (SMD = 0.335, $p = 0.000$) had a significant intervention effect on VSWM, whereas acute exercise did not have a significant effect ($p = 0.192$), as shown by the results of the subgroup analysis of acute and chronic exercise.

The results of subgroup analysis showed that exercise intervention duration had an impact on the effect size. Significant effect sizes were observed when the exercise duration was 30–59 min (SMD = 0.349, $p = 0.008$) and ≥60 min (SMD = 0.357, $p = 0.000$), whereas the improvement effect on VSWM was not significant when the duration was <30 min. In addition, the exercise intervention period can also have an impact on the intervention effect. The exercise intervention period was divided into three subgroups (<30, 30–89, and ≥90 days) for the analysis. The results showed that when the period was ≥90 days (SMD = 0.383, $p = 0.000$), the effect of the intervention was the best, which was slightly better than the 30–89-day period (SMD = 0.257, $p = 0.044$), while the <30-day effect was not significant (Table 4).

3.6. Meta-regression analysis

To test the effect of exercise interventions on VSWM in healthy individuals, a meta-regression analysis was conducted on the variables, including age, quality of evidence, type of control group, exercise intensity, exercise intervention duration, intervention period, and type of intervention, using pooled RT and Score studies. The results showed that children ($\beta = 0.41$, $p = 0.021$), seniors ($\beta = 0.336$, $p = 0.013$), PEDro score ($\beta = 0.108$, $p = 0.031$), low intensity ($\beta = 0.407$, $p = 0.017$), intervention duration ($\beta = -0.006$, $p = 0.029$), and intervention period

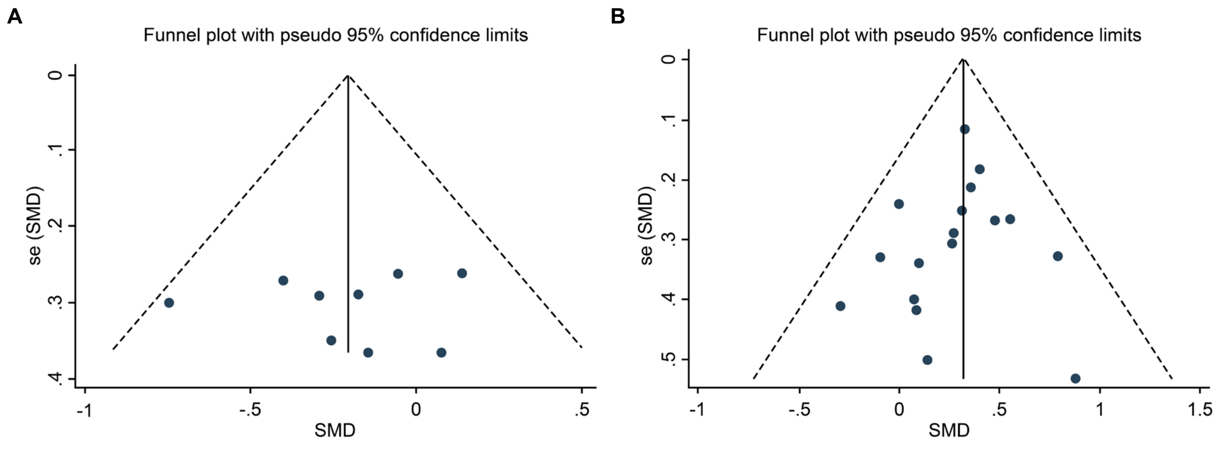

FIGURE 3
Funnel Plot of Publication Bias of RT Studies **(A)** and Score Studies **(B)**.

($\beta = 0.012$, $p = 0.036$) were significantly correlated with VSWM. However, sedentary behavior ($p = 0.717$), daily routine ($p = 0.645$), vigorous exercise ($p = 0.106$), acute exercise ($p = 0.541$), and high-level cognition ($p = 0.843$) were not significantly associated. In the multivariate meta-regression analysis results, $tau^2 = 0$ and Adj $R^2 = 1$, indicating that the selected variables explained the source of heterogeneity between studies. Consequently, we conducted multivariate meta-regression analysis based on a data-driven model that included variables that were significantly correlated with effect size prediction. The results showed that when controlling for other variables, two variables could significantly predict the effect size of exercise intervention on VSWM: old age and duration of exercise intervention (Table 5).

4. Discussion

4.1. Summary of evidence

Overall, physical activity had a small but significant positive impact on VSWM in healthy individuals, mainly reflected by the accuracy of the test (i.e., scores). The effect size concerning quantity (Score) was large and highly significant. There was no heterogeneity between studies and no publication bias. The quality of evidence was high, and the results of the meta-analysis were credible. Regarding speed (RT), the effect size was small and non-significant. There was mild heterogeneity between studies but no publication bias. The quality of the evidence was slightly below the eligibility standard; however, the results of the meta-analysis were relatively reliable. To the best of our knowledge, this meta-analysis is the first study to explore the prescription of exercise interventions for VSWM, covering healthy people of all ages. It is necessary to further investigate whether other potential moderators influence the effects of exercise intervention on VSWM. The total effect size was slightly higher ($0.341 > 0.217$) than that in a previous study in which Score was used as an outcome indicator (Ludyga et al., 2020).

Subgroup analysis showed that the variables age, intervention time, and intervention period had selective effects. The intervention effects were significant for children and older adults, and non-significant for young adults, with almost non-existent effect sizes. There are two possible explanations for this. One is that the VSWM capacity in healthy young adults is at its peak, and increasing it significantly is difficult. Age advantage gives young adults better filtering performance in VWM capacity compared with healthy older adults (Jost et al., 2011). Second, these physical activity prescriptions may not be appropriate for healthy young adults to improve their VSWM ability, and the intervention effects may be associated with factors such as exercise intensity, intervention period, and intervention mode.

The finding that chronic exercise had a significant effect, while acute exercise produced non-significant improvement, in VSWM in healthy individuals is consistent with the results of a previous meta-analysis (Rathore and Lom, 2017). The lack of an effect size may be related to the limited number of relevant studies included. However, previous meta-analyses on children showed large and significant effect sizes for acute exercise in improving children's WM capacity, even exceeding the effect sizes for chronic exercise (Liu et al., 2020). From this perspective, it would be interesting to see whether the intervention effect of acute exercise is related to the age of participants. The effect of the intervention was significant when the duration of the intervention was ≥30 days, whereas the improvement in cognition was not significant when it was <30 days. Evidence from studies relating white matter plasticity to exercise showed that prolonged intervention and practice was required for at least several weeks (Fields, 2015). An intervention duration of <30 days is relatively short, and changes in white matter are not sufficient to cause significant improvements in WM. Therefore, short-term interventions and measurements cannot ascertain the effect of exercise on the improvement in VSWM.

The variables cognitive engagement, exercise intensity, and intervention duration showed general effects in that no between-group differences were observed in their subgroups, and all had significant effect sizes. Relatively high cognitive engagement, low to moderate exercise intensity, and ≥60 min of intervention length had larger effect sizes than the other subgroups. However, the relative superiority should be interpreted with caution because of the small between-group differences in effect sizes, as we currently do not know the pathway of their mechanisms.

Regression analysis showed that age was positively associated with the overall intervention effect in the univariate regression model. The included studies showed a significant enhancement effect of physical activity on VSWM capacity in healthy populations (mainly children and older adults). Data on young adults were excluded because of covariance issues, and research on healthy adolescents and healthy middle-aged

TABLE 4 Result of subgroup analysis.

Moderator	Subgroup	Score					
		SMD	95%CI	Z	Q	df	P
Age	Children	0.343	[0.148,0.538]	3.45	0.34	10	0.001
	Young adults	−0.043	[−0.408,0.321]	0.23	2.76	2	0.816
	Seniors	0.361	[0.207,0.514]	4.61	6.68	2	0.000
Level of cognitive engagement	High	0.336	[0.203,0.469]	4.96	2.35	10	0.000
	Low	0.254	[0.029,0.478]	2.21	7.76	5	0.027
Exercise intensity	Low and moderate	0.366	[0.216,0.517]	4.78	6.99	12	0.000
	Vigorous	0.299	[0.104,0.494]	3.01	2.88	3	0.003
Intervention times	Acute exercise	0.274	[−0.138,0.686]	1.30	2.59	1	0.192
	Chronic exercise	0.335	[0.207,0.463]	5.13	7.45	14	0.000
Intervention period	<30 days	−0.043	[−0.40,0.321]	0.23	2.76	2	0.208
	30–89 days	0.257	[0.008,0.507]	2.02	3.75	6	0.044
	≥90 days	0.383	[0.246,0.521]	5.46	2.53	6	0.000
Intervention duration	<30 min	0.256	[0.075,0.436]	2.78	3.32	4	0.005
	30–59 min	0.349	[0.092,0.607]	2.66	0.16	3	0.008
	≥60 min	0.357	[0.176,0.538]	3.87	6.60	8	0.000

(Q-value, heterogeneity statistic; df, degrees of freedom).

TABLE 5 Results of the meta-regression models investigating potential moderators of the effect of exercise on VSWM.

Model	Covariate	β	Lower 95% CI	Upper 95% CI	P	R^2 analog	Tau^2
1	Age					0.14	0.012
	Children	0.41	0.677	0.753	0.021		
	Seniors	0.336	0.084	0.64	0.013		
2	PEDro score	0.108	0.010	0.207	0.031	0.02	0.47
	Control type						
	Sedentary	−0.065	−0.436	0.304	0.717		
	Daily routine	−0.109	−0.59	0.3744	0.645		
3	Exercise intensity					0.017	0.53
	Low	0.407	0.078	0.735	0.017		
	Vigorous	0.272	−0.062	0.607	0.106		
4	Intervention period	0.012	0.0008	0.023	0.036	0.01	0.73
	Intervention duration	−0.006	−0.012	−0.0007	0.029		
5	Acute exercise	0.096	−0.223	0.415	0.541	−0.15	0.044
	High-level cognitive exercise	0.029	−0.278	0.338	0.843		
6	Children	0.28	−0.115	0.668	0.153	1	0
	Seniors	0.617	0.22	1.01	0.004		
	PEDro score	0.001	−0.125	0.128	0.982		
	Low intensity	0.108	−0.218	0.435	0.497		
	Intervention period	−0.000	−0.15	0.13	0.893		
	Intervention duration	−0.01	−0.17	0.003	0.006		

adults was scant. From a neuroscience perspective, WM develops comprehensively throughout childhood, which depends, to some extent, on the maturity of the white matter microstructure of the brain and the development of neural connections. Changes in white matter bundles are associated with changes in children's VSWM ability but not significantly with changes in phonological WM ability (Krogsrud et al., 2018). VSWM changes in healthy older adults are associated with white matter integrity. Mean diffusivity, a measure of white matter integrity, increases with age, and white matter integrity decreases, affecting WM function. However, previous studies have confirmed that the intervention pathway to achieve a positive impact on WM is to improve white matter integrity, and thus WM capacity, by reducing mean diffusivity in the fiber tracts associated with the frontoparietal network (Dziemian et al., 2021).

In addition to age, the low and moderate intensity groups were positively associated with the overall intervention effect. Motor cognition involves the brain region responsible for motor control and the neural integration of movement and cognition (Leisman et al., 2016). Physical fatigue owing to excessive physical activity and cognitive fatigue owing to prolonged intellectual activity share common basal ganglia (Blain et al., 2019). There are also studies that present a neurological perspective based on motor fatigue: top–down (cognitive and physical efforts) and bottom–up (body sensations) processes act in parallel with arousing mechanisms to determine cognitive outcomes (Schmit and Brisswalter, 2020). From this perspective, low-to-moderate-intensity exercise has some neurological benefits concerning cognitive improvement compared with vigorous intensity.

The study's quality factor had a small but significant influence on the total effect size. Even though the review team screened the literature in strict accordance with the patient/population, intervention, comparison, and outcomes principle and confirmed the absence of significant publication bias, there could still be relatively low-quality studies that did not meet the individual criteria of the quality assessment, thereby affecting the overall intervention effect. The intervention period and duration also had significant but negligible effects on the total effect size. The analysis of moderating factors showed that the effect size of the period and duration was positively correlated with its own value. However, a previous meta-analysis indicated an interaction between intervention period and duration (Ludyga et al., 2020). Thus, a longer single intervention would be more effective with a minimum of a 30-day intervention.

The exercise interventions identified in the study were specifically targeted at VSWM in healthy individuals, while other exercise interventions were mostly targeted at WM, executive function, or other cognitive abilities in an unhealthy population. Therefore, independent exercise programs can be provided to healthy individuals who want to enhance or improve their VSWM performance and reduce the risk for associated cognitive decline or impairment. In addition, it also provides a new way of thinking and direction for clinical treatment of VSWM-related diseases.

Participants in different RCTs have different initial cognitive levels, which could be a vital factor affecting the findings. For example, participants with high initial VSWM level may be less affected by short-term exercise intervention and cannot significantly improve their VSWM level, which may lead to bias in results. Moreover, there may also be some objective and artificial differences in the operating procedures of each RCT, such as intervention characteristics, the instruction level and the physical activity practiced. In these included studies, some interventions were purely physical, while others were a combination of physical and cognitive activities. Meanwhile, the difference in the level of instruction from therapists may also lead to the participants receiving the physical activity intervention is not as effective as it should be. Overall, it is difficult to completely unify the results of all studies.

A logical next step for future trials would be to fill the gap in studies on adolescents and middle-aged adults; add studies on young adults, older adults, and men; and report detailed exercise intervention programs, including but not limited to the type of exercise, site and equipment if required, intervention period, intervention frequency, intervention duration, and intervention intensity (reporting criteria for intensity, such as heart rate, subjective feeling, and other ways in which practitioners can timely judge intensity during or after exercise). Second, the improvement effect of ball games on VSWM can also be explored, especially ball games that require quick judgment and decision-making. We have already identified 28 studies; however, the total number of participants enrolled so far ($N = 1{,}564$) is too small for us to be confident that the treatment is effective. Moreover, about 80% of participants are women. Third, future studies may consider increasing follow-up after intervention, or even strengthening relevant longitudinal studies, to investigate reliable intervention effects in longer time dimensions. This is because it remains unclear how long these changes persist and to what extent they can be preserved with or without continuation of training. Fourth, the quality of RCTs should be improved, and the type of blinding method (i.e., participants blinding, therapist blinding, and assessor blinding) should be appropriately increased to reduce possible bias. More importantly, future research should focus on more specific objectives. Very few studies exist on specific VSWM, and most studies synchronize the measurement and analysis of VSWM with WM, which may lead to bias and ambiguity in the results.

4.2. Limitations

Although this meta-analysis used a reasonable and comprehensive analysis method, there are some unavoidable limitations.

1. This meta-analysis investigated the effects of exercise interventions on VSWM capacity. However, because of the few RCTs that have studied VSWM alone and as WM includes VSWM and phonologic WM, the review panel members decided to include WM-related studies and excluded phonologic WM measures after consultation.
2. Different measurement tools may result in various improvements. In the same intervention study, the effect size and significance of the differences could vary greatly if different measures were used (Gentile et al., 2020). This suggests that researchers should be careful in selecting more accurate measurement tools, especially in the measurement of different types of cognitive performance.
3. In the regression analysis model, only two types of exercise classification criteria were included: high-and low-cognitive, and acute and chronic exercise. However, this does not mean that other types of exercise do not have exercise-induced cognitive benefits. Future research should try to combine multiple exercise programs with high exercise-induced cognitive benefits, determine their commonalities, and identify more beneficial types of exercise programs for cognitive improvement.
4. There was a disproportional distribution of studies regarding participants' age; therefore, we obtained only a few effect sizes for the populations of children, young adults, and seniors. Therefore, the absence of a relationship between age and the summary effect should be interpreted with caution.
5. Regarding participant characteristics, we limited moderator analysis only to age, as this variable was reported in all studies. The sex variable was not reported in one study; therefore, it could not be analyzed as a moderator variable. To derive more personalized exercise recommendations, the influence of other characteristics, such as socioeconomic status and body mass index, needs to be investigated as soon as more studies are available.

5. Conclusion

Our meta-regression analysis supports only small to moderate improvements in VSWM of children and seniors after long-term exercise and informs healthy practitioners about ways in which this benefit can be maximized. This meta-analysis confirmed a significant positive impact of physical activity on VSWM in healthy children and seniors; the lack of sufficient statistical power may have accounted for the limited effect observed in young adults. Combining the results of this meta-analysis, prescription of programs involving high-level cognitive engagement, low and moderate exercise intensity, chronic exercise, exercise for >30 min per session, and exercise for more than 3 months is recommended for children and seniors. Practitioners should choose exercise programs based on cost-effective and safety considerations and physical and social accessibility of physical activity sites. Factors such as physical state and weather should also be assessed in advance.

Based on our findings, an ideal exercise program should be recommended for the populations validated as effective in this meta-analysis and systematic review. Improvements in VSWM through physical activity interventions were more significant in healthy children aged 4–11 years and healthy older adults aged 58–88 years than in other age groups. For both groups, we a relatively ideal exercise intervention program would be recommended: (1) low to moderate exercise intensity is suitable. There are two main methods to measure and adjust it, which are 40 to 75 percent of the maximum heart rate and 10 to13 on the Borg Rating of Perceived Exertion (RPE) scale (low intensity exercise is prescribed at 10–11, and moderate intensity at 12–13; Carrie, 2012); (2) three to four sessions per week. More often is not better. It should depend on the state of bodily function; (3) exercise for over 30 min per session; (4) chronic exercise is even better, and exercise regularly for at least more than 3 months; (5) the ideal types of exercise include aerobic exercise (i.e., jogging, brisk walking and aerobics), coordination exercise (i.e., calisthenics, table tennis and badminton) and resistance exercise (i.e., half squat in place, heel in place and kneel push-ups), and team sports are more significant; (6) using motor-cognitive dual-task training could increase the level of cognitive engagement (Norouzi et al., 2019). Incorporate cognitive tasks into exercise routine, such as mental arithmetic, memorizing graphs, and reciting phone numbers backwards. Overall, although this is a universal program, individuals can adjust their exercise plans within this safe range for specific circumstances.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

QZ and YZ: topic, and theoretical basis. QZ, JD, and DL: methodology. QZ, JD, CX, DL, and MY: collecting and sorting out study data. JD and DL: data analysis. QZ and JD: validation. QZ: writing section Introduction, Method, Discussion, and Conclusion. JD: writing section Results. QZ, YZ, and LG: Revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Baddeley, A. D. (2001). Is working memory still working? *Eur. Psychol.* 7, 85–97. doi: 10.1027/1016-9040.7.2.85

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839. doi: 10.1038/nrn1201

Baddeley, A. D., and Hitch, G. (1974). "Working memory" in *Recent Advances in Learning and Motivation*. ed. G. A. Bower, vol. *8* (New York: Academic Press), 47–89.

Benzing, V., Chang, Y. K., and Schmidt, M. (2018). Acute physical activity enhances executive functions in children with ADHD. *Sci. Rep.* 8:12382. doi: 10.1038/s41598-018-30067-8

Blain, B., Schmit, C., Aubry, A., Hausswirth, C., Le Meur, Y., and Pessiglione, M. (2019). Neuro-computational impact of physical training overload on economic decision-making. *Curr. Biol.* 29, 3289–3297.e4. doi: 10.1016/j.cub.2019.08.054

Bo, J., Borza, V., and Seidler, R. D. (2009). Age-related declines in visuospatial working memory correlate with deficits in explicit motor sequence learning. *J. Neurophysiol.* 102, 2744–2754. doi: 10.1152/jn.00393.2009

Brondino, N., Rocchetti, M., Fusar-Poli, L., Codrons, E., Correale, L., Vandoni, M., et al. (2017). A systematic review of cognitive effects of exercise in depression. *Acta Psychiatr. Scand.* 135, 285–295. doi: 10.1111/acps.12690

Brown, A. K., Liu-Ambrose, T., Tate, R., and Lord, S. R. (2009). The effect of group-based exercise on cognitive performance and mood in seniors residing in intermediate care and self-care retirement facilities: a randomised controlled trial. *Br. J. Sports Med.* 43, 608–614. doi: 10.1136/bjsm.2008.049882

Bustamante, E. E., Davis, C. L., Frazier, S. L., Rusch, D., Fogg, L. F., Atkins, M. S., et al. (2016). Randomized controlled trial of exercise for ADHD and disruptive behavior disorders. *Med. Sci. Sports Exerc.* 48, 1397–1407. doi: 10.1249/MSS.0000000000000891

Carrie, R. (2012). Rating of perceived exertion (RPE). *J. Physiother.* 58:62. doi: 10.1016/S1836-9553(12)70078-4

Cheng, S. T., Chow, P. K., Song, Y. Q., Yu, E. C. S., Chan, A. C. M., Lee, T. M. C., et al. (2014). Mental and physical activities delay cognitive decline in older persons with dementia. *Am. J. Geriatr. Psychiatry* 22, 63–74. doi: 10.1016/j.jagp.2013.01.060

Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., and Elkins, M. (2003). Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys. Ther.* 83, 713–721. doi: 10.1093/ptj/83.8.713

Dziemian, S., Appenzeller, S., von Bastian, C. C., Jäncke, L., and Langer, N. (2021). Working memory training effects on white matter integrity in young and older adults. *Front. Hum. Neurosci.* 15:605213. doi: 10.3389/fnhum.2021.605213

Elkana, O., Krueger Bustanai, N. Y., Louzia-Timen, R., Kodesh, E., Franco, M., and Doniger, G. M. (2018). Conscientiousness is associated with improvement in visuospatial working memory and mood following acute physical exercise: a randomized controlled trial. *Pers. Individ. Differ.* 132, 126–132. doi: 10.1016/j.paid.2018.05.018

Erickson, K. I., Raji, C. A., Lopez, O. L., Becker, J. T., Rosano, C., Newman, A. B., et al. (2010). Physical activity predicts gray matter volume in late adulthood: the cardiovascular health study. *Neurology* 75, 1415–1422. doi: 10.1212/wnl.0b013e3181f88359

Erickson, K. I., Weinstein, A. M., Sutton, B. P., Prakash, R. S., Voss, M. W., Chaddock, L., et al. (2012). Beyond vascularization: aerobic fitness is associated with *N*-acetylaspartate and working memory. *Brain Behav.* 2, 32–41. doi: 10.1002/brb3.30

Fabre, K., Chamari, P., Mucci, J., Masse-Biron, J., and Prefaut, C. (2002). Improvement of cognitive function by mental and/or individualized aerobic training in healthy elderly subjects. *Int. J. Sports Med.* 23, 415–421. doi: 10.1055/s-2002-33735

Feder, K. P., and Majnemer, A. (2007). Handwriting development, competency, and intervention. *Dev. Med. Child Neurol.* 49, 312–317. doi: 10.1111/j.1469-8749.2007.00312.x

Feder, K. P., Majnemer, A., Bourbonnais, D., Platt, R., Blayney, M., and Synnes, A. (2005). Handwriting performance in preterm children compared with term peers at age 6 to 7 years. *Dev. Med. Child Neurol.* 47, 163–170. doi: 10.1017/S0012162205000307

Ferretti, G., Mazzotti, S., and Brizzolara, D. (2008). Visual scanning and reading ability in normal and dyslexic children. *Behav. Neurol.* 19, 87–92. doi: 10.1155/2008/564561

Fields, R. D. (2015). A new mechanism of nervous system plasticity: activity-dependent myelination. *Nat. Rev. Neurosci.* 16, 756–767. doi: 10.1038/nrn4023

Fletcher-Flinn, C. M., and Thompson, G. B. (2007). Dissociation between deficits in explicit procedures and implicit processes in the visual-spatial and the phonological systems during reading acquisition. *Cogn. Neuropsychol.* 24, 471–484. doi: 10.1080/02643290701423689

Formenti, D., Trecroci, A., Duca, M., Cavaggioni, L., D'Angelo, F., Passi, A., et al. (2021). Differences in inhibitory control and motor fitness in children practicing open and closed skill sports. *Sci. Rep.* 11:4033. doi: 10.1038/s41598-021-82698-z

Fujii, K., Yoshihara, Y., Matsumoto, Y., Tose, K., Takeuchi, H., Isobe, M., et al. (2020). Cognition and interpersonal coordination of patients with schizophrenia who have sports habits. *PLoS One* 15:e0241863. doi: 10.1371/journal.pone.0241863

Furst, A. J., and Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Mem. Cogn.* 28, 774–782. doi: 10.3758/bf03198412

Garcia, P. C., Real, C., and Britto, L. (2017). The impact of short and long-term exercise on the expression of arc and AMPARs during evolution of the 6-Hydroxy-dopamine animal model of Parkinson's disease. *J. Mol. Neurosci.* 61, 542–552. doi: 10.1007/s12031-017-0896-y

Gentile, A., Boca, S., Şahin, F. N., Güler, Ö., Pajaujiene, S., Indriuniene, V., et al. (2020). The effect of an enriched sport program on children's executive functions: the ESA program. *Front. Psychol.* 11:657. doi: 10.3389/fpsyg.2020.00657

Greer, T. L., Grannemann, B. D., Chansard, M., Karim, A. I., and Trivedi, M. H. (2015). Dose-dependent changes in cognitive function with exercise augmentation for major depression: results from the TREAD study. *Eur. Neuropsychopharmacol.* 25, 248–256. doi: 10.1016/j.euroneuro.2014.10.001

Guo, W., Wang, B., Lu, Y., Zhu, Q., Shi, Z., and Ren, J. (2016). The relationship between different exercise modes and visuospatial working memory in older adults: a cross-sectional study. *PeerJ* 4:e2254. doi: 10.7717/peerj.2254

Hariprasad, V. R., Koparde, V., Sivakumar, P. T., Varambally, S., Thirthalli, J., Varghese, M., et al. (2013). Randomized clinical trial of yoga-based intervention in residents from elderly homes: effects on cognitive function. *Indian J. Psychiatry* 55, S357–S363. doi: 10.4103/0019-5545.116308

Hong, S. G., Kim, J. H., and Jun, T. W. (2018). Effects of 12-week resistance exercise on electroencephalogram patterns and cognitive function in the elderly with mild cognitive impairment: a randomized controlled trial. *Clin. J. Sport Med.* 28, 500–508. doi: 10.1097/JSM.0000000000000476

Jost, K., Bryck, R. L., Vogel, E. K., and Mayr, U. (2011). Are old adults just like low working memory young adults? Filtering efficiency and age differences in visual working memory. *Cereb. Cortex* 21, 1147–1154. doi: 10.1093/cercor/bhq185

Kalbe, E., Roheger, M., Paluszak, K., Meyer, J., Becker, J., Fink, G. R., et al. (2018). Effects of a cognitive training with and without additional physical activity in healthy older adults: a follow-up 1 year after a randomized controlled trial. *Front. Aging Neurosci.* 10:407. doi: 10.3389/fnagi.2018.00407

Kofler, M. J., Harmon, S. L., Aduen, P. A., Day, T. N., Austin, K. E., Spiegel, J. A., et al. (2018). Neurocognitive and behavioral predictors of social problems in ADHD: a Bayesian framework. *Neuropsychol* 32, 344–355. doi: 10.1037/neu0000416

Kramer, A. F., Hahn, S., McAuley, E., Cohen, N. J., Banich, M. T., Harrison, C., et al. (2002). "Exercise, aging and cognition: healthy body, healthy mind" in *Human Factors Interventions for the Health Care of Older Adults*. eds. W. A. Rogers and A. D. Fisk (Hillsdale, NJ: Lawrence Erlbaum Associates Publishers), 91–120.

Krogsrud, S. K., Fjell, A. M., Tamnes, C. K., Grydeland, H., Due-Tønnessen, P., Bjørnerud, A., et al. (2018). Development of white matter microstructure in relation to verbal and visuospatial working memory—a longitudinal study. *PLoS One* 13:e0195540. doi: 10.1371/journal.pone.0195540

Kupis, L., Goodman, Z. T., Kornfeld, S., Hoang, S., Romero, C., Dirks, B., et al. (2021). Brain dynamics underlying cognitive flexibility across the lifespan. *Cereb. Cortex* 31, 5263–5274. doi: 10.1093/cercor/bhab156

Law, L. L. F., Barnett, F., Yau, M. K., and Gray, M. A. (2013). Development and initial testing of functional task exercise on older adults with cognitive impairment at risk of Alzheimer's disease – FcTSim Programme – a feasibility study. *Occup. Ther. Int.* 20, 185–197. doi: 10.1002/oti.1355

Leisman, G., Moustafa, A. A., and Shafir, T. (2016). Thinking, walking, talking: integratory motor and cognitive brain function. *Front. Public Health* 4:94. doi: 10.3389/fpubh.2016.00094

Leung, N. T. Y., Tam, H. M. K., Chu, L. W., Kwok, T. C. Y., Chan, F., Lam, L. C. W., et al. (2015). Neural plastic effects of cognitive training on aging brain. *Neural Plast.* 2015, 1–9. doi: 10.1155/2015/535618

Li, S. (2016). *The Effect of Baduanjin on Global Cognitive Function and Memory in Old Patient with Mild Cognitive Impairment*. Fujian: Fujian University of Traditional Chinese Medicine.

Li, S. (2019). *Study on the Intervention Effect of Health Qigong Wuqinxi on the Cognitive Function of the Elderly*. Shanghai: Shanghai University of Sport.

Li, L., Cui, J., Xiang, Q., and Fu, H. (2020). Impact of 8-week exercise of different types on executive function of female college students. *Chin J. Sports Med.* 39, 810–816. doi: 10.16038/j.1000-6710.2020.10.010

Liao, Y. Y., Liu, M. N., Wang, H. C., Walsh, V., and Lau, C. I. (2021). Combining transcranial direct current stimulation with tai chi to improve dual-task gait performance in older adults with mild cognitive impairment: a randomized controlled trial. *Front. Aging Neurosci.* 13:766649. doi: 10.3389/fnagi.2021.766649

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., et al. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ* 339:b2700. doi: 10.1136/bmj.b2700

Lindheimer, J. B., O'Connor, P. J., McCully, K. K., and Dishman, R. K. (2017). The effect of light-intensity cycling on mood and working memory in response to a randomized, placebo-controlled design. *Psychosom. Med.* 79, 243–253. doi: 10.1097/PSY.0000000000000381

Liu, S., Yu, Q., Li, Z., Cunha, P. M., Zhang, Y., Kong, Z., et al. (2020). Effects of acute and chronic exercises on executive function in children and adolescents: a systemic review and meta-analysis. *Front. Psychol.* 11:3482. doi: 10.3389/fpsyg.2020.554915

Loprinzi, P., Rigdon, B., Javadi, A.-H., and Kelemen, W. L. (2022). Effects of acute exercise intensity on source episodic memory and metamemory accuracy. *Q. J. Exp. Psychol.* 75, 2232–2243. doi: 10.1177/17470218211069856

Loprinzi, P., Roig, M., Etnier, J., Tomporowski, P., and Voss, M. (2021). Acute and chronic exercise effects on human memory: what we know and where to go from here. *J. Clin. Med.* 10:4812. doi: 10.3390/jcm10214812

Ludyga, S., Gerber, M., and Kamijo, K. (2022). Exercise types and working memory components during development. *Trends Cogn. Sci.* 26, 191–203. doi: 10.1016/j.tics.2021.12.004

Ludyga, S., Gerber, M., Pühse, U., Looser, V. N., and Kamijo, K. (2020). Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in healthy individuals. *Nat. Hum. Behav.* 4, 603–612. doi: 10.1038/s41562-020-0851-8

Maliszewska-Cyna, E., Lynch, M., Oore, J. J., Nagy, P. M., and Aubert, I. (2017). The benefits of exercise and metabolic interventions for the prevention and early treatment of Alzheimer's disease. *Curr. Alzheimer Res.* 14, 47–60. doi: 10.2174/156720501366616 0819125400

McMorris, T., Sproule, J., Turner, A., and Hale, B. J. (2011). Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: a meta-analytical comparison of effects. *Physiol. Behav.* 102, 421–428. doi: 10.1016/j.physbeh.2010.12.007

Mesulam, M. M. (2000). *Principles of Behavioural and Cognitive Neurology*. London: Oxford University Press.

Moreau, D., Kirk, I. J., and Waldie, K. E. (2017). High-intensity training enhances executive function in children in a randomized, placebo-controlled trial. *eLife* 6:e25062. doi: 10.7554/eLife.25062.001

Mueller, S. C., Shechner, T., Rosen, D., Nelson, E. E., Pine, D. S., and Ernst, M. (2015). Incidental threat during visuospatial working memory in adolescent anxiety: an emotional memory-guided saccade task. *Depress. Anxiety* 32, 289–295. doi: 10.1002/da.22350

Nishiguchi, S., Yamada, M., Tanigawa, T., Sekiyama, K., Kawagoe, T., Suzuki, M., et al. (2015). A 12-week physical and cognitive exercise program can improve cognitive function and neural efficiency in community-dwelling older adults: a randomized controlled trial. *J. Am. Geriatr. Soc.* 63, 1355–1363. doi: 10.1111/jgs.13481

Norouzi, E., Vaezmosavi, M., Gerber, M., Pühse, U., and Brand, S. (2019). Dual-task training on cognition and resistance training improved both balance and working memory in older people. *Phys. Sports Med.* 47, 471–478. doi: 10.1080/00913847.2019.1623996

Nouchi, R., Taki, Y., Takeuchi, H., Sekiguchi, A., Hashizume, H., Nozawa, T., et al. (2014). Four weeks of combination exercise training improved executive functions, episodic memory, and processing speed in healthy elderly people: evidence from a randomized controlled trial. *Age* 36, 787–799. doi: 10.1007/s11357-013-9588-x

Peng, Y., and Zhou, C. (2016). The time course effect of acute aerobic exercise on working memory of female undergraduates. *Chin J. Sports Med.* 35, 473–477+480. doi: 10.16038/j.1000-6710.2016.05.011

Pham, A. V., and Hasson, R. M. (2014). Verbal and visuospatial working memory as predictors of children's reading ability. *Arch. Clin. Neuropsychol.* 29, 467–477. doi: 10.1093/arclin/acu024

Rasmussen, C., and Bisanz, J. (2005). Representation and working memory in early arithmetic. *J. Exp. Child Psychol.* 91, 137–157. doi: 10.1016/j.jecp.2005.01.004

Rathore, A., and Lom, B. (2017). The effects of chronic and acute physical activity on working memory performance in healthy participants: a systematic review with meta-analysis of randomized controlled trials. *Syst. Rev.* 6, 124–116. doi: 10.1186/s13643-017-0514-7

Sable, H. J., MacDonnchadh, J. J., Lee, H. W., Butawan, M., Simpson, R. N., Krueger, K. M., et al. (2021). Working memory and hippocampal expression of BDNF, ARC, and P-STAT3 in rats: effects of diet and exercise. *Nutr. Neurosci.* 25, 1609–1622. doi: 10.1080/1028415X.2021.1885230

Schmit, C., and Brisswalter, J. (2020). Executive functioning during prolonged exercise: a fatigue-based neurocognitive perspective. *Int. Rev. Sport Exerc. Psychol.* 13, 21–39. doi: 10.1080/1750984X.2018.1483527

Serra, L., Raimondi, S., Di Domenico, C., Maffei, S., Lardone, A., Liparoti, M., et al. (2021). The beneficial effects of physical exercise on visuospatial working memory in preadolescent children. *AIMS Neurosci.* 8, 496–509. doi: 10.3934/Neuroscience.2021026

Sinaei, M., Alaei, H., Nazem, F., Kargarfard, M., Feizi, A., Talebi, A., et al. (2021). Endurance exercise improves avoidance learning and spatial memory, through changes in genes of GABA and relaxin-3, in rats. *Biochem. Biophys. Res. Commun.* 566, 204–210. doi: 10.1016/j.bbrc.2021.05.080

Smith, J. C., Nielson, K. A., Woodard, J. L., Seidenberg, M., Durgerian, S., Antuono, P., et al. (2011). Interactive effects of physical activity and APOE-ε4 on BOLD semantic memory activation in healthy elders. *NeuroImage* 54, 635–644. doi: 10.1016/j.neuroimage.2010.07.070

St Clair-Thompson, H. L., and Gathercole, S. E. (2006). Executive functions and achievements in school: shifting, updating, inhibition, and working memory. *Q. J. Exp. Psychol.* 59, 745–759. doi: 10.1080/17470210500162854

Tottori, N., Morita, N., Ueta, K., and Fujita, S. (2019). Effects of high intensity interval training on executive function in children aged 8–12 years. *Int. J. Environ. Res. Public Health* 16:4127. doi: 10.3390/ijerph16214127

Tsai, C. L., Chang, Y. K., Chen, F. C., Hung, T. M., Pan, C. Y., and Wang, C. H. (2014). Effects of cardiorespiratory fitness enhancement on deficits in visuospatial working memory in children with developmental coordination disorder: a cognitive electrophysiological study. *Arch. Clin. Neuropsychol.* 29, 173–185. doi: 10.1093/arclin/act081

Tsai, C. L., Sun, H. S., Kuo, Y. M., and Pai, M. C. (2019). The role of physical fitness in cognitive-related biomarkers in persons at genetic risk of familial Alzheimer's disease. *J. Clin. Med.* 8:1639. doi: 10.3390/jcm8101639

Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R., and Hennessey, J. M. (1998). Creative discovery in imagery and perception: combining is relatively easy, restructuring takes a sketch. *Acta Psychol.* 99, 177–200. doi: 10.1016/S0001-6918(98)00010-9

Wei, G.-X., Yang, L., Imm, K., Loprinzi, P. D., Smith, L., Zhang, X., et al. (2020). Effects of mind–body exercises on schizophrenia: a systematic review with meta-analysis. *Front. Psych.* 11:819. doi: 10.3389/fpsyt.2020.00819

Wilke, J. (2020). Functional high-intensity exercise is more effective in acutely increasing working memory than aerobic walking: an exploratory randomized controlled trial. *Sci. Rep.* 10:12235. doi: 10.1038/s41598-020-69139-z

Wu, W. (2021). *Study on the Effect of Happy Gymnastics on Executive Function of 4–5-Year-Old Children-Taking Shanghai Yangpu No. 2 Art Kindergarten as an Example* Shanghai: Shanghai University of Sport.

Xi, G., Hui, J., Zhang, Z., Liu, S., Zhang, X., Teng, G., et al. (2011). Learning and memory alterations are associated with hippocampal N-acetylaspartate in a rat model of depression as measured by 1h-mrs. *PLoS One* 6:e28686. doi: 10.1371/journal.pone.0028686

Xiong, J., Ye, M., Wang, L., and Zheng, G. (2021). Effects of physical exercise on executive function in cognitively healthy older adults: a systematic review and meta-analysis of randomized controlled trials: physical exercise for executive function. *Int. J. Nurs. Stud.* 114:103810. doi: 10.1016/j.ijnurstu.2020.103810

Yang, Z., Mei, J., Chen, S., Pan, Y., Yuan, X., He, H., et al. (2019). Effect of tai chi and Square dance exercise on working memory of female elderly: an ERP study. *J. Tianjin Univ. Sport* 34, 86–92. doi: 10.13297/j.cnki.issn1005-0000.2019.01.013

Zhang, B. (2021). *Rhythmic Aerobics Has an Effect on the Movement Coordination, Working Memory and the Sixth-Grade Pupils of a School.* Beijing: Capital Institute of Physical Education

Zhang, H. (2021). *Study on the Effect of Exercise Intervention on Working Memory and BDNF in College Students.* Jiangsu: Yangzhou University.

Zhu, H., Chen, A., Guo, W., Zhu, F., and Wang, B. (2020). Which type of exercise is more beneficial for cognitive function? A meta-analysis of the effects of open-skill exercise versus closed-skill exercise among children, adults, and elderly populations. *Appl. Sci.* 10:2737. doi: 10.3390/APP10082737

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The spectral profile of cortical activation during a visuospatial mental rotation task and its correlation with working memory

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Introduction: The search for a cortical signature of intelligent behavior has been a longtime motivation in Neuroscience. One noticeable characteristic of intelligence is its association with visuospatial skills. This has led to a steady focus on the functional and structural characteristics of the frontoparietal network (FPN) of areas involved with higher cognition and spatial behavior in humans, including the question of whether intelligence is correlated with larger or smaller activity in this important cortical circuit. This question has broad significance, including speculations about the evolution of human cognition. One way to indirectly measure cortical activity with millisecond precision is to evaluate the event-related spectral perturbation (ERSP) of alpha power (alpha ERSP) during cognitive tasks. Mental rotation, or the ability to transform a mental representation of an object to accurately predict how the object would look from a different angle, is an important feature of everyday activities and has been shown in previous work by our group to be positively correlated with intelligence. In the present work, we evaluate whether alpha ERSP recorded over the parietal, frontal, temporal, and occipital regions of adolescents performing easy and difficult trials of the Shepard–Metzler's mental rotation task, correlates or are predicted by intelligence measures of the Weschler's intelligence scale.

Methods: We used a database obtained from a previous study of intellectually gifted (N = 15) and average intelligence (N = 15) adolescents.

Results: Our findings suggest that in challenging task conditions, there is a notable difference in the prominence of alpha event-related spectral perturbation (ERSP) activity between various cortical regions. Specifically, we found that alpha ERSP in the parietal region was less prominent relative to those in the frontal, temporal and occipital regions. Working memory scores predict alpha ERSP values in the frontal and parietal regions. In the frontal cortex, alpha ERSP of difficult trials was negatively correlated with working memory scores.

Discussion: Thus, our results suggest that even though the FPN is task-relevant during mental rotation tasks, only the frontal alpha ERSP is correlated with working memory score in mental rotation tasks.

KEYWORDS

intelligence, alpha rhythm, mental rotation, working memory, EEG

1. Introduction

The concept of intelligence is a timeless and fundamental aspect of human cognition, predating recorded history. It originated from observations of individuals attempting to solve practical, everyday problems (Hambrick et al., 2019). A key factor in successful problem-solving is the ability to create a spatial representation of the environment (National Research Council, 2006). In humans, there is a clear evolutionary connection between complex cognition and visual spatial abilities. These abilities are essential not only for navigation and route planning, but also for organizing the surrounding space. A recent study (Kedar et al., 2022) has demonstrated that early human groups were able to strategically position their hearths within paleolithic caves to avoid smoke suffocation. This further emphasizes the critical role of spatial intelligence in human survival and success.

The robust association between visuospatial skills and intelligence has many examples in the careers of notable physicists, mathematicians, inventors, and other professions of the science, technology, engineering, and mathematics (STEM) areas (National Research Council, 2006). In the educational context, several studies have shown that spatial ability not only correlates significantly with students' interest and performance in STEM disciplines, even above mathematical and language skills, but also influences their future occupational choices (Stieff and Uttal, 2015). More interestingly, researchers have shown that spatial ability is a teachable ability (Stieff and Uttal, 2015) and enhanced spatial skills can help improve grades and retention rates of STEM students (Veurink and Sorby, 2019).

Among visuospatial reasoning abilities, mental rotation is a pervasive and regular feature of everyday activities (e.g., driving, reading maps, filling the dishwasher, building Lego sets), while also being particularly important for STEM activities (Wai et al., 2009; Sisman et al., 2021). Mental rotation is the ability to transform a mental representation of an object to accurately predict how the object would look from a different angle (Shepard and Metzler, 1971). The pioneer studies by Shepard and Metzler (1971) showed that response time for parity judgment of same figures in their classic mental rotation task increased with increasing angular disparity, a linear function often referred to as the angular disparity effect.

Performance on the Shepard-Metzler's mental rotation task (SMT) involves flexibly switching between cognitive strategies, namely a motor simulation-based mental rotation strategy and a working memory-intensive analytic approach based on task difficulty (Gardony et al., 2017). Thus, when the angular difference between the two figures in the test is large (i.e., the task is more difficult), the subjects' strategy shifts from motor simulation to working memory (Gardony et al., 2017). This finding was validated by our previous results showing that subjects with high intelligence quotient (IQ) perform better than average-IQ subjects in the SMT when the disparity angle of the figures increases (Anomal et al., 2020). Moreover, since subjects rely more on cognitive and visuospatial than motor strategies during difficult trials, we would expect to see increased neural activity in frontal and parietal areas (Gardony et al., 2017). These regions form the frontal-parietal network, which is characterized by the integration of frontal areas associated with higher cognition and parietal areas subserving spatial cognition. The frontal-parietal network, according to the parieto-frontal integration theory (PFIT), provides the structural substrate for the interaction of decision-making top-down signals and visual-spatial bottom-up inputs necessary to solve spatial tasks, Jung and Haier (2007).

Electrical oscillatory activity is a prominent characteristic of human electroencephalographic (EEG) recordings and are believed to improve neural communication and information processing in cortical networks (Buzsáki and Draguhn, 2004). Alpha band oscillations (8–12 Hz) have been linked to various cognitive processes, including attention and the maintenance of information in working memory (Klimesch, 2012), among other cognitive processes. One seminal discovery in the history of alpha oscillations is the "Berger effect," named after its discoverer, which refers to the decrease in alpha amplitude due to neural desynchronization when the eyes are opened or cognitive demands increase (Doppelmayr et al., 2005). This phenomenon (the suppression of alpha oscillations by incoming visual information) has supported the idea that alpha oscillations are a passive cortical phenomenon, meaning that they are simply a byproduct of other neural processes and do not play an active role in information processing or other cognitive functions (Pfurtscheller et al., 1996; Pfurtscheller and Lopes da Silva, 1999). Another domain-general process associated with alpha desynchronization is "gating by inhibition" (Jensen and Mazaheri, 2010) or the conception that alpha oscillations control or reduce brain activity in specific regions, thus permitting the selective filtering of information. When alpha oscillations are suppressed in response to a task or stimulus, this release of control allows for a heightened level of activity and information processing to occur in other parts of the brain (Wang et al., 2019). A recent study demonstrated that alpha oscillations monitor memory storage in a content-specific manner, not just by keeping track of the number of items but also their level of complexity (Chen et al., 2022).

Energetic trade-offs play an important role in brain size evolution (Isler, 2013). As brains get larger, neural networks are topologically optimized for energy efficiency since longer axon pathways are comparatively less energy-efficient (wiring costs) (Avena-Koenigsberger et al., 2018). The Cortical Neural Efficiency Hypothesis (NEH) of cognitive and motor control proposes that the metabolic profile of brain function adapts to behavioral demands through a cost-efficient process (Nakata et al., 2010; Dunst et al., 2014). Studies that support the Cortical Neural Efficiency Hypothesis (NEH) often use neuroimaging techniques such as Positron Emission Tomography (PET), Single-Photon Emission Computed Tomography (SPECT), Functional Magnetic Resonance Imaging (fMRI), and Electroencephalography (EEG) to examine the relationship between the allocation of metabolic resources in cortical regions and measures of intelligence quotient (IQ) or physical expertise. While some research supports the Cortical Neural Efficiency Hypothesis (NEH), linking intelligence quotient (IQ) and physical proficiency with more focused and lower (more efficient) brain activation (Haier et al., 1992, 2003; Rypma et al., 2002; Neubauer and Fink, 2009), other studies challenge the validity of this hypothesis. Some studies have found that the NEH is only applicable when the task difficulty is moderate to low (Doppelmayr et al., 2005), while others have found that during a visuospatial task with football scenes, football players showed greater parietal cortical activity than controls (Del Percio et al., 2019). These findings suggest that the relationship between cognitive or motor abilities and metabolic resource allocation in the brain is complex and may depend on various factors, such as task difficulty and domain-specific expertise.

In the present work, we used EEG to investigate the neural correlates of the association between cortical activation and visuospatial skills. We performed event-related spectral perturbation (ERSP) analyses (Makeig, 1993) and looked at changes in event-related desynchronization (ERD) of the EEG alpha band during performance of the visuospatial SMT by subjects belonging to two groups: adolescents with average IQ or in the very superior (gifted) range. ERD reflects a decrease in spectral power from baseline values and has been associated with cortical excitatory processes (Pfurtscheller and Lopes da Silva, 1999). Our hypothesis is that activation of the PFN but not of other areas will be correlated with IQ measures and behavioral data, such as accuracy and response time.

2. Materials and methods

2 1. Participants

All procedures were approved by the Ethics Committee of the Federal University of Rio Grande do Norte (UFRN; CAAE: 50197415.9.0000.5537). All participants or their legal guardians signed an informed consent for participating in the study. The participants had no diagnostic of neurological dysfunction and had no uncorrected visual impairments.

We used data from a database obtained from a previous study in our laboratory (see Anomal et al., 2020). Participants were assigned to either one of two experimental groups (control and gifted) according to scores obtained with the Wechsler's intelligence scales (WISC and WAIS). The total IQ score is composed of the following sub-scores: (1) verbal comprehension, (2) perceptual organization, (3) working memory, and (4) processing speed (Wechsler, 2003, 2008). Total IQ scores equal to and above 130 were considered "very superior," between 120 and 129 "superior," and between 80 and 119 "average" (Weiss, 2006). The gifted group (N = 15) was composed of adolescents (13–21 y.o.) with "very superior" total IQ scores. An age-matched control group (N = 15) had total IQ scores ranging from 80 to 128 (average and superior). Subjects in both groups were enrolled in the Gifted Program of the Digital Metropolis Institute of UFRN.[1] Participants were 19 male and 11 female, 24 right-handed and 6 left-handed, and the total IQ of the control group ranged from 94 to 121, and 129 to 143 in the gifted group.

2.2. Experimental design

Participants performed a classic SMT (Shepard and Metzler, 1971), while their electroencephalographic signals were simultaneously recorded (see details below). The stimuli were presented on an LCD computer monitor (1,920 × 1,080 pixels) located 1.0 m in front of the participant. The experimental session contained 160 trials organized randomly. The experimental design shown in **Figure 1** had the following sequence: (1) appearance of a fixation cross for 3 s, (2) display of stimulus for up to 30 s, and (3) inter-trial interval of 4 s (Neubauer et al., 2010; Anomal et al., 2020). When response times were longer than 30 s, the trial was halted and a new one was initiated by the software (PsychoPy, v1.90.d) (Peirce, 2007, 2009). The stimulus was composed of a pair of three-dimensional objects: the reference object on the left of the screen and the target located on the right (Ganis and Kievit, 2015; Anomal et al., 2020). Targets were rotated clockwise around the longitudinal axis in 50° increments from 0 to 150° (angle of disparity) and could be a mirror image of the reference image. In each trial, participants were asked to mentally rotate the target to determine whether they were the same or different (mirrored) from the reference. A total of 80 trials were presented for both conditions (same or different), with 20 trials for each angle disparity (0, 50, 100, and 150°).

Prior to the task, participants were briefed about the experiment's design and purpose *via* a slide presentation and were instructed: (1) to perform a mental rotation to solve the test, (2) to press either the right or the left button of the mouse for the same or different condition, respectively, (3) to respond as fast as possible, and (3) to avoid committing errors.

2.3. Electroencephalographic recording and processing

The EEG was continuously recorded during task performance with a 1,000 Hz sampling rate from 64 Ag/AgCl cap-mounted electrodes organized according to the international 10–20 system (BrainAmp system, Brain Products). Eye movements were recorded by electrodes EOGz, EOG1, and EOG2, positioned at the glabella, and lateral to the left and right eye, respectively. The EEG recordings took place in a darkened room, with sound attenuation and temperature control. The electrical impedance of electrodes was kept under 25 k Ohms, and the signals were referenced to the electrode FCz. EEG data were analyzed with the EEGLab toolbox (Delorme and Makeig, 2004) running in Matlab (Mathworks, Inc., Natick, MA, USA). Channels were re-referenced to the average

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[1] www.metropoledigital.ufrn.br

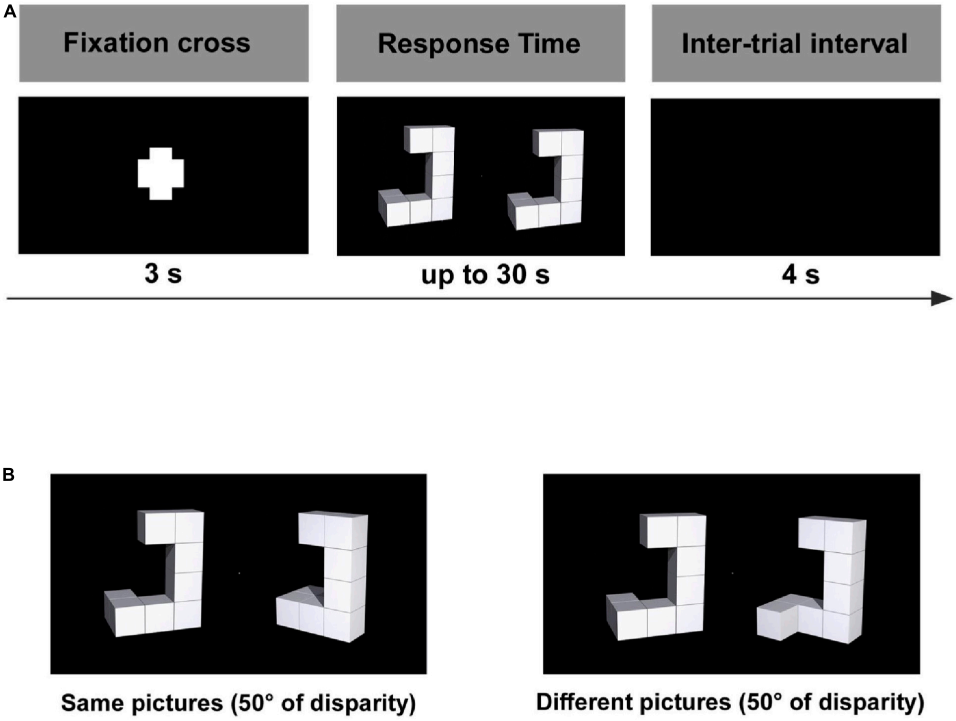

FIGURE 1
(A) Experimental design and **(B)** experimental conditions: same and different stimulus pairs (Anomal et al., 2020).

of all electrodes and band-pass filtered between 0.1 and 35 Hz. Ocular and muscular artifacts were removed through Independent Component Analysis. Electrodes with consistently poor signal quality were removed and reconstructed with interpolation using the PREP pipeline tool of the EEGLab toolbox.

The EEG was epoched to 500 ms before stimulus onset and 4,000 ms post-stimulus onset and submitted to a short-time Fourier Transform with a 250 ms Hanning window with frequency limits 0.5–40 Hz using the EEGLAB function "newtimef." The resulting signal was then divided, point by point, by the average power of the full epoch. Corrected epochs were averaged by stimulus angle and subjected to division, also point by point, by the mean potency at baseline (–500 to 0 ms) to obtain the ERSP. Data from error trials and those with a signal amplitude above 100 μV were excluded from the analysis. We included only participants who performed at least 120 trials (75% of total trials).

Stimulus-related alpha (8–12 Hz) activity changes were computed by ERSP methods, which provide a 2-D representation of the mean change in spectral power (in dB) from baseline synchronized with the stimulus (Makeig et al., 2004). Differences in ERSP were investigated during the time interval which comprised the intervals of the rotation-related negativity (mental rotation interval) for the same pictures (963–1183 ms) observed in our previous work (Anomal et al., 2020). We did not analyze "different" pictures, or mirrored trials, because in these trials participants are supposed to use different strategies than mental rotation to solve the task, such as image flip (Hamm et al., 2004a,b). To perform our ERSP analysis, we employed a temporal window that was defined based on the event-related potential (ERP) interval exhibiting a stronger linear trend between stimulus angles. Specifically, we determined the onset and offset of the linear voltage changes related to orientation by identifying the time interval that exceeded the negative peak of the grand-averaged linear event-related potentials (ERPs) by 20%, following the approach described by Milivojevic et al. (2009). To analyze the ERPs of individual subjects for each of the four stimulus orientations (0, 50, 100, and 150°), we multiplied the ERP values by linear weight constants (–3, –1, 1, 3, respectively). We then scaled the resulting values for each orientation by the square root of the sum of the squares of the weights, as per standard practice.

2.4. Statistical analysis

Individual performance during the mental rotation task was expressed by both accuracy and response time measures (see Anomal et al., 2020). Regions of interest (ROIs) were defined based on the following electrodes: frontal (F1, F2, F3, F4, F5, F6, F7, and F8), parietal (P1, P2, P3, P4, P5, P6, P7, P8), temporal (T7, T8, TP9, TP10, TP7, TP8), and occipital (O1 and O2). Alpha ERSP was evaluated within the 8–12 Hz band. We investigated the effects of group (control and gifted), angle of disparity (0 and 150°), and region (parietal, frontal, temporal, and occipital) on alpha ERSP during RRN intervals. To examine these effects, we conducted a three-way mixed ANOVA (2 × 2 × 4), treating group as a between-subject factor and angle of disparity and region as within-subject factors. We selected the trials with 0 and 150° angles of disparity as easy and difficult trials, respectively, to assess the impact of angle of disparity on alpha ERSP values.

We used stepwise multiple linear regression to determine which factors predicted alpha ERSP, response time, and accuracy. For the alpha ERSP analysis, we calculated separate equations for each ROI (frontal, parietal, temporal, and occipital) and stimulus orientation (0 and 150° of disparity), using total IQ, working memory, perceptual organization, processing speed, and verbal comprehension as independent variables. The resulting equations were as follows:

(1) alpha ERSP (frontal ROI/0° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(2) alpha ERSP (parietal ROI/0° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(3) alpha ERSP (temporal ROI/0° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(4) alpha ERSP (occipital ROI/0° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(5) alpha ERSP (frontal ROI/150° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(6) alpha ERSP (parietal ROI/150° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(7) alpha ERSP (temporal ROI/150° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u;

(8) alpha ERSP (occipital ROI/150° of disparity) = B0 + B1 (total IQ) + B2 (working memory) + B3 (perceptual organization) + B4 (processing speed) + B5 (verbal comprehension) + u.

To predict behavioral data, we created two equations using alpha ERSP from the four ROIs at 150° of disparity as independent variables and accuracy or response time as the dependent variable. The resulting equations were as follows:

(1) accuracy (150° of disparity) = B0 + B1 (alpha ERSP frontal) + B2 (alpha ERSP parietal) + B3 (alpha ERSP temporal) + B4 (alpha ERSP occipital) + u;

(2) response time (150° of disparity) = B0 + B1 (alpha ERSP frontal) + B2 (alpha ERSP parietal) + B3 (alpha ERSP temporal) + B4 (alpha ERSP occipital) + u.

In these equations, B0 represents the constant, and B1-B5 represent the coefficients of the independent variables, while u represents the standard error of the estimate.

We used Cook's distance (Cook's D) to identify outliers in the multiple linear regression and correlation analyses. ERSP values with a Cook's D larger than 0.13 (4/n, considering n total = 30) were removed from the analysis.

We used the Shapiro-Wilk normality test to evaluate whether the data followed a normal (Gaussian) distribution. We calculated the mean squared error (MSE) and effect size (partial eta-squared: partial $\eta 2$) for the ANOVAs. We used Sidak's Method as a multiple comparison *post-hoc* test. For the correlation analysis, we used Pearson's correlation coefficient or its non-parametric alternative, Spearman's rank coefficient. Data were presented as mean ± SEM (standard error of the mean), and the criterion for significance was set at 0.05 for ANOVA analysis. When multiple analyses were performed, p was adjusted according to Bonferroni correction (0.05/n, n = number of analyses).

3. Results

3.1. Topographic map and regional activation during the mental rotation interval

A three-way repeated measures ANOVA was conducted to assess the effects of group (control, gifted), region (frontal, temporal, parietal, occipital), and angle of disparity (0, 150°) on alpha event-related spectral perturbations (ERSP). The analysis revealed a significant main effect of region [F (1, 28) = 17.522, MSE = 207.780, $p < 0.001$, partial $\eta^2 = 0.385$], with the frontal region showing alpha ERSPs (–10.090 ± 2.232 µV) higher than in the parietal (–20.135 ± 2.061 µV; $p < 0.001$) and occipital regions (–17.716 ± 2.750 µV; $p = 0.005$), but not different from the temporal region (–10.676 ± 1.657 µV; $p = 0.998$). The alpha ERSP values recorded over the parietal ROI were lower than those recorded over the temporal ($p < 0.001$) and occipital ROIs ($p = 0.795$). In addition, there was a significant main effect of angle of disparity [F (1, 28) = 18.883, MSE = 207.780, $p < 0.001$, partial $\eta^2 = 0.403$], with 150° showing higher alpha ERSP (–10.630 ± 2.052 µV) than 0° (–18.678 ± 2.259 µV; $p < 0.001$). Finally, there was no statistically significant interaction of alpha ERSP with group, region, and angle of disparity [F (1, 28) = 0.844, MSE = 207.780, $p = 0.459$, partial $\eta^2 = 0.029$].

The topographic map of alpha ERSP for trials with 0 and 150° disparity did not indicate any significant differences between the control and gifted groups (**Figure 2**). However, for trials with 150° disparity, there was a noticeable trend toward more negative alpha ERSP values over the frontal regions of interest (ROIs) in gifted adolescents, compared to the control group (**Figure 2**).

3.2. Intelligence quotient and its sub-scores during the mental rotation interval (MRI)

After Bonferroni correction ($p < 0.006$, 0.05/8), multiple linear regression between alpha ERSP and intelligence scores for trials of 0° of disparity did not result in significant models for the frontal [F (1, 28) = 3.702, $p = 0.019$, $R^2 = 0.402$], parietal [F (1, 28) = 3.054, $p = 0.038$, $R^2 = 0.357$], temporal [F (1, 28) = 2.987, $p = 0.041$, $R^2 = 0.352$], and occipital ROIs [F (1, 28) = 4.969, $p = 0.016$, $R^2 = 0.293$].

Considering that the results of the multiple linear regression for trials of 0° of angle disparity were not statistically significant, we tested the correlation between alpha ERSP and intelligence scores in easy and difficult trials. There was a negative correlation between alpha ERSP values recorded over the occipital ROI and working memory scores in trials of 0° of disparity ($r = -0.533$; $p = 0.002$; Bonferroni corrected) (**Figure 3** and **Table 1**). For trials of 150° of disparity, alpha ERSP amplitude had a negative correlation

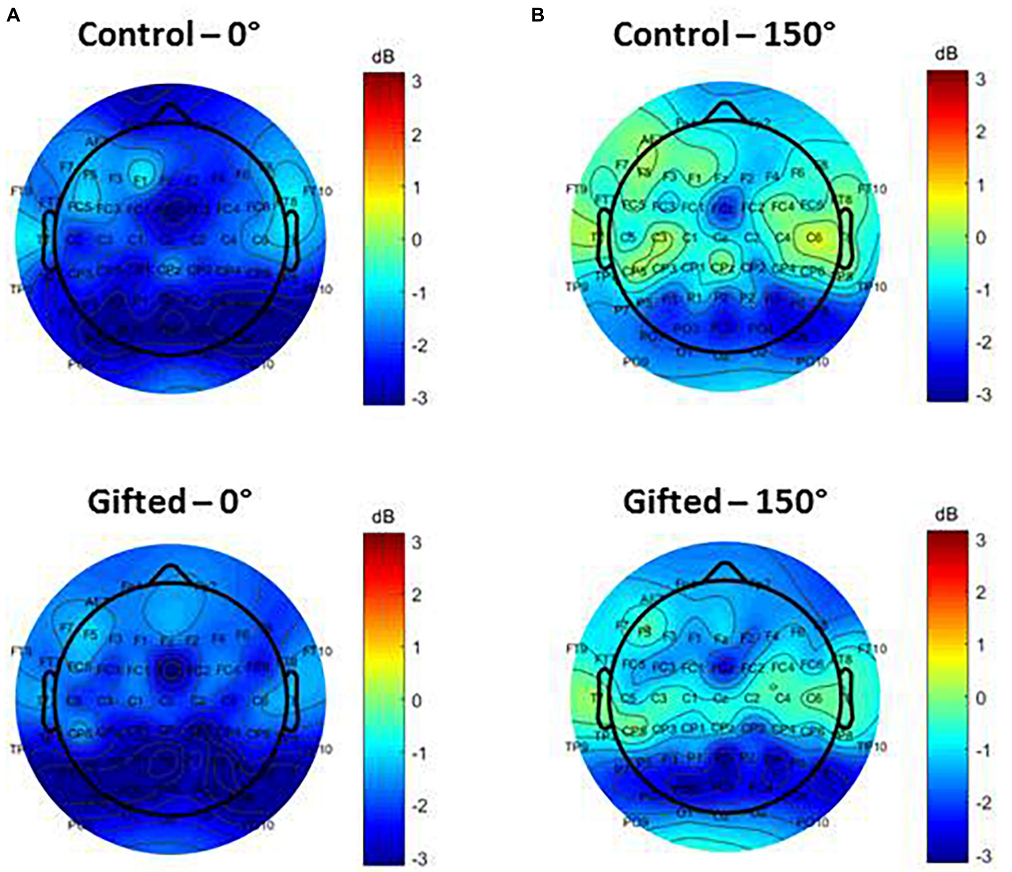

FIGURE 2
Electroencephalographic (EEG) scalp topography of alpha ERSP during the mental rotation interval (963–1183 ms). The maps are based on average alpha ERSP of the participants during trials with 0° **(A)** and 150° **(B)** of disparity between the template and target stimuli. Topographic maps of controls are on the top of the gifted group on the bottom. Values correspond to the mental rotation interval (defined by Anomal et al., 2020) and are color-coded according to ERSP's amplitude in μV.

with working memory scores in frontal ($r = -0.616$; $p < 0.001$) and occipital ($r = -0.504$; $p = 0.004$; Bonferroni corrected) ROIs (**Figures 3**, **4** and **Table 1**). No correlation was observed between the temporal ROI and intelligence scores for trials of 0 and 150° of disparity (**Figure 4** and **Table 1**).

3.3. Behavioral data during the mental rotation interval

We conducted multiple linear regression analyses to investigate the relationship between behavioral data (response time and accuracy, Anomal et al., 2020) and alpha ERSP values recorded over the parietal, frontal, temporal, and occipital ROIs during difficult trials of 150° of disparity (Bonferroni correction $p < 0.025$, 0.05/2). However, the results did not yield a statistically significant model for alpha ERSP and accuracy [F (1, 28) = 1.405, $p = 0.256$, $R^2 = 0.149$] or for alpha ERSP and response time [F (1, 28) = 1.364, $p = 0.280$, $R^2 = 0.206$]. Considering the above results and the mentioned correlation between alpha ERSP and working memory in trials of 150° of angle disparity, we verified if there was a correlation between behavioral data and alpha ERSP. **Table 2** shows that there were no significant correlations between alpha ERSP values and behavioral data during trials of 150° of disparity. While these results may seem counterintuitive, they suggest that alpha ERSPs may not be directly related to behavioral performance during difficult trials of the SMT.

4. Discussion

There has been a longtime quest for the biological underpinnings of human intelligence, including its genetic basis and whether there are any differences between the brains of intellectually gifted and neurotypical individuals. This pursuit received a good amount of public attention in the XX century after the publication of a series of postmortem studies of Albert Einstein's brain. Some findings from those studies included a higher ratio of glial to neuron cells and relatively enlarged parietal lobes (Diamond et al., 1985; Witelson et al., 1999). In a previous ERP study (Anomal et al., 2020), we showed that intellectually gifted adolescents not only outperform control subjects in a visuospatial task, but the profile of electrical activity in the brain of those two groups is also different, especially in the FPN. In the present work, we continue our search for the functional cortical substrates underlying superior intelligence and its relationship to

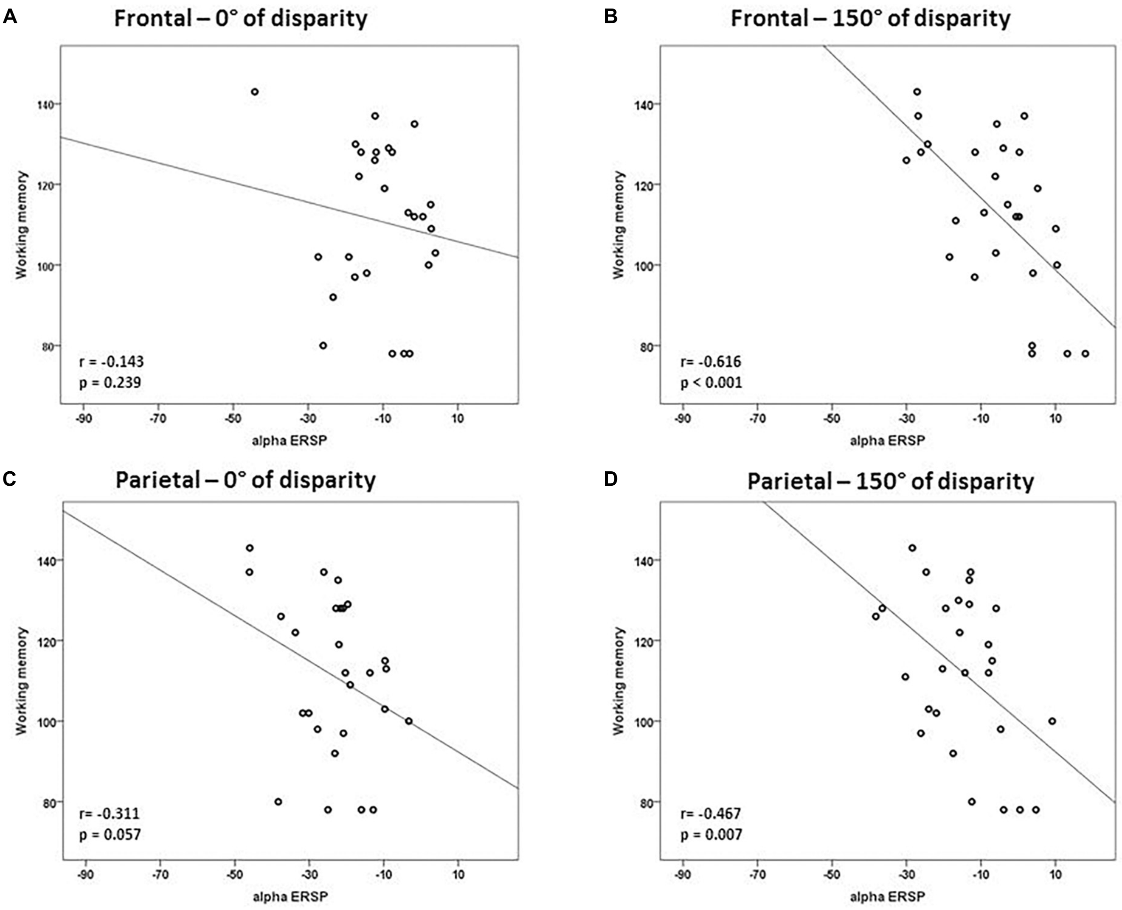

FIGURE 3
Correlations between intelligence scores and alpha event-related spectral perturbation (ERSP) in frontal and parietal regions of interest. There was a strong correlation between working memory scores and alpha ERSP values recorded over the frontal ROI during trials of 150° of disparity **(B)**. Correlations of easy trials of 0° of disparity are in panels **(A,C)**, and of difficult trials of 150° are in panels **(B,D)**. Values are in μV.

visuospatial cognition. During difficult trials, our findings suggest that working memory scores have a predictive effect on alpha ERSP amplitude in both the frontal and parietal regions. In addition, we observed a negative correlation between working memory scores and ERSPs specifically in the frontal region. Our study yielded intriguing results, indicating a negative correlation between alpha ERSP values and working memory scores in the occipital region, regardless of task difficulty. Additionally, we found that the parietal region demonstrated significantly greater activation compared to the frontal, temporal, and occipital cortices. Interestingly, the frontal region exhibited lower activation than the parietal and occipital regions.

Our study employed visuospatial skill as a proxy for intelligence measures, a methodology supported by the close relationship between visuospatial skill and intelligence measures. Research has shown that there is a positive correlation between visuospatial abilities and overall intelligence, and that people with higher IQ scores tend to perform better on tests of visuospatial skills. Additionally, visuospatial skills are thought to play a role in the development of other aspects of intelligence, such as mathematical and scientific reasoning.

We demonstrated that in the FPN network, the parietal region is more active than the frontal, temporal and occipital regions during the mental rotation interval, as indicated by ERSP following stimulus appearance. Thus, we suggest that alpha power is up-modulated during task performance in these regions involved in the processing of task-irrelevant or distracting information, as an attentional suppression mechanism (Foxe and Snyder, 2011; Fiebelkorn and Kastner, 2019).

4.1. Intelligence scores and alpha ERSP

There has been conflicting evidence regarding the relationship between alpha ERSP and intelligence scores. Early studies indicated that during the execution of cognitive tasks, intelligence scores correlate positively with alpha ERSP (Grabner et al., 2003, 2004). Subsequent findings suggested that the positive correlation between intelligence scores and alpha ERSP depended on several factors, such as sex, task type, and fluid vs. crystalized intelligence scores (Neubauer et al., 1995, 1999, 2002, 2004; Grabner et al., 2003, 2004; Neubauer and Fink, 2003). Our findings indicate that alpha ERSP in the frontal cortex is negatively correlated with working memory scores in difficult trials of the SMT. More recent studies have suggested that alpha ERSP correlates negatively with intelligence scores and task performance (Klimesch et al., 1993,

TABLE 1 Correlation coefficients between alpha event-related spectral perturbation (ERSP) values and intelligence sub-scores.

Alpha ERSP (0° of angle disparity)						
ROIs		Intelligence quotient	Working memory	Perceptual organization	Speed processing	Verbal comprehension
Frontal	R	−0.153	−0.143	−0.073	−0.263	−0.148
	P	0.224	0.239	0.360	0.093	0.231
Parietal	R	−0.308	−0.311	0.001	0.047	−0.259
	P	0.059	0.057	0.499	0.408	0.096
Temporal	R	−0.221	−0.233	0.136	0.141	−0.137
	P	0.134	0.121	0.249	0.241	0.248
Occipital	R	−0.328	−0.533	−0.278	−0.328	−0.333
	P	0.048	***0.002***	0.081	0.048	0.045
Alpha ERSP (150° of angle disparity)						
Frontal	R	−0.382	−0.616	−0.312	−0.315	−0.165
	P	0.025	***<0.001***	0.056	0.055	0.206
Parietal	R	−0.089	−0.467	−0.074	−0.104	0.070
	P	0.330	0.007	0.358	0.303	0.364
Temporal	R	−0.221	−0.233	−0.295	0.141	−0.137
	P	0.132	0.121	0.067	0.241	0.248
Occipital	R	−0.212	−0.504	−0.165	−0.325	−0.074
	P	0.144	***0.004***	0.206	0.049	0.357

We considered the *post-hoc* correction for the above analysis (0.05/8, $p < 0.006$). Bolded italic values represent the statistically significant.

1997; Doppelmayr et al., 2005). In mental rotation, task difficulty is represented by progressive increments of angle disparity between target and reference images and is reflected by increased response time (Shepard and Metzler, 1971) and higher RRN (Anomal et al., 2020). Using functional magnetic resonance imaging (fMRI), Lipp et al. (2012) showed augmented cortical activation with increased angles of disparity, in individuals with higher intelligence scores in the right frontal and inferior parietal cortex during a visuospatial task variant of the standard Posner task (Lipp et al., 2012). In accordance with our current findings, other studies have shown that lower and widespread alpha ERSP is more associated with complex than easy tasks (Dujardin et al., 1995; Wilson et al., 1999; Stipacek et al., 2003; Doppelmayr et al., 2005).

Our results of high frontal activation in adolescents with higher working memory scores are at odds with the NEH of intelligence (Haier et al., 1992; Haier et al., 2003), which suggests lower glucose usage in the brain of more intelligent individuals. It has been proposed that the interaction between the frontal and parietal cortex is metabolically costly for the brain (Bullmore and Sporns, 2012), because it involves coordinated activity between distant cortical regions and associated increased metabolic wiring costs. Hara et al. (2014) showed that scores in a delayed non-matching-to-sample task performed by monkeys is inversely correlated with the amount of malformed, energetically inefficient mitochondria in presynaptic boutons in the dorsolateral prefrontal cortex (Hara et al., 2014). This result and others suggest that the neuro-metabolism in prefrontal areas associated with higher cognition increases with task demands and can result in cognitive fatigue due to the necessity of recycling potentially toxic substances accumulated during cognitive control exertion (Wiehler et al., 2022). Thus, though gifted and average intelligence subjects display different oscillatory patterns in the alpha range, this may depend on moderating variables such as task difficulty, task type, sex, and brain area under investigation (Euler and Anna-Lena, 2021).

Further, according to our results, adolescents with a higher percentage of correct responses during the task, had low ERSP values in the frontal cortex, though they were not faster than their counterparts (Anomal et al., 2020). This is consistent with Yoon and Mann (2017) findings that students who spent more time on a spatial test tended to score higher than those who did not (Yoon and Mann, 2017). These results suggest that gifted students may be cautious or more perfectionists, taking longer to respond.

4.2. Working memory and the mental rotation task

In our study, during difficult trials, alpha ERSP was negatively correlated with working memory scores, but not with total IQ. In the Shephard-Metzler's task, the underlying brain processing steps involve perceptual encoding, identification and discrimination of the objects, identification of their orientation, mental rotation, judgment of parity, response selection, and response execution (Heil, 2002; Heil and Rolke, 2002). We propose that working memory should be of particular importance during task performance, since the mental representation of the target object must be held online in working memory while being rotated and compared to the reference object (Hyun and Luck, 2007; Prime and Jolicoeur, 2010).

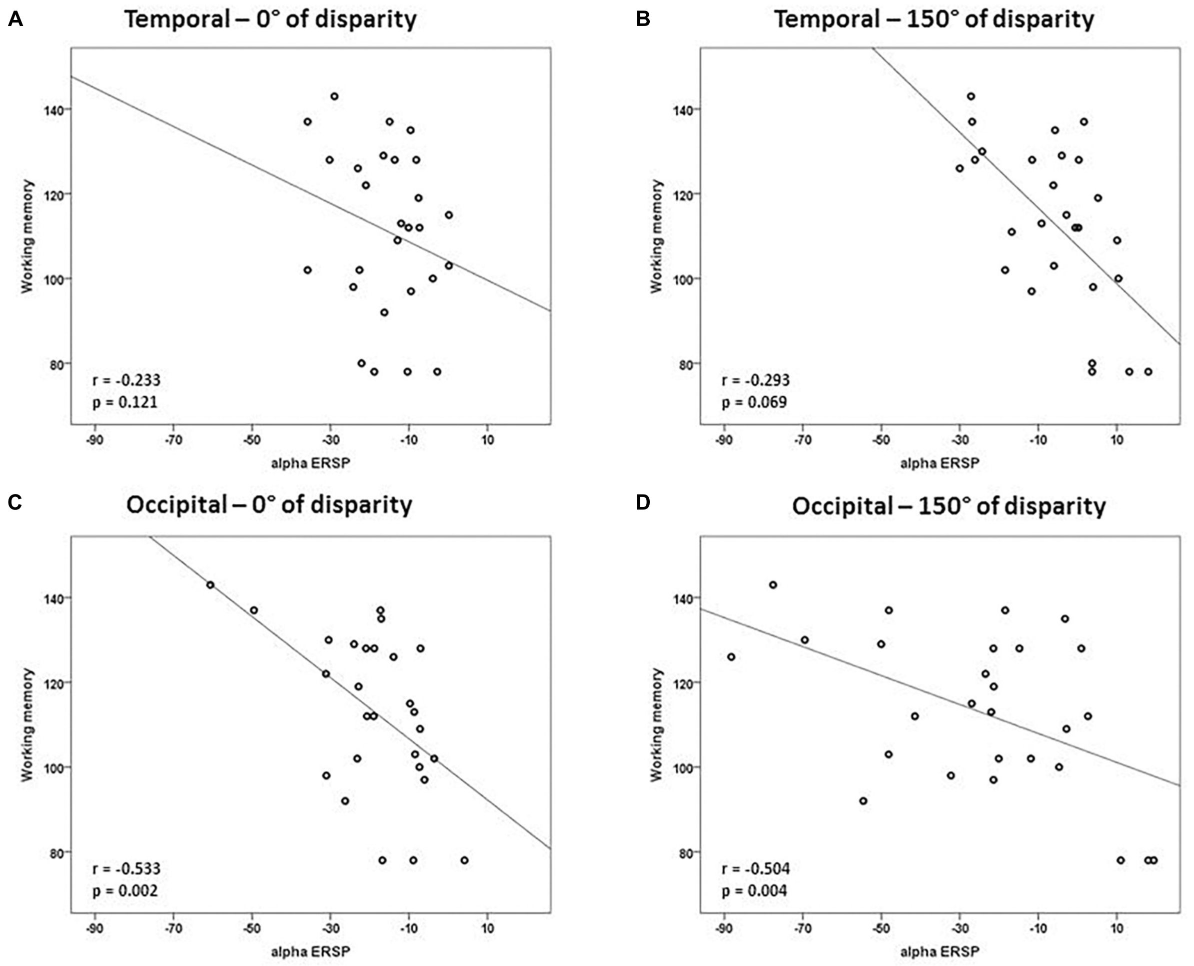

FIGURE 4
Correlations between intelligence scores and alpha ERSP in temporal and occipital ROIs. In the occipital ROI, there was a negative correlation between alpha ERSP values and working memory scores during trials with 0 and 150° of disparity between images. Correlations of easy trials of 0° of disparity are in panels **(A,C)**, and of difficult trials of 150° are in panels **(B,D)**. Values are in µV.

Our findings also show that working memory scores correlate negatively with alpha ERSP in the occipital cortex during both easy and difficult trials. The role of this region in working memory processing has been investigated since fMRI studies demonstrated that early visual areas can retain specific information about visual features held in working memory (Ester et al., 2009; Harrison and Tong, 2009), and that transcranial magnetic stimulation (TMS) over the occipital cortex reduces visual working memory consolidation (van de Ven et al., 2012). Another study of anodal direct current stimulation of the visual cortex, which increases neuronal excitability, shows improved visual working memory consolidation in a standard change detection task (Makovski and Lavidor, 2014).

TABLE 2 Correlation coefficients between alpha event-related spectral perturbation (ERSP) values and behavioral data (150° of angle disparity).

ROIs		Response time	Accuracy
Frontal	R	−0.016	−0.220
	P	0.468	0.130
Parietal	R	0.041	−0.313
	P	0.421	0.052
Temporal	R	−0.091	−0.100
	P	0.329	0.306
Occipital	R	−0.234	−0.231
	P	0.125	0.119

We considered the post-hoc correction for the above analysis (0.05/2, $p < 0.025$).

We also observed that in difficult trials, alpha ERSP recorded in the parietal and frontal cortex is closely associated with working memory scores. This involvement of the parietal and prefrontal cortex in the retention of visual working memory information is already well-established (Miller et al., 1996; Todd and Marois, 2004). In a previous work, we had already shown that working memory scores are correlated with ERP amplitude in both the FPN during the rotation-related negativity interval of the SMT (Anomal et al., 2020). Other studies have shown that the communication between frontal and posterior regions during a working memory task is modulated according to the cognitive demands required for a successful performance (Fernández et al., 2021).

5. Conclusion

Our findings reveal a heightened activation of the parietal cortex in comparison to other regions, further emphasizing the significance of the Frontoparietal Network (FPN) in the successful completion of spatial mental rotation tasks (SMT). The correlation between working memory and alpha event-related spectral perturbation (ERSP) occurred in the frontal cortex and highlights the vital role of this region in working memory, which is a crucial aspect of SMT. Additionally, the link between occipital cortex activity and working memory scores supports our hypothesis that this region plays an important role in supporting working memory tasks.

Initially, it was believed that low cortical activation in highly intelligent individuals indicated a more economical use of brain glucose and efficient neural functioning. However, our findings also demonstrate that alpha ERSP amplitude is influenced by task difficulty.

One surprising outcome of our study was the correlation between alpha ERSP and working memory (WM), but not IQ. It is important to keep in mind, however, that although previous research has indicated a positive relationship between WM capacity and IQ, WM is only one of the many factors that contribute to a person's intellectual ability (Engle, 2002). Other factors, such as motivation, education, and life history, can also have a significant impact on an individual's IQ (Engle, 2002).

The correlation between mental rotation and intelligence has significant implications for STEM fields and careers, given their reliance on visuospatial ability, making it crucial to understand the relationship between the two. To enhance the development of visuospatial intelligence, we suggest that educational curricula should place more emphasis on activities relying on visuospatial ability, including mental rotation tasks.

However, a limitation of our study is the relatively small sample size, which precluded us from examining potential gender differences in brain activation patterns during visuospatial tasks. Previous research has shown that, on average, males generally score higher than females on measures of spatial ability, including visuospatial tasks (Linn and Petersen, 1985). In future studies, it would be interesting to increase the sample of both males and females and examine whether any gender differences exist in brain activation patterns during visuospatial tasks. Additionally, it would be interesting to explore the potential influence of cultural and social factors on these differences and disentangle their relative weight.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Federal University of Rio Grande do Norte. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

AP conceived the project. RA, SS, SP, and IH performed the experiments. AP, RA, RS, DB, and SS analyzed the data. AP and RA wrote the manuscript. All authors contributed to read the manuscript and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Anomal, R. F., Brandão, D. S., Porto, S. B., de Oliveira, S. S., de Souza, R., Fiel, J. S., et al. (2020). The role of frontal and parietal cortex in the performance of gifted and average adolescents in a mental rotation task. *PLoS One* 15:e0232660. doi: 10.1371/journal.pone.0232660

Avena-Koenigsberger, A., Misic, B., and Sporns, O. (2018). Communication dynamics in complex brain networks. *Nat. Rev. Neurosci.* 19, 17–33. doi: 10.1038/nrn.2017.149

Bullmore, E., and Sporns, O. (2012). The economy of brain network organization. *Nat. Rev. Neurosci.* 13, 336–349. doi: 10.1038/nrn3214

Buzsáki, G., and Draguhn, A. (2004). Neuronal oscillations in cortical networks. *Science* 304, 1926–1929. doi: 10.1126/science.1099745

Chen, Y. T., van Ede, F., and Kuo, B. C. (2022). Alpha oscillations track content-specific working memory capacity. *J. Neurosci.* 42, 7285–7293. doi: 10.1523/JNEUROSCI.2296-21.2022

Delorme, A., and Makeig, S. (2004). EEGLAB: An open-source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci.* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

Del Percio, C., Franzetti, M., De Matti, A. J., Noce, G., Lizio, R., Lopez, S., et al. (2019). Football players do not show "neural efficiency" in cortical activity related to visuospatial information processing during football scenes: An EEG mapping study. *Front. Psychol.* 26:890.

Diamond, M. C., Scheibel, A. B., Murphy, G. M. Jr., and Harvey, T. (1985). On the brain of a scientist: Albert Einstein. *Exp. Neurol.* 88, 198–204.

Doppelmayr, M., Klimesch, W., Sauseng, P., Hödlmoser, K., Stadler, W., and Hanslmayr, S. (2005). Intelligence related differences in EEG-band power. *Neurosci. Lett.* 381, 309–313. doi: 10.1016/j.neulet.2005.02.037

Dujardin, K., Bourriez, J. L., and Guieu, J. D. (1995). Event-related desynchronization (ERD) patterns during memory processes: Effects of aging and task difficulty. *Electroencephalogr. Clin. Neurophysiol.* 96, 169–182. doi: 10.1016/0168-5597(94)00284-L

Dunst, B., Benedek, M., Jauk, E., Bergner, S., Koschutnig, K., Sommer, M., et al. (2014). Neural efficiency as a function of task demands. *Intelligence* 42, 22–30. doi: 10.1016/j.intell.2013.09.005

Engle, R. W. (2002). Working memory capacity as executive attention. *Curr. Direct. Psychol. Sci.* 11, 19–23.

Ester, E. F., Serences, J. T., and Awh, E. (2009). Spatially global representations in human primary visual cortex during working memory maintenance. *J. Neurosci.* 29, 15258–15265. doi: 10.1523/JNEUROSCI.4388-09.2009

Euler, M. J., and Anna-Lena, S. (2021). Recent developments, current challenges, and future directions in electrophysiological approaches to studying intelligence. *Intelligence* 88:101569. doi: 10.1016/j.intell.2021.101569

Fernández, A., Pinal, D., Díaz, F., and Zurrón, M. (2021). Working memory load modulates oscillatory activity and the distribution of fast frequencies across frontal theta phase during working memory maintenance. *Neurobiol. Learn. Mem.* 183:107476. doi: 10.1016/j.nlm.2021.107476

Fiebelkorn, I. C., and Kastner, S. (2019). A rhythmic theory of attention. *Trends. Cogn. Sci.* 23, 87–101. doi: 10.1016/j.tics.2018.11.009

Foxe, J. J., and Snyder, A. C. (2011). The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. *Front. Psychol.* 2:154. doi: 10.3389/fpsyg.2011.00154

Ganis, G., and Kievit, R. (2015). A new set of three-dimensional shapes for investigating mental rotation processes: Validation data and stimulus. *J. Open Psychol.* 3, 1–7. doi: 10.5334/jopd.ai

Gardony, A. L., Eddy, M. D., Brunyé, T. T., and Taylor, H. A. (2017). Cognitive strategies in the mental rotation task revealed by EEG spectral power. *Brain Cogn.* 118, 1–18. doi: 10.1016/j.bandc.2017.07.003

Grabner, H. R., Fink, A., Stipacek, A., Neuper, C., and Neubauer, A. C. (2004). Intelligence and working memory systems: Evidence of neural efficiency in alpha band ERD. *Cogn. Brain Res.* 20, 212–225. doi: 10.1016/j.cogbrainres.2004.02.010

Grabner, H. R., Stern, E., and Neubauer, A. C. (2003). When intelligence loses its impact: Neural efficiency during reasoning in a familiar area. *Int. J. Psychophysiol.* 49, 89–98. doi: 10.1016/S0167-8760(03)00095-3

Haier, R. J., Siegel, B., Tang, C., Abel, L., and Buchsbaum, M. S. (1992). Intelligence and changes in regional cerebral glucose metabolic rate following learning. *Intelligence* 16, 415–426. doi: 10.1016/0160-2896(92)90018-M

Haier, R. J., White, N. S., and Alkire, M. T. (2003). Individual differences in general intelligence correlate with brain function during nonreasoning tasks. *Intelligence* 31, 429–441. doi: 10.1016/S0160-2896(03)00025-4

Hambrick, D. Z., Burgoyne, A. P., and Oswald, F. L. (2019). "Domain-general models of expertise: The role of cognitive ability," in *The Oxford handbook of expertise*, eds P. Ward, J. M. Schraagen, J. Gore, and E. Roth (Oxford: Oxford University Press), 56–84. doi: 10.1093/oxfordhb/9780198795872.013.3

Hamm, J., Johnson, B. W., and Corballis, M. (2004a). A model of rotated mirror/normal letter discriminations. *Mem. Cogn.* 38, 206–220. doi: 10.3758/MC.38.2.206

Hamm, J., Johnson, B. W., and Corballis, M. (2004b). One good turn deserves another: An event-related brain potential study of rotated mirror–normal letter discriminations. *Neuropsychologia* 42, 810–820. doi: 10.1016/j.neuropsychologia.2003.11.009

Hara, Y., Yuk, F., Puri, R., Janssen, W. G., Rapp, P. R., and Morrison, J. H. (2014). Presynaptic mitochondrial morphology in monkey prefrontal cortex correlates with working memory and is improved with estrogen treatment. *Proc. Natl. Acad. Sci. U. S. A.* 111, 486–491. doi: 10.1073/pnas.1311310110

Harrison, S., and Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature* 458, 632–635. doi: 10.1038/nature07832

Heil, M. (2002). The functional significance of ERP effects during mental rotation. *Psychophysiology* 39, 535–545. doi: 10.1111/1469-8986.3950535

Heil, M., and Rolke, B. (2002). Toward a chronopsychophysiology of mental rotation. *Psychophysiology* 39, 414–422. doi: 10.1111/1469-8986.3940414

Hyun, J. S., and Luck, S. J. (2007). Visual working memory as the substrate for mental rotation. *Psychon. Bull. Rev.* 14, 154–158. doi: 10.3758/BF03194043

Isler, K. (2013). Brain size evolution: How fish pay for being smart. *Curr. Biol.* 23, R63–R65. doi: 10.1016/j.cub.2012.11.042

Jensen, O., and Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. *Front. Hum. Neurosci.* 4:186.

Jung, R. E., and Haier, R. J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behav. Brain Sci.* 30, 135–187. doi: 10.1017/S0140525X07001185

Kedar, Y., Kedar, G., and Barkai, R. (2022). The influence of smoke density on hearth location and activity areas at lower paleolithic lazaret cave France. *Sci. Rep.* 12:1469. doi: 10.1038/s41598-022-05517-z

Klimesch, W. (2012). α-band oscillations, attention, and controlled access to stored information. *Trends Cogn. Sci.* 16, 606–617. doi: 10.1016/j.tics.2012.10.007

Klimesch, W., Doppelmayr, M., Pachinger, T., and Ripper, B. (1997). Brain oscillations and human memory: EEG correlates in upper alpha and theta band. *Neurosci. Lett.* 237, 1–4. doi: 10.1016/S0304-3940(97)00771-4

Klimesch, W., Schimke, H., and Pfurtscheller, G. (1993). Alpha frequency, cognitive load and memory performance. *Brain Topogr.* 5, 241–251. doi: 10.1007/BF01128991

Linn, M. C., and Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Dev.* 56, 1479–1498.

Lipp, I., Benedek, M., Fink, A., Koschutnig, K., Reishofer, G., Bergner, S., et al. (2012). Investigating neural efficiency in the visuo-spatial domain: An FMRI study. *PLoS One* 7:e51316. doi: 10.1371/journal.pone.0051316

Makeig, S. (1993). Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones. *Electroencephalogr. Clin. Neurophysiol.* 86, 283–293.

Makeig, S., Debener, S., Onton, J., and Delorme, A. (2004). Mining event-related brain dynamics. *Trends Cogn. Sci.* 8, 204–210. doi: 10.1016/j.tics.2004.03.008

Makovski, T., and Lavidor, M. (2014). Stimulating occipital cortex enhances visual working memory consolidation. *Behav. Brain Res.* 275, 84–87. doi: 10.1016/j.bbr.2014.09.004

Milivojevic, B., Hamm, J. P., and Corballis, M. C. (2009). Hemispheric dominance for mental rotation: It is a matter of time. *Neuroreport* 20, 1507–1512. doi: 10.1097/WNR.0b013e32832ea6fd

Miller, E. K., Erickson, C. A., and Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *J. Neurosci.* 16, 5154–5167. doi: 10.1523/JNEUROSCI.16-16-05154.1996

Nakata, H., Yoshie, M., Miura, A., and Kudo, K. (2010). Characteristics of the athletes' brain: Evidence from neurophysiology and neuroimaging. *Brain Res. Rev.* 62, 197–211.

National Research Council (2006). *Learning to think spatially*. Washington, DC: The National Academies Press.

Neubauer, A., Sange, G., and Pfurtscheller, G. (1999). "Psychometric intelligence and event-related desynchronization during performance of a letter matching task," in *Event-Related Desynchronization. Handbook of electroencephalography and clinical neurophysiology*, eds G. Pfurtscheller and F. H. Lopes da Silva (Amsterdam: Elsevier), 219–231.

Neubauer, A. C., Bergner, S., and Schatz, M. (2010). Two- vs. three-dimensional presentation of mental rotation tasks: Sex differences and effects of training on performance and brain activation. *Intelligence* 38, 529–539. doi: 10.1016/j.intell.2010.06.001

Neubauer, A. C., and Fink, A. (2003). Fluid intelligence and neural efficiency: Effects of task complexity and sex. *Pers. Individ. Differ.* 35, 811–827. doi: 10.1016/S0191-8869(02)00285-4

Neubauer, A. C., and Fink, A. (2009). Intelligence and neural efficiency. *Neurosci. Biobehav. Rev.* 33, 1004–1023.

Neubauer, A. C., Fink, A., and Schrausser, D. G. (2002). Intelligence and neural efficiency: The influence of task content and sex on the brain–IQ relationship. *Intelligence* 30, 515–536. doi: 10.1016/S0160-2896(02)00091-0

Neubauer, A. C., Freudenthaler, H. H., and Pfurtscheller, G. (1995). Intelligence and spatiotemporal patterns of event-related desynchronization (ERD). *Intelligence* 20, 2249–2166. doi: 10.1016/0160-2896(95)90010-1

Neubauer, A. C., Grabner, R. H., Freudenthaler, H. H., Beckmann, J. F., and Guthke, J. (2004). Intelligence and individual differences in becoming neurally efficient. *Acta Psychol.* 116, 55–74. doi: 10.1016/j.actpsy.2003.11.005

Peirce, J. W. (2007). PsychoPy-Psychophysics software in Python. *J. Neurosci. Methods* 162, 8–13. doi: 10.1016/j.jneumeth.2006.11.017

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Front. Neuroinform.* 2:10. doi: 10.3389/neuro.11.010.2008

Pfurtscheller, G., and Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clin. Neurophysiol.* 110, 1842–1857. doi: 10.1016/S1388-2457(99)00141-8

Pfurtscheller, G., Stancák, A. Jr., and Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band–an electrophysiological correlate of cortical idling: A review. *Int. J. Psychophysiol.* 24, 39–46.

Prime, D. J., and Jolicoeur, P. (2010). Mental rotation requires visual short-term memory: Evidence from human electric cortical activity. *J. Cogn. Neurosci.* 22, 2437–2446. doi: 10.1162/jocn.2009.21337

Rypma, B., Berger, J. S., and D'Esposito, M. (2002). The influence of working-memory demand and subject performance on prefrontal cortical activity. *J. Cogn. Neurosci.* 14, 721–731.

Shepard, R. N., and Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science* 171, 701–703. doi: 10.1126/science.171.3972.701

Sisman, B., Kucuk, S., and Yaman, Y. (2021). The effects of robotics training on children's spatial ability and attitude toward stem. *Int. J. Soc. Robot.* 13, 379–389. doi: 10.1007/s12369-020-00646-9

Stieff, M., and Uttal, D. (2015). How much can spatial training improve stem achievement? *Educ. Psychol. Rev.* 27, 607–615. doi: 10.1007/s10648-015-9304-8

Stipacek, A., Grabner, R. H., Neuper, C., Fink, A., and Neubauer, A. C. (2003). Sensitivity of human EEG alpha band desynchronization to different working memory components and increasing levels of memory load. *Neurosci. Lett.* 353, 193–196. doi: 10.1016/j.neulet.2003.09.044

Todd, J., and Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 428, 751–754. doi: 10.1038/nature02466

van de Ven, V., Jacobs, C., and Sack, A. T. (2012). Topographic contribution of early visual cortex to short-term memory consolidation: A transcranial magnetic stimulation study. *J. Neurosci.* 32, 4–11. doi: 10.1523/JNEUROSCI.3261-11.2012

Veurink, N. L., and Sorby, S. A. (2019). Longitudinal study of the impact of requiring training for students with initially weak spatial skills. *Eur. J. Eng. Educ.* 44, 153–163. doi: 10.1080/03043797.2017.1390547

Wai, J., Lubinski, D., and Benbow, C. P. (2009). Spatial ability for stem domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *J. Educ. Psychol.* 101, 817–835. doi: 10.1037/a0016127

Wang, B., van Driel, J., Ort, E., and Theeuwes, J. (2019). Anticipatory distractor suppression elicited by statistical regularities in visual search. *J. Cogn. Neurosci.* 31, 1535–1548. doi: 10.1162/jocn_a_01433

Wechsler, D. (2003). *Wechsler intelligence scale for children. fourth edition technical and interpretive manual*. San Antonio: The Psychological Corporation. doi: 10.1037/t15174-000

Wechsler, D. (2008). *Wechsler adult intelligence scale. fourth edition technical manual*. San Antonio: The Psychological Corporation. doi: 10.1037/t15169-000

Weiss, R. H. (2006). *Culture fair intelligence test scale 2-revision (CFT 20-R)*. Göttingen: Hogrefe.

Wiehler, A., Branzoli, F., Adanyeguh, I., Mochel, F., and Pessiglione, M. (2022). A neuro-metabolic account of why daylong cognitive work alters the control of economic decisions. *Curr. Biol.* 32, 3564–3575. doi: 10.1016/j.cub.2022.07.010

Wilson, G. F., Swain, C. R., and Ullsperger, P. (1999). EEG power changes during a multiple level memory retention task. *Int. J. Psychophysiol.* 32, 107–118. doi: 10.1016/S0167-8760(99)00005-7

Witelson, S. F., Kigar, D. L., and Harvey, T. (1999). The exceptional brain of Albert Einstein. *Lancet* 353, 2149–2153.

Yoon, S. Y., and Mann, E. L. (2017). Exploring the spatial ability of undergraduate students: Association with gender, stem majors, and gifted program membership. *Gift. Child Q.* 61, 313–327. doi: 10.1177/0016986217722614

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Reward prospect affects strategic adjustments in stop signal task

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Interaction with the environment requires us to predict the potential reward that will follow our choices. Rewards could change depending on the context and our behavior adapts accordingly. Previous studies have shown that, depending on reward regimes, actions can be facilitated (i.e., increasing the reward for response) or interfered (i.e., increasing the reward for suppression). Here we studied how the change in reward perspective can influence subjects' adaptation strategy. Students were asked to perform a modified version of the Stop-Signal task. Specifically, at the beginning of each trial, a Cue Signal informed subjects of the value of the reward they would receive; in one condition, Go Trials were rewarded more than Stop Trials, in another, Stop Trials were rewarded more than Go Trials, and in the last, both trials were rewarded equally. Subjects participated in a virtual competition, and the reward consisted of points to be earned to climb the leaderboard and win (as in a video game contest). The sum of points earned was updated with each trial. After a learning phase in which the three conditions were presented separately, each subject performed 600 trials testing phase in which the three conditions were randomly mixed. Based on the previous studies, we hypothesized that subjects could employ different strategies to perform the task, including modulating inhibition efficiency, adjusting response speed, or employing a constant behavior across contexts. We found that to perform the task, subjects preferentially employed a strategy-related speed of response adjustment, while the duration of the inhibition process did not change significantly across the conditions. The investigation of strategic motor adjustments to reward's prospect is relevant not only to understanding how action control is typically regulated, but also to work on various groups of patients who exhibit cognitive control deficits, suggesting that the ability to inhibit can be modulated by employing reward prospects as motivational factors.

KEYWORDS

stop signal task, cognitive control, inhibitory control, reward, strategic adjustments, motor control

1. Introduction

In everyday life, it is important to behave appropriately in relation to the shifting situations we encounter and the effects of our choices. This requires, for example, assessing the potential reward that could be obtained in a specific context before deciding whether or not to act, and being able to stop quickly if sudden changes in the environment make the action no longer useful. A widely used experimental paradigm to study choice behavior is the Stop-Signal Task (SST) in both human and non-human primates (Vince, 1948; Logan and Cowan, 1984; Hanes and Carpenter, 1999; Scangos and Stuphorn, 2010; Brunamonti et al., 2012; Pani et al., 2014; Montanari et al., 2017; Schall et al., 2017; Pani et al., 2018; Bardella et al., 2020; Fiori et al., 2020; Giarrocco et al., 2021; Andujar et al., 2022; Hervault et al., 2022; Pani et al., 2022; Bardella et al., 2023; Marc et al., 2023). The SST requires the subjects to respond as quickly as possible when a Go Signal is presented (for example by pressing a button) and to interrupt the response when unpredictably a Stop Signal is presented after a variable time from the Go Signal. In its original conception, this task creates a competition between two processes: the Go process, triggered by the Go Signal, and the Stop process, triggered by the Stop Signal (race model, Logan and Cowan, 1984). The competition is evident especially in Stop Trials, when first the Go Signal and then the Stop Signal are presented. The choice of moving or stopping that the subject makes will depend on the speed of each of the processes (Logan and Cowan, 1984; Boucher et al., 2007), and on the delay between the Go Signal and Stop Signal (Stop Signal Delay, SSD). The race model suggests that the higher these SSDs are, the greater the probability of moving despite the presentation of the Stop Signal. Effects of choice competition are also present in the trials where only the Go Signal is presented. Indeed, the Go process is affected when subjects know that a Stop Signal is possible as demonstrated by the observation that the same Go responses in tasks without Stop Trials are faster (Mirabella et al., 2008; Pani et al., 2013).

The dual-task nature of the paradigm makes it possible to study two control strategies that support behavior in accordance with the dual-mechanisms framework (DMC): proactive control and reactive control (Braver et al., 2007; Braver, 2012). Correct performance in Stop Trials often requires reactive control, as it allows us to quickly inhibit or reorganize our actions when an unexpected event occurs, rendering planned actions no longer appropriate. The SST provides a measure of this control corresponding to the latency of the reactive inhibition process, i.e., the Stop Signal Reaction Time (SSRT). However, proactive control is also necessary to achieve optimal performance in the task. It allows us to reach a balance between the demand of the task (i.e., responding as quickly as possible), and making as few mistakes as possible on Stop Trials (i.e., optimize the inhibition process). In the SST, for example, the subjects tend to procrastinate their responses as a Stop Signal could possibly be presented. Depending on the context, both control processes can be affected by different factors, such as attention, reward, and motivation (Engelmann and Pessoa, 2007; Mohanty et al., 2008; Engelmann et al., 2009; Krebs et al., 2009; Pessoa and Engelmann, 2010; Padmala et al., 2011; Stoppel et al., 2011; Marc et al., 2023).

Despite thorough exploration of various features of inhibition processes, few studies have investigated how reward can influence motor control, and whether the influence of reward varies depending on how the reward is manipulated. Some studies have manipulated the reward only in the Stop Trials (e.g., Boehler et al., 2012, 2014; Verbruggen and McLaren, 2018). For example, Boehler et al. (2012, 2014), found that SSRTs were shorter when the Stop Signal was associated with a reward for the correct trials, compared to when no reward was associated. However, other studies have not found the evidence to confirm this effect (Schevernels et al., 2015; Verbruggen and McLaren, 2018). In further investigations, the tasks were administered in blocks, and the subjects were informed *a priori* about the reward they would receive for the Correct Stop Trial (Leotti and Wager, 2010; Greenhouse and Wessel, 2013). In these studies, subjects adopted strategies pertaining to the lengthening of RTs, to improve their ability to inhibit. However, when only Go Trials were rewarded, response inhibition was impaired (Padmala and Pessoa, 2010).

To extend this line of research, we investigated how reward perspective can influence one or both controls, reactive and proactive. To this aim, we administered a modified SST in which three different proportions of reward values were randomly presented by informing the subjects about them at the beginning of each trial. Subjects could gain a higher reward (points in a virtual game) for correct Go Trials than for correct Stop Trials, or the same amount of reward for both correct Go and Stop trials, or even a higher reward for correct Stop Trials than for correct Go trials. We found that the subjects employed a strategy based on the modulation of the response's speed to the Go signal, while the duration of the inhibition process remained unaffected, therefore showing that the behavioral adjustment relied on proactive control.

2. Materials and methods

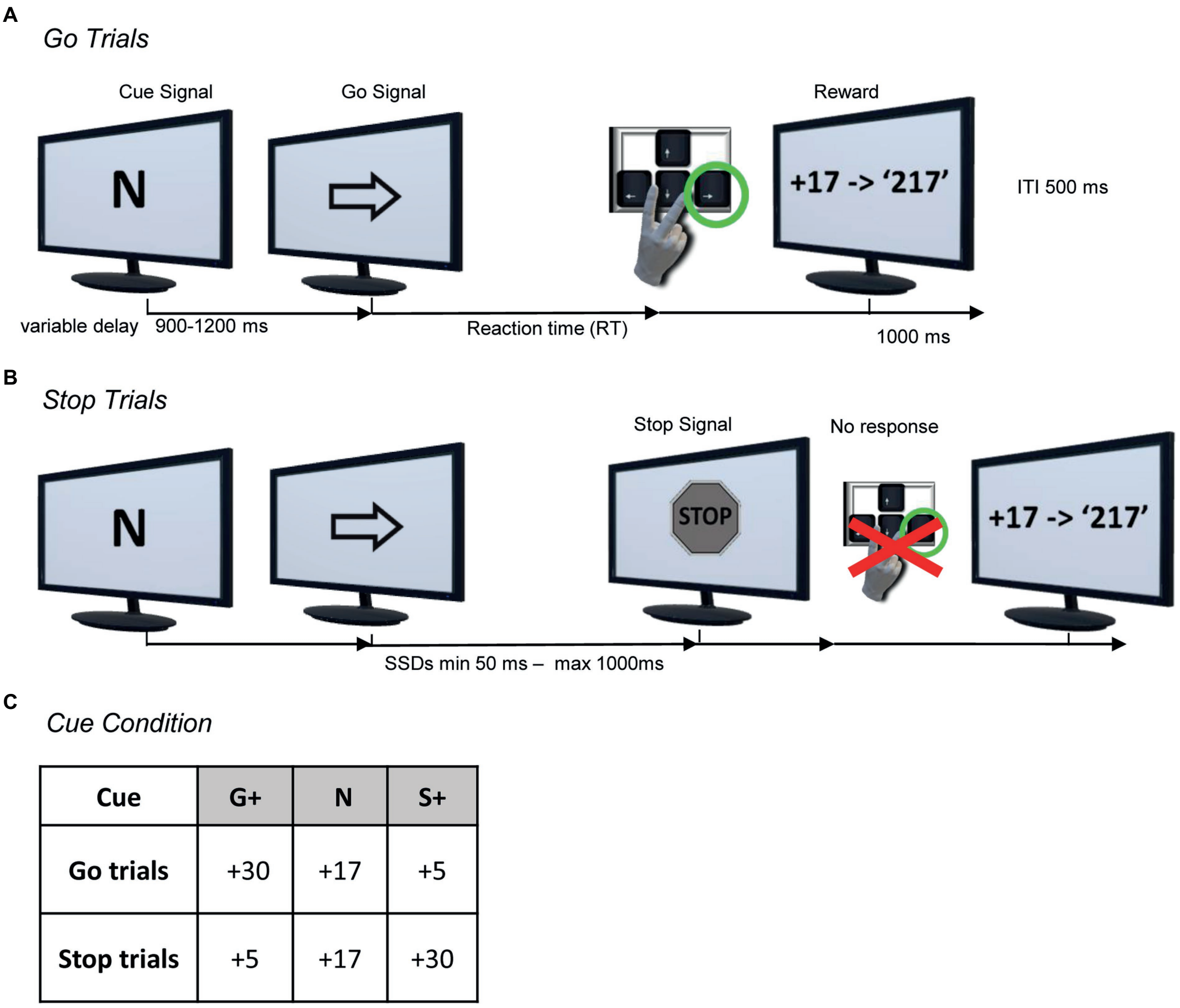
2.1. Subjects

We estimated *a priori* the sample size of 14 subjects, on the basis of power 0.90 to detect an effect size in a within-subject design of 0.42 based on partial eta squared (η^2_p) 0.15 using GPower 3.1.9.7 (Faul et al., 2007, 2009), as reported in the previous studies employing similar tasks(Mirabella et al., 2008; Andujar et al., 2022; Marc et al., 2023). Eighteen subjects (4 males & 14 females, mean age = 26.5) were recruited for the study. All the subjects were right-handed, had normal or corrected vision, and had no history of psychiatric or neurological disorders.

All subjects were checked for race model violations and respect the unimodality assumption for Stop Signal Delay (SSD) in the Stop Trials prior to testing. Four participants out of 18 were excluded because they did not respect the unimodality assumption for Stop Signal Delay (SSD) in the Stop Trials (see methods for details). All procedures were performed in accordance with the Declaration of Helsinki and after obtaining a written informed consent from each subject. The procedure was approved by the Ethics Committee of "Roma Tre" University.

2.2. Apparatus and task

Subjects were seated in a darkened and sound attenuated chamber, in front of a 20-inch monitor (LCD, 1920 × 1,080 resolution, 60 Hz) placed 40 cm away. Stimuli presentation and behavioral events collection were controlled using the MATLAB-Psychophysics Toolbox Version 3 (PTB-3). They performed a modified version of the Stop Signal Task (Logan and Cowan, 1984; Logan, 1994). As in the classical SST, they were required to perform two types of trials, Go Trials (the majority of trials, 70%) and Stop Trials (the minority of trials, 30%),



Cue	G+	N	S+
Go trials	+30	+17	+5
Stop trials	+5	+17	+30

FIGURE 1
Behavioral paradigm. **(A,B)** Modified version of the Stop-Signal Task (sequence of events for the Neutral Condition; i.e. Cue: N). Each trial started with the Cue Signal, which indicated the type of reward condition to the subject; i.e., the amount of the reward they should expect if they correctly performed the Go Trial (see **A**) or a Stop trial (see **B**). After a variable delay, a Go Signal (right or left arrow) appeared and the subject had to press the arrow key on the keyboard according to the Go Signal to receive the reward as points (see **A**). Occasionally, at a variable delay (SSD) from the Go Signal, a Stop Signal appeared and the subject had to inhibit the action to receive the reward (see **B**). **(C)** Overview of the Cue Signals associated with the respective rewards for each Cue Condition. The amount of reward for every Cue Condition was differently associated with Go and Stop Trials as follows: Go+ Condition (G+, as Cue Signal) was associated with higher reward for successful Go Trials compared to successful Stop Trials; Stop+ Condition (S+, as Cue Signal) was associated with reversed reward amount; Neutral Condition (N, as Cue Signal) was associated with equal amounts of reward for successful Go or Stop Trials.

but presented under three different experimental conditions, indicated by a Cue Signal, (i.e., G+, S+ or N) presented at the beginning of each trial (Figure 1).

In *Go Trials*, after a variable time (900–1,200 ms) from the Cue Signal, a Go Signal (left or right pointing arrow) was presented. The Go Signal required the subjects to press the left or right arrow key on the keyboard as fast as possible with their right index or middle finger, indicated by the presented Go Signal, within an upper reaction time of 1.5 s. If the subject responded correctly (i.e., Correct Go Trial), visual and positive auditory feedback (1 s) were presented with the score obtained in relation to the trial condition.

If the subject did not respond correctly (Failed Go Trial) by failing to press the corresponding key to the Go Signal or not responding within the upper reaction time (Go omission) after the Go Signal, visual feedback, "*0 Score*" or "*0 Score, too late!*," respectively, was provided along with a negative audio feedback.

In *Stop Trials*, the initial sequence of events was identical to that of the Go Trials, but after a variable time from the Go Signal presentation (Stop Signal Delay [SSD]), a Stop Signal appeared, which required subjects to inhibit the movement triggered by the Go Signal. If the subject withheld the movement correctly (Correct Stop Trial), after the disappearance of the Stop Signal (1 s.), a visual and positive auditory feedback (1 s.) appeared with the score obtained in relation to the trial condition. If the subject did not respond correctly (Failed Stop Trial), by failing to inhibit the movement, visual feedback, "*0 Score*," was provided to the subjects along with a negative audio feedback.

In the Stop Trials, a staircase procedure adjusted the SSD based on subjects' performance. The SSD started at an initial value of 50 milliseconds (ms), and the SSDs following Correct Stop Trials were increased by one step (50 ms) while SSDs following Error Stop Trials were decreased by one step in the next Stop Trial. The minimum and maximum limits of the SSD presentation were set to 50 milliseconds and 1 s, respectively. The intertrial interval was 500 ms.

This method keeps the probability of error at the presentation of the stop signal around 50%, deterring the subject from using strategies in which he is expected to wait for the stop signal (Verbruggen et al., 2019).

The two types of trials, Stop and Go Trials, were presented with the same proportions (i.e., 30% Stop Trials and 70% Go Trials) in the three different experimental conditions in mixed order.

Go + Condition. In the Go+ condition, subjects were informed that performing Correct Go Trials would allow them to earn a higher reward (+30 points), whereas Correct Stop Trials would allow them to earn a lower reward (+5 points).

Stop + Conditions. On the contrary, in the Stop+ condition, subjects were informed that Correct Go Trials would allow them to earn a lower reward (+5 points), whereas Correct Stop Trials would allow them to earn a higher reward (+30 points).

Neutral Conditions. In the Neutral condition, the amount of reward subjects could earn was the same in Correct Go Trials and Correct Stop Trials (+17 points).

For all the conditions, the positive auditory feedback was the same but differed in pitch according to the amount of reward the subject received upon the completion of a correct trial (i.e., high frequency = +30 scores; low frequency = +5 score).

2.3. Experimental procedure

Subjects executed the three different experimental Cue Conditions in two phases, a learning phase and a testing phase.

2.3.1. Learning phase

Each subject performed separately, in blocks of 200 trials, the three conditions with an independent staircase procedure for the presentation of the SSDs. The order in which the blocks were presented was randomized and counterbalanced between all subjects.

2.3.2. Test phase

One week after the learning phase, each subject performed a single block of 600 trials comprising the three conditions in a mixed order, with an equal probability of presentation and randomized trial-by-trial. In this way, the subjects became aware of which reward they would earn at each trial only at the presentation of the Cue signal. In the test phase, 1/3 of the trials (Go and Stop Trials) were designated to the Go+ condition, 1/3 to the Neutral condition and 1/3 to the Stop+ condition. Within this phase, three independent staircases for the three conditions were used.

2.3.3. Instructions

Before each block, subjects were instructed to perform the task in that specific condition, incentivizing them to respond as quickly as possible and at the same time to be ready to stop at the appearance of the Stop Signal to earn as many rewards (points) as possible to outperform the other subjects. Additionally, the staircase procedure was also explained to subjects to further discourage a waiting strategy (see Verbruggen et al., 2019). Immediately afterwards, an actual and updated ranking of the previous subjects' scores for that condition was shown, inviting the subject to beat the current record. Except for the first subject, who was shown the highest score attainable with the best performance in the task.

2.4. Data analysis

Since the Learning Phase served only for the subjects to become familiar with the three Cue Conditions and to understand the experimental procedures, the reported analyses were performed only on the Test Phase.

To verify whether there was an effect of the Cue Condition on the subject's strategy across the conditions, we considered different variables as follows: (1) the reaction time (RT) in Go Trials; (2) the probability of Go omissions; (3) the probability of response [p(response)] in Stop Trials (Failed Stop); (4) the average SSD and (5) Stop Signal Reaction Time (SSRT). The RTs in Go Trials were calculated as the time between the appearance of the Go signal and the subjects' response. All subjects' performances were checked for compliance with assumption of independence of race model and unimodality tests for SSDs in the Stop Trials prior to further analyses. Hartigan's dip test statistic for unimodality was applied on RTs and SSDs (Hartigan, 1985; Hartigan and Hartigan, 1985). In order to test for significance, bootstrap was set at 1,000.

Four subjects were excluded because they did not respect the unimodality assumption for SSD in the Stop Trials (Mean = 0.08; $p < 0.05$).

Then, the probability of Go omission was calculated as the number of Go omissions divided by the total number of Go Trials. The probability of response in Stop Trials (Failed Stop) was calculated as the number of Failed Stop Trials divided by the total number of Stop Trials. SSRT was calculated using the integration method (with replacement of Go omission) (see Verbruggen et al., 2019), after verifying that none of the subjects had violated the horse race model's assumption of independence, and the p(response) in Stop Trials was between 35 and 65%. All variables of interest were computed for each subject individually and for each Cue Condition in the Test Phase. To test whether the three Cue Conditions influenced the subjects' strategy, comparisons between Cue Conditions and within subjects were performed by repeated measures factorial ANOVAs, followed by post-hoc comparisons by Tukey–Kramer test. To assess how typical or uncommon the effect measured within the population mean is we applied Bayesian analysis (Ince et al., 2021, 2022). Bayesian prevalence returns a posterior distribution over the population prevalence, given the observed distribution of RTs for each Cue Condition. From this, we computed the maximum a posterior (MAP) estimate, that is the value of the population parameter. To quantify the uncertainty of this estimate, calculation of Bayesian highest posterior density intervals (HPDIs) allowed us to have a range within which the true population value lies with the specified probability.

Finally, we investigated with an exploratory approach which internal component (Luce, 1986; Ratcliff, 1988) could explain the difference between the conditions highlighted in the RTs distribution by fitting the drift diffusion model (DDM) to the data through DMAT toolbox (Vandekerckhove and Tuerlinckx, 2007, 2008).

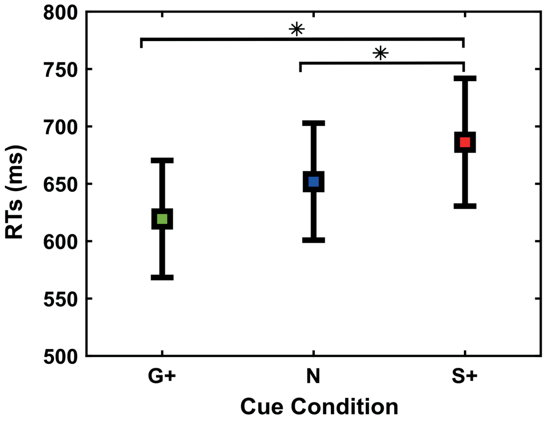


FIGURE 2
Reaction times [RTs (ms)] (mean and±1SEM) of Go Trials in the different cue conditions (G+, N, S+).

Following this model, the decision process is represented as an accumulation of evidence toward a decision criterion represented by a boundary. More specifically, subjects start to accumulate sensory evidence at an initial point (*z*) until the process reaches a boundary [or threshold (*a*)], and the response (choice) is generated. There are diverse parameters that can explain the features of the RTs distributions observed. Specifically: (a) the boundary separation (*a*), that is the distance between two boundaries, one corresponding to the correct responses and the other to wrong responses; b) the starting point of the evidence accumulation process (*z*); (c) the rate of growth toward the boundary [drift rate (*v*)]; (d) the duration of the non-decision process (T*er*); (e) the variability in starting point (*sz*); (f) the variability in non-decision time (*st*); (g) and the variability in stimulus quality (η) (Ratcliff, 1979, 2002; Voss et al., 2004; Ratcliff and McKoon, 2008).

In our investigation we postulate that the accumulation process (i.e., decision process) in our task is influenced by the Cue signal which, by providing information about the reward schedule, introduces a choice bias before the presentation of the Go signal (Ratcliff, 1985; Carpenter and Williams, 1995; Gold and Shadlen, 2002; Ratcliff and McKoon, 2008; Lauwereyns, 2011). Previous studies have identified two ways in which *a priori* information can bias the decision process: by shifting the starting point for the accumulation process of sensory information over time to a decision threshold (Edwards, 1965; Link and Heath, 1975; Ratcliff, 1985; Voss et al., 2004; Bogacz et al., 2006; Diederich and Busemeyer, 2006; Wagenmakers et al., 2008); or by changing the drift rate, i.e., the speed at which sensory information accumulates over time (Ashby, 1983; Ratcliff, 1985; Diederich and Busemeyer, 2006).

Both models would generate faster RTs in the Go+ condition and slower RTs in the Stop+ condition.

We therefore fitted the DDM to the RTs from each subject and each condition (Go +, Stop +, Neutral) with three different models. In the first both drift rate(v) and starting point(z) varied between conditions. In the second and the third either the drift rate(v) only, or the starting point(z) only, varied.

The RTs data were divided into percentiles, and we used a chi-square (χ^2) percentile-based method as an estimation method. The relative fit of the models was tested as follows: the difference in BIC scores was calculated for each individual subject and model and the model with the lowest BIC was found to be a better fit to the data.

Finally, we applied the non-parametric Friedman's test to assess whether the estimated parameters were different between conditions.

The RTs data were divided into percentiles, and we used a multinomial Likelihood percentile-based method as estimation method. Finally, we applied the non-parametric Friedman's test to assess whether the estimated parameters were different between conditions.

Data processing and analysis were performed by custom functions developed in Matlab.[1]

3. Results

3.1. Influence of reward on reaction time

One of the aims of the experiment was to assess how the reward context could modulate the strategy used by the subjects in order to execute or inhibit their movement. Therefore, we first tested whether the RTs changed between Cue Conditions using repeated measures ANOVA (Figure 2).

We found that subjects adjusted RTs according to the Cue Conditions [Go+ Condition (Mean = 619 ms, SD = 180 ms, SEM = 48 ms); Neutral Condition (Mean = 652 ms, SD = 191 ms, SEM = 51 ms); Stop+ Condition (Mean = 686 ms, SD = 208 ms, SEM = 56 ms)], $F(2,26) = 9.71$; $p < 0.001$.

Post-hoc analysis shows that the responses in both Go+ and Neutral Conditions were faster than responses in Stop+ Condition, $p = 0.01$ and $p = 0.02$. This suggests that the subjects were slower in responding in the Stop+ Condition, in which a higher reward was provided for Correct Stop Trials, while no significant difference was found between RTs in the Neutral and Go+ Condition, $p = 0.07$.

3.2. Influence of reward condition on inhibition strategy

To assess whether the reward prospects exerted an influence on the subjects' inhibition ability, for each Cue Condition we analyzed three variables: SSRTs, mean of SSDs, and p(response) to the Stop Signal. First, repeated measures ANOVA was used to analyze SSRTs between conditions [Go+ Condition (Mean = 230 ms, SD = 41 ms, SEM = 11 ms); Neutral Condition (Mean = 253 ms, SD = 46 ms, SEM = 12 ms); Stop+ Condition (Mean = 230 ms, SD = 32 ms, SEM = 8 ms)], as it measures the time it takes for each subject to successfully interrupt the action in progress (Figure 3). Results showed no significant differences between conditions, $F(2,26) = 3.17$; $p = 0.058$.

We also tested another closely related behavioral marker dependent on the inhibition process, namely the SSD, between Cue Conditions [Go+ Condition (Mean = 352 ms, SD = 179 ms, SEM = 48 ms); Neutral Condition (Mean = 368 ms, SD = 175 ms,

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[1] https://it.mathworks.com/

SEM = 46 ms); Stop+ Condition (Mean = 420 ms, SD = 195 ms, SEM = 52 ms)]. Specifically, SSDs can provide crucial insights into behavioral adjustments through the inhibition task (van Boxtel et al., 2001; Band et al., 2003). Repeated measures ANOVA analysis showed a main effect of Cue Conditions (Figure 4A) on SSDs $F(2,26) = 8.45$; $p = 0.001$.

Post-hoc analyses revealed that SSDs were significantly longer when correct performance was rewarded more in Stop Trials, i.e., Stop+ Condition, than at the Neutral and Go+ Condition ($p = 0.01$; $p = 0.03$, respectively), and no significant difference was found between SSDs in the Go+ and Neutral Condition ($p = 0.6$). Despite the increase in SSDs in the Neutral and Stop+ Conditions, subjects did not show significant differences in p(response) on Stop Trials (Figure 4B), $F(2,26) = 0.46$; $p = 0.6$, nor in the probability of Go omission, $F(2,26) = 2.19$; $p = 0.1$. These results suggest that the increase in SSDs between Cue Conditions shows a greater capacity for inhibition in subjects when correct Stop Trials were rewarded more than correct Go Trials.

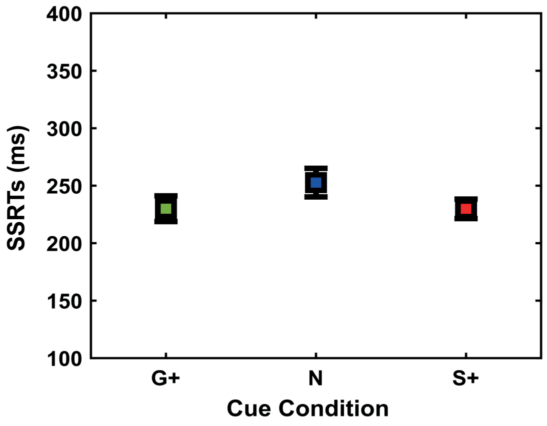

FIGURE 3
Stop signal reaction time [SSRT (ms)] (mean and±1SEM) estimated in the different cue conditions (G+, N, S+).

3.3. Proactive strategic adjustment to the reward conditions

Our analysis suggests that subjects coped with the task by lengthening their RTs according to the different Cue Conditions, while their probability of response (p(response)) and inhibition speed (SSRTs) were kept constant. These data suggest that the subject adopted a proactive strategy. If this was the case, we should expect that the SSDs changed accordingly to the RTs. Indeed, by slowing down their RTs, subjects should be able to inhibit at the same speed (SSRT), and at the same probability (p(response)) at longer SSDs. To test this hypothesis, we estimated the correlation between RTs and SSRTs in the different Cue Conditions (Figure 5A), and we found that there was no correlation (Pearson correlation, $r < 0.25$; $p > 0.5$). We then tested the correlation between RTs and SSDs in the different Cue Conditions (Figure 5B), and we found a significant positive correlation (Pearson correlation, $r > 0.97$, $p < 0.001$).

3.4. Prevalence of the effects in the population

Once we established that the results support the adoption of a proactive strategy to perform the task, we tested the prevalence in the population of the main effects we found. To this aim, we employed Bayesian inference by applying t-tests to paired within-subject samples at the first level to compare the distribution of RTs between Cue Conditions (Figure 6).

The population prevalence proportion of the within-subject t-test between RTs in the Go+ and Neutral Cue Conditions (Figure 6A) showed the MAP estimate of prevalence to be 0.85 (96% HPDI: [0.59 0.97]), whereas RTs in the Go+ vs. Stop+ (Figure 6B) and Stop+ vs. Neutral (Figure 6C) Conditions showed the MAP estimate of prevalence to be equal 1 (96% HPDI: [0.80 1]).

Based on this result, we concluded that it is highly probable that more than 59% of the population would show a true significant effect when comparing the Go+ condition to the Neutral condition, and

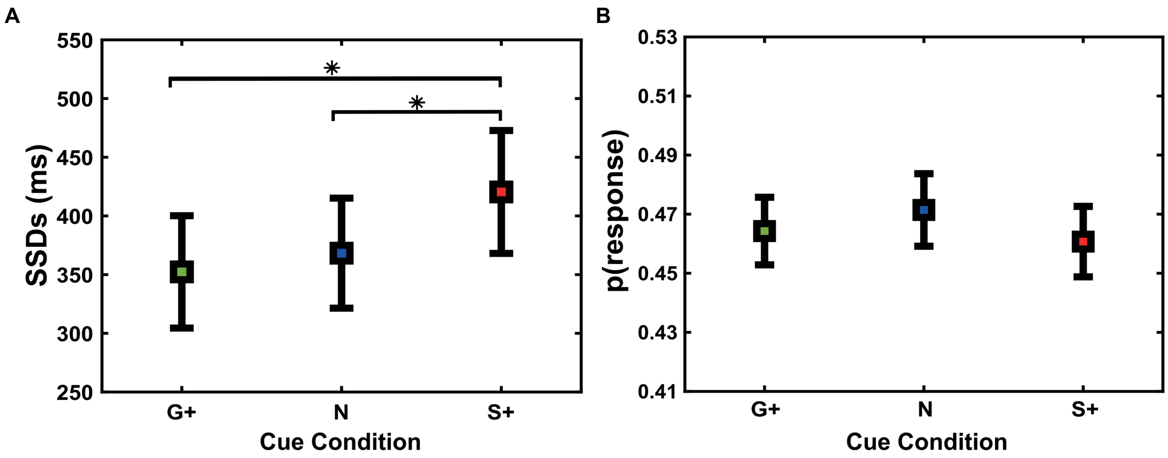

FIGURE 4
(A) Average stop-signal delays (SSD) (mean and±1SEM) and **(B)** probabilities to respond to the stop-signal [p(response)] (mean and±1SEM) as a function of cue conditions (G+, N, S+).

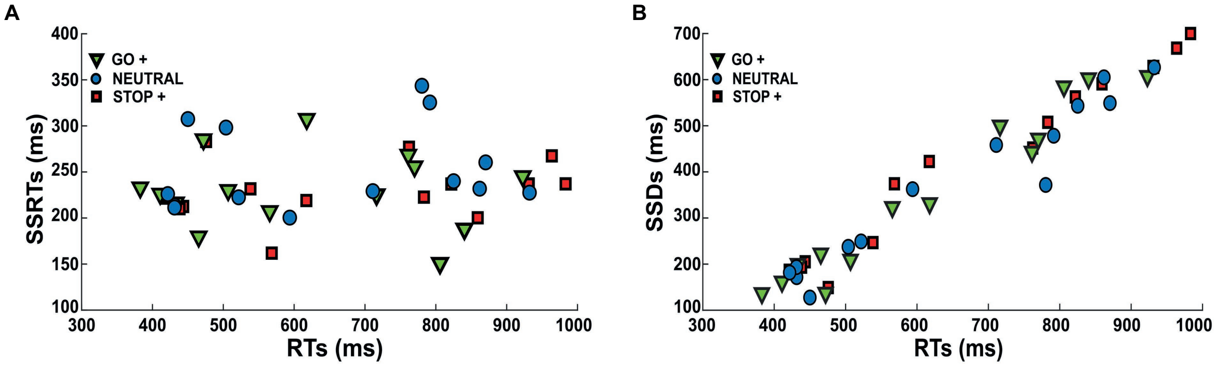

FIGURE 5

Scatter diagrams show **(A)** RTs as a function of SSRTs and **(B)** RTs as a function of SSDs in each Cue Condition.

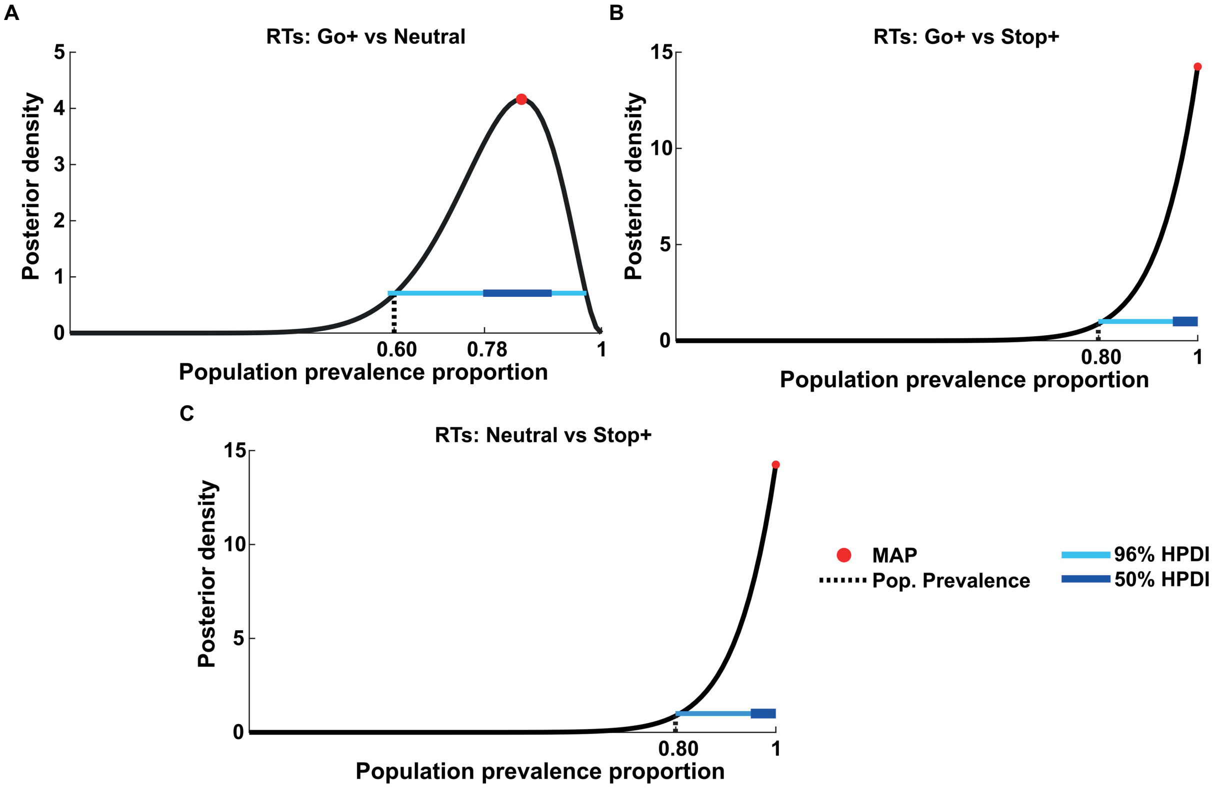

FIGURE 6

Bayesian inference of population prevalence for RTs. Each panel shows posterior density (black curve) with MAP (red circle), 50% and 96% HPDI (thick/thin blue lines), obtained from within-subject inference at $p=0.05$ of RTs for each Cue Condition interaction: **(A)** RTs tested on Go+ Condition versus Neutral Condition; **(B)** RTs tested on Go+ condition versus Stop+ Condition; **(C)** RTs tested on Stop+ Condition versus Neutral Condition.

we would also consider it highly probable that the result obtained between the Go+ vs. Stop+ and Stop+ vs. Neutral RTs would recur at 80% when tested in the same experiment.

We also tested the effect found for SSDs. Similarly, we applied the t-tests to paired within-subject samples at the first level to compare the SSD distribution between conditions (Figure 7).

The effects found in SSDs are not as strong as those shown in RTs. In fact, this analysis shows that if other subjects were to be tested in the same experiment, the probability of obtaining the same results is possible between 32% (MAP = 0.55, 96% HPDI: [0.28 0.79], 50% HPDI: [0.46 0.64], Figure 7A) and 39% of the tested subjects (MAP = 0.62, 96% HPDI [0.35 0.85], 50% HPDI: [0.46 0.64], Figures 7C,D).

These data integrate the previous findings by showing that despite the subjects employing the strategy of elongating the RTs when higher reward is provided for Stop than for Go trials, some change in the speed of inhibition can also be at play. In fact, as also shown by the SSRT results, the tendency to decrease SSRTs in the

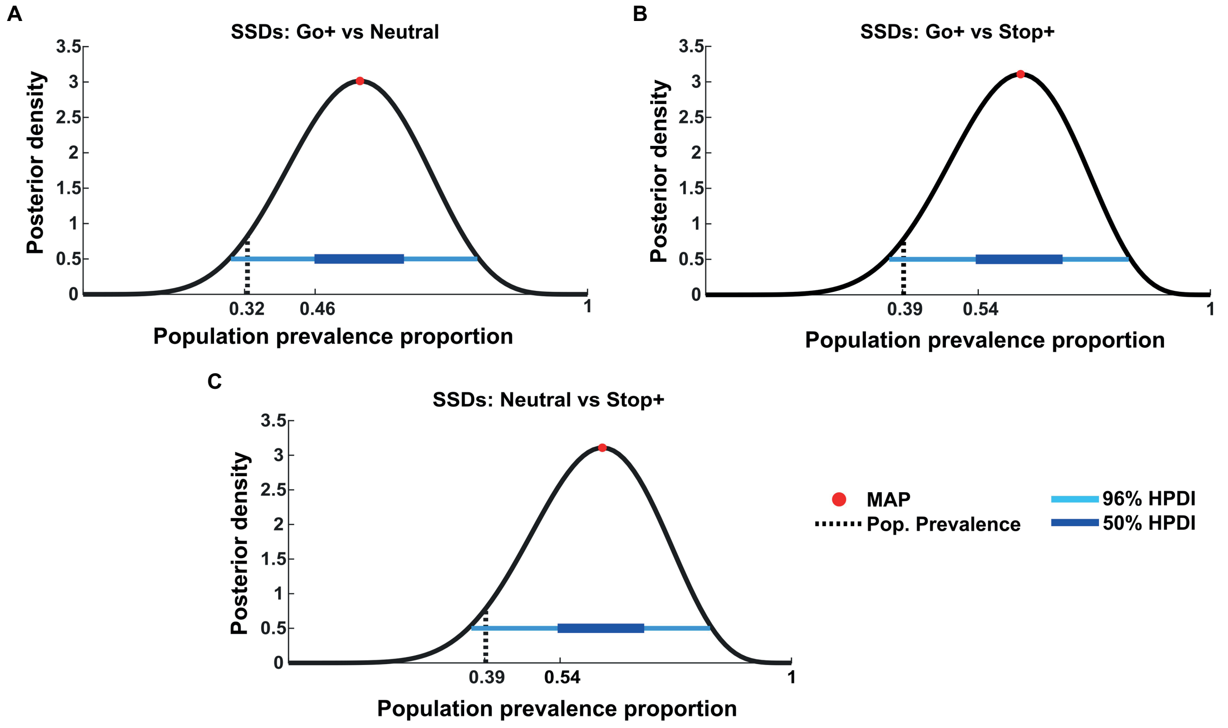

FIGURE 7
Bayesian inference of population prevalence for SSDs. Each panel shows posterior density (black curve) with MAP (red circle), 50% and 96% HPDI (thick/thin blue lines), obtained from within-subject inference at $p=0.05$ of RTs for each Cue Condition interaction: **(A)** SSDs tested on Go+ Condition versus Neutral Condition; **(B)** SSDs tested on Go+ Condition versus Stop+ Condition; **(C)** SSDs tested on Stop+ Condition versus Neutral Condition.

Stop+ Condition, could indicate that for some subjects the higher reward for Stop Trials can also lower SSRT.

3.5. Fitting the drift diffusion model to the RTs distribution

We evaluate different models to investigate which parameters of the DDM could explain the changes in RTs distributions associated with the different reward conditions. Specifically, in the Go+ condition the shortening of RTs with respect to the Stop+ condition can be explained by: a higher drift rate (drift rate (v)), i.e. a fast decision process; a higher starting point (starting point (z)) for the decision process, that has been set following the Cue signal; or a modulation of both (Figure 8A). We estimated three different models (model 1 = 'affect Drift and Starting point'; model 2 = 'effect only on v' and model 3 = 'effect only on z'). We also tested intermediate models to evaluate the goodness of the fit.

The sum of Bayesian information criterion values (BIC; Schwarz, 1978) across subjects show a lower value for the model 'effect only on z' than for the drift model (BIC: 'effect only on v' = 2.25 + e04; 'effect only on z' = 2.25 + e04; 'effect on drift and z'=: 2.18 + e04). At the individual level, we compared the BICs of the models within each subject for the two model without interaction, and we found that for 10 out of 14 subjects the fitting was better with 'effect only on z'; and for the others 4 showed better fitting was obtained for the model 'effect only on v'.

Finally, the mixed model, even at the individual level, had the lowest values of BIC. Therefore, we took this as the model that fitted best with our data.

To assess how the estimated parameters vary between conditions, we applied the Friedman test that shows a significant difference across conditions for the starting point(z) ($p < 0.01$), but no difference was found for the drift rate(v) across conditions. The post-hoc shows a significant difference between the Go+ condition and the Stop + condition ($p < 0.01$), but no difference is present between the Neutral condition and the Go+ ($p = 0.14$) and versus Stop+ ($p = 0.38$) (Figure 8B). To conclude the changes in RTs observed between conditions can be mostly related to changes in the starting point of the accumulation process.

4. Discussion

The primary goal of this study was to compare how different reward conditions affect the strategy of control in a complex context. Previous studies have shown that the reward perspective influences cognitive functions, such as working memory (Gilbert and Fiez, 2004; Beck et al., 2010) and attention (Krebs et al., 2009; Padmala et al., 2011; Stoppel et al., 2011; Schevernels et al., 2015). In these studies, the reward availability, compared to conditions when no reward was delivered, enabled an improvement in proactive processes through top-down control (Pessoa and Engelmann, 2010; Chelazzi et al., 2013). The few studies that have investigated the influence of reward on response inhibition have employed paradigms in which the motivation revolved around the presence or absence of reward (Scheres et al., 2001; Greenhouse and Wessel, 2013; Rosell-Negre et al., 2014), or specifically, for response inhibition the type of Stop Signal presented informed about the

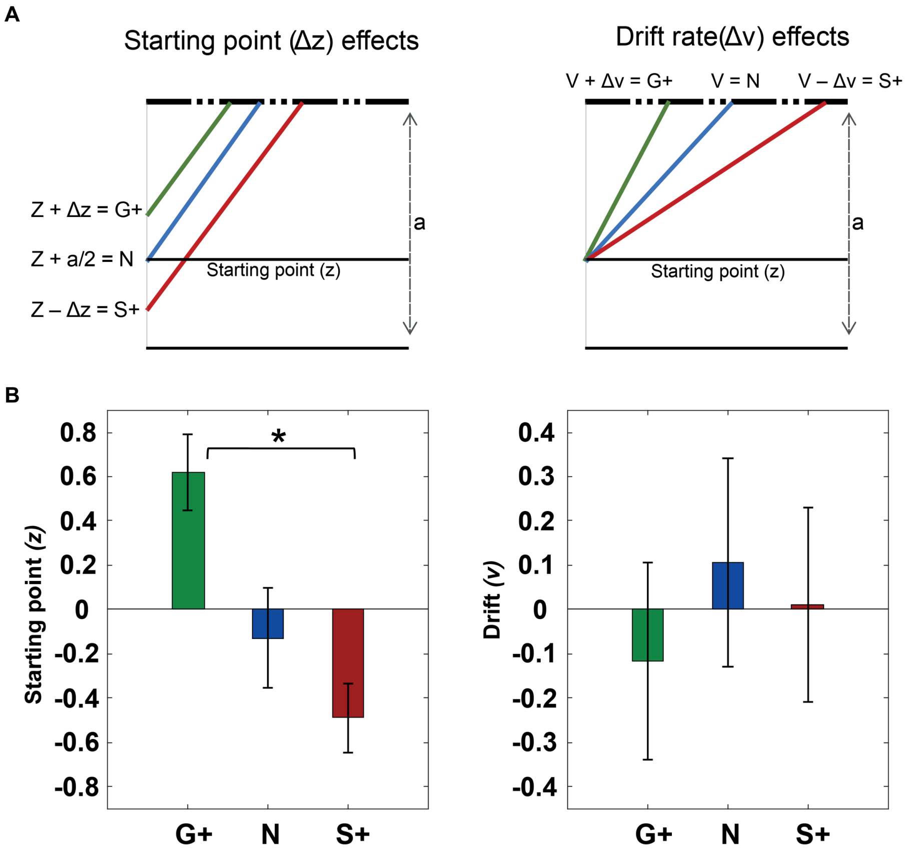

FIGURE 8
Fit data to drift diffusion model (DDM). **(A)** Fit data to drift diffusion model (DDM). **(A)** Effects explained with DDM. the effect at the starting point z, we assume that it is close to the boundary in the Go+ condition, in the middle of the threshold (a) in the neutral condition, and finally moving away from the correct boundary in the Stop+ condition. Similarly in the drift model (v), we assume that it increases for the Go+ condition and decreases in the Neutral and Stop+ conditions. **(B)** The zscore average of the effect of the starting point parameter (z) and the zscore average of the parameters of the drift rate(v) (right panel). Error bars represent 1 SE from the mean.

presence or type of reward (Boehler et al., 2012, 2014; Wilbertz et al., 2014).

In the wake of these studies, we administered a modified SST, in which we introduced different amounts of reward following a dynamic presentation that varied trial by trial, to investigate how reward influenced the proactive and/or reactive strategy on Go and Stop processes. Our results show that the value of the reward has an effect on the RTs of the subjects. Subjects tended to be faster when correctly responding to the Go Signal was rewarded more than correctly performing the Stop Trials, compared to the other context when response inhibition was rewarded more.

Subjects tended to respond faster when the Go trials were rewarded more than the Stop Trials, and vice versa. This is congruent with previous findings, revealing the effects of reward bias on Stop-signal task performance (Leotti and Wager, 2010; Padmala and Pessoa, 2010). Slowing down in the Stop+ versus Neutral and Go+ condition, can be attributed to adjustments in proactive inhibitory control by trading speed at the Go Trial for success at the Stop Trials (Verbruggen et al., 2009; Aron, 2011). These adjustments were performed according to the cues presented at the beginning of the trials.

No significant effect on SSRTs was observed across conditions, which is coherent with other studies (Logan et al., 1986; Ramautar et al., 2004; Lansbergen et al., 2007; Zandbelt et al., 2013; Verbruggen and McLaren, 2018; Andujar et al., 2022). This could be due to the strategy used by the subjects.

In our task a staircase algorithm has been employed to change the SSD according to the performance in Stop Trials. The goal of this procedure was to keep the p(response) as close as possible to 0.50. Therefore, an important index to consider in our study is SSD, and how it changed according to the context to provide information regarding the strategy that the subjects have been using during the task (van Boxtel et al., 2001; Band et al., 2003).

In line with the goal of the staircase procedure, we did not find a difference in p(response) between conditions; however, we found that SSDs correlated positively with RTs, and longer SSDs were attributed to the Stop + condition. This shows that the subjects were able to inhibit the movement at longer SSD by lengthening their RT. Thus, the higher reward for Correct Stop Trials prompted the subjects to slow down their response that, consequently, required the increase of SSD to obtain the p(response) by the staircase algorithm. In this context, we observed only slight changes in the SSRT, supporting the idea that subjects approached the task mostly changing their RT while keeping their speed of inhibition unaffected.

However, our prevalence analysis has shown that SSD changes were not as strong as RT changes. This suggests that the subjects could also have partially adopted another strategy, based on the concurrent modulation of the speed of inhibition. It is indeed possible that in Stop+ trials the subjects have also shortened their SSRT, thus making them able to inhibit at an even longer SSD.

Our results are consistent with the theoretical approach which suggests that adopting a proactive control strategy in reward conditions improves goal attainment (Braver, 2012). In this sense Jimura et al. (2010) argued that the adoption of a proactive control strategy involves the maintenance and preparatory updating of task goals, which facilitates performance in reward contexts.

We investigated the behavioral results by employing the Drift Diffusion Model and we found that in most subjects the choice bias is mainly determined by adjusting the starting point of the accumulation process rather than by changing the accumulation rate itself. This suggests that, at least in this study, proactive control is obtained by adjusting the starting point of the response preparation process following the Go presentation. Thus, following the Stop+ cue, the lowering of the starting point will require more time to reach the boundary producing longer RTs. These findings are in line with results obtained from cortical premotor neuronal recordings in primates performing similar tasks (Giamundo et al., 2021). Indeed, premotor neuronal activity reflects the level of motivation to move before the Go signal: higher activity for the Go+ than for Neutral and Stop+ conditions (see Figure 3 of Giamundo et al., 2021). This modulation is reminiscent of the starting point modulation that we observed. Furthermore, human studies that used model-based approaches to investigate bias in choice behavior show similar results(Ratcliff, 1988; Voss et al., 2004; Palmer et al., 2005; Bogacz et al., 2006; Forstmann et al., 2010; Mulder et al., 2012).

One of the interesting results of the study concerns the Neutral condition. Subjects tended to have RTs whose values were between the RTs of the Go+ and Stop+ Condition but had slightly longer SSDs compared to the Go+ Condition, and higher SSRTs compared to the other two Conditions, thus slightly increasing the p(response) in Stop trials.

It could be argued that this condition implies greater cognitive effort for the subject, because the reward of correct Go and Stop Trials have equal value, implying greater effort to do the two types of trials correctly.

In line with the theory of effort allocation, these results show that subjects are able to improve performance if the task has a high value relative to cognitive effort (i.e., Go+ and Stop+ Condition) and, conversely, performance decreases if the task has a low value relative to task demand(i.e., Neutral condition) (Kurzban et al., 2013; Thomson et al., 2015; Massar et al., 2016).

Instead, in the Go+ and Stop+ conditions, the higher reward and a lower one could be seen by the subject as a reinforcement (+30 points) and a punishment (+5 points, in accordance with the Cue Condition) by shifting the focus to performing one type of trials correctly rather than the other.

Moreover, previous studies suggest such reward perception encourages flexible behavior (Maddox and Markman, 2010), in fact in the Go+ and Stop+ Conditions, the strategy adopted changes and appears to be consistent with receiving the high reward (Verbruggen et al., 2017; Verbruggen and McLaren, 2018).

With these results, subsequent studies could investigate how reward value influences motor control, using electrophysiological measures of cognitive effort to test their relationship. Furthermore, the results obtained through Bayesian analysis show a reproducibility of the SSD-related effect of less than 40%. In order to verify whether a reactive strategy was used more in some subjects, a future study should also include testing the reactive strategy within the task.

5. Conclusion

In accordance with previous studies, subjects could employ different strategies to perform the task, including adjusting the speed of response or modulating the efficiency of inhibition. Subjects preferentially adjusted their speed of response, although in some cases a concurrent adjustment of the speed of inhibition could have been at play.

The investigation of strategic motor adjustments based on reward perspectives is relevant not only for understanding how action control is typically regulated, but also for studying genetic underpinnings of control strategies (Mione et al., 2015) and various groups of patients with cognitive control deficits (Brunamonti et al., 2011; Pani et al., 2013; Duprez et al., 2016; Olivito et al., 2017; Menghini et al., 2018). These studies will help to understand how the control processes (proactive and reactive) can be regulated by using reward perspectives as motivational factors.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The procedure was approved by the Ethics Committee of "Roma Tre" University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

PP and VG conceived the original idea. PP, EB, and SFe supervised the project. VG created the task and collected the data. PP, IM, and VG conceived and performed the data analysis. VG, IM, SR, and PP wrote the paper. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Andujar, M., Marc, I. B., Giuffrida, V., Ferraina, S., Brunamonti, E., and Pani, P. (2022). Response preparation affects cognitive motor control. *Hum. Factors* 00187208221132749:001872082211327. doi: 10.1177/00187208221132749

Aron, A. R. (2011). From reactive to proactive and selective control: developing a richer model for stopping inappropriate responses. *Biol. Psychiatry* 69, e55–e68. doi: 10.1016/j.biopsych.2010.07.024

Ashby, F. G. J. J. O. M. P. (1983). A biased random walk model for two choice reaction times. *J. Math. Psychol* 27, 277–297. doi: 10.1016/0022-2496(83)90011-1

Band, G. P., van der Molen, M. W., and Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychol.* 112, 105–142. doi: 10.1016/s0001-6918(02)00079-3

Bardella, G., Giarrocco, F., Giuffrida, V., Brunamonti, E., Pani, P., and Ferraina, S. (2023). Response inhibition in premotor cortex corresponds to a complex reshuffle of the mesoscopic information network. 2021.2003.2015.435381. J bioRxiv [Preprint]. doi: 10.1101/2021.03.15.435381

Bardella, G., Pani, P., Brunamonti, E., Giarrocco, F., and Ferraina, S. (2020). The small scale functional topology of movement control: Hierarchical organization of local activity anticipates movement generation in the premotor cortex of primates. *Neuroimage* 207:116354. doi: 10.1016/j.neuroimage.2019.116354

Beck, S. M., Locke, H. S., Savine, A. C., Jimura, K., and Braver, T. S. (2010). Primary and secondary rewards differentially modulate neural activity dynamics during working memory. *PLoS One* 5:e9251. doi: 10.1371/journal.pone.0009251

Boehler, C. N., Hopf, J.-M., Stoppel, C. M., and Krebs, R. M. (2012). Motivating inhibition – reward prospect speeds up response cancellation. *Cognition* 125, 498–503. doi: 10.1016/j.cognition.2012.07.018

Boehler, C. N., Schevernels, H., Hopf, J.-M., Stoppel, C. M., and Krebs, R. M. (2014). Reward prospect rapidly speeds up response inhibition via reactive control. *Cogn. Affect. Behav. Neurosci.* 14, 593–609. doi: 10.3758/s13415-014-0251-5

Bogacz, R., Brown, E., Moehlis, J., Holmes, P., and Cohen, J. D. (2006). The physics of optimal decision making: a formal analysis of models of performance in two-alternative forced-choice tasks. *Psychol. Rev.* 113, 700–765. doi: 10.1037/0033-295x.113.4.700

Boucher, L., Palmeri, T. J., Logan, G. D., and Schall, J. D. (2007). Inhibitory control in mind and brain: an interactive race model of countermanding saccades. *Psychol. Rev.* 114, 376–397. doi: 10.1037/0033-295x.114.2.376

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends Cogn. Sci.* 16, 106–113. doi: 10.1016/j.tics.2011.12.010

Braver, T. S., Gray, J. R., and Burgess, G. C. (2007). "Explaining the many varieties of working memory variation: dual mechanisms of cognitive control" in *Variation in working memory* (New York, NY, US: Oxford University Press), 76–106.

Brunamonti, E., Ferraina, S., and Paré, M. (2012). Controlled movement processing: evidence for a common inhibitory control of finger, wrist, and arm movements. *Neuroscience* 215, 69–78. doi: 10.1016/j.neuroscience.2012.04.051

Brunamonti, E., Pani, P., Papazachariadis, O., Onorati, P., Albertini, G., and Ferraina, S. (2011). Cognitive control of movement in down syndrome. *Res. Dev. Disabil.* 32, 1792–1797. doi: 10.1016/j.ridd.2011.03.008

Carpenter, R. H., and Williams, M. L. (1995). Neural computation of log likelihood in control of saccadic eye movements. *Nature* 377, 59–62. doi: 10.1038/377059a0

Chelazzi, L., Perlato, A., Santandrea, E., and Della Libera, C. (2013). Rewards teach visual selective attention. *Vis. Res.* 85, 58–72. doi: 10.1016/j.visres.2012.12.005

Diederich, A., and Busemeyer, J. R. (2006). Modeling the effects of payoff on response bias in a perceptual discrimination task: bound-change, drift-rate-change, or two-stage-processing hypothesis. *Percept. Psychophys.* 68, 194–207. doi: 10.3758/bf03193669

Duprez, J., Houvenaghel, J.-F., Naudet, F., Dondaine, T., Auffret, M., Robert, G., et al. (2016). Evaluating cognitive action control using eye-movement analysis: an oculomotor adaptation of the simon task. *Front. Hum. Neurosci.* 10:84. doi: 10.3389/fnhum.2016.00084

Edwards, W. J. J. O. M. P. (1965). Optimal strategies for seeking information: models for statistics, choice reaction times, and human information processing. *J. Math. Psychol.* 2, 312–329. doi: 10.1016/0022-2496(65)90007-6

Engelmann, J., Damaraju, E., Padmala, S., and Pessoa, L. (2009). Combined effects of attention and motivation on visual task performance: transient and sustained motivational effects. *Front. Hum. Neurosci.* 3:3. doi: 10.3389/neuro.09.004.2009

Engelmann, J., and Pessoa, L. (2007). Motivation sharpens exogenous spatial attention. *Emotion* 7, 668–674. doi: 10.1037/1528-3542.7.3.668

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. (2009). Statistical power analyses using G*power 3.1: tests for correlation and regression analyses. *Behav. Res. Methods* 41, 1149–1160. doi: 10.3758/BRM.41.4.1149

Faul, F., Erdfelder, E., Lang, A.-G., and Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Fiori, L., Marc, I. B., Ramawat, S., Tatarelli, T., Chini, G., Ranavolo, A., et al. (2022). Motor inhibition parameters are reflected in the kinetic and kinematic of gait initiation in a step version of the Stop Signal Task. *Gait & Posture.* 97:9. doi: 10.1016/j.gaitpost.2022.09.021

Forstmann, B. U., Brown, S., Dutilh, G., Neumann, J., and Wagenmakers, E. J. (2010). The neural substrate of prior information in perceptual decision making: a model-based analysis. *Front. Hum. Neurosci.* 4:40. doi: 10.3389/fnhum.2010.00040

Giamundo, M., Giarrocco, F., Brunamonti, E., Fabbrini, F., Pani, P., and Ferraina, S. (2021). Neuronal activity in the premotor cortex of monkeys reflects both cue salience and motivation for action generation and inhibition. *J. Neurosci.* 41, 7591–7606. doi: 10.1523/JNEUROSCI.0641-20.2021

Giarrocco, F., Bardella, G., Giamundo, M., Fabbrini, F., Brunamonti, E., Pani, P., et al. (2021). Neuronal dynamics of signal selective motor plan cancellation in the macaque dorsal premotor cortex. *Cortex* 135, 326–340. doi: 10.1016/j.cortex.2020.09.032

Gilbert, A. M., and Fiez, J. A. (2004). Integrating rewards and cognition in the frontal cortex. *Cogn. Affect. Behav. Neurosci.* 4, 540–552. doi: 10.3758/CABN.4.4.540

Gold, J. I., and Shadlen, M. N. (2002). Banburismus and the brain: decoding the relationship between sensory stimuli, decisions, and reward. *Neuron* 36, 299–308. doi: 10.1016/s0896-6273(02)00971-6

Greenhouse, I., and Wessel, J. R. (2013). EEG signatures associated with stopping are sensitive to preparation. *Psychophysiology* 50, 900–908. doi: 10.1111/psyp.12070

Hanes, D. P., and Carpenter, R. H. S. (1999). Countermanding saccades in humans. *Vis. Res.* 39, 2777–2791. doi: 10.1016/S0042-6989(99)00011-5

Hartigan, P. M. (1985). Algorithm AS 217: computation of the dip statistic to test for Unimodality. *J. R. Stat. Soc. Ser. C* 34, 320–325. doi: 10.2307/2347485

Hartigan, J. A., and Hartigan, P. M. (1985). The dip test of Unimodality. *Ann. Stat.* 13, 70–84. doi: 10.1214/aos/1176346577

Hervault, M., Zanone, P.-G., Buisson, J.-C., and Huys, R. (2022). Hold your horses: differences in EEG correlates of inhibition in cancelling and stopping an action. *Neuropsychologia* 172:108255. doi: 10.1016/j.neuropsychologia.2022.108255

Ince, R. A. A., Kay, J. W., and Schyns, P. G. (2022). Within-participant statistics for cognitive science. *Trends Cogn. Sci.* 26, 626–630. doi: 10.1016/j.tics.2022.05.008

Ince, R. A. A., Paton, A. T., Kay, J. W., and Schyns, P. G. (2021). Bayesian inference of population prevalence. *elife* 10:e62461. doi: 10.7554/eLife.62461

Jimura, K., Locke, H. S., and Braver, T. S. J. P. O. T. N. A. O. S. (2010). Prefrontal cortex mediation of cognitive enhancement in rewarding motivational contexts. *PNAS* 107, 8871–8876. doi: 10.1073/pnas.1002007107

Krebs, R. M., Schott, B. H., Schütze, H., and Düzel, E. (2009). The novelty exploration bonus and its attentional modulation. *Neuropsychologia* 47, 2272–2281. doi: 10.1016/j.neuropsychologia.2009.01.015

Kurzban, R., Duckworth, A., Kable, J. W., and Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behav. Brain Sci.* 36, 661–679. doi: 10.1017/s0140525x12003196

Lansbergen, M. M., Böcker, K. B., Bekker, E. M., and Kenemans, J. L. J. C. N. (2007). Neural correlates of stopping and self-reported impulsivity. *Clin. Neurophysiol.* 118, 2089–2103. doi: 10.1016/j.clinph.2007.06.011

Lauwereyns, J. (2011). *The anatomy of bias: How neural circuits weigh the options*. Cambridge, MA: MIT Press.

Leotti, L. A., and Wager, T. D. (2010). Motivational influences on response inhibition measures. *J. Exp. Psychol. Hum. Percept. Perform.* 36, 430–447. doi: 10.1037/a0016802

Link, S., and Heath, R. J. P. (1975). A sequential theory of psychological discrimination. *Psychometrika* 40, 77–105. doi: 10.1007/BF02291481

Logan, G. D. (1994). "On the ability to inhibit thought and action: a users' guide to the stop signal paradigm" in *Inhibitory processes in attention, memory, and language* (San Diego, CA, US: Academic Press), 189–239.

Logan, G. D., and Burkell, J. J. J. O. E. P. H. P.Performance (1986). Dependence and independence in responding to double stimulation: a comparison of stop, change, and dual-task paradigms. *J. Exp. Psychol. Hum. Percept. Perform.* 12, 549–563. doi: 10.1037/0096-1523.12.4.549

Logan, G. D., and Cowan, W. B. (1984). On the ability to inhibit thought and action: a theory of an act of control. *Psychol. Rev.* 91, 295–327. doi: 10.1037/0033-295X.91.3.295

Luce, R.D. (1986). *Response times: their role in inferring elementary mental organization.* New York: Oxford University Press.

Maddox, W. T., and Markman, A. B. (2010). The motivation-cognition Interface in learning and decision-making. *Curr. Dir. Psychol. Sci.* 19, 106–110. doi: 10.1177/0963721410364008

Marc, I. B. G. V., Ramawat, S., Fiori, L., Fontana, R., Bardella, G., Fagioli, S., et al. (2023). Restart errors reaction time of a two-step inhibition process account for the violation of the race model's independence in multi-effector selective stop signal task. *Front. Hum. Neurosci.* 17:1106298. doi: 10.3389/fnhum.2023.1106298

Massar, S. A., Lim, J., Sasmita, K., and Chee, M. W. (2016). Rewards boost sustained attention through higher effort: a value-based decision making approach. *Biol. Psychol.* 120, 21–27. doi: 10.1016/j.biopsycho.2016.07.019

Menghini, D., Armando, M., Calcagni, M., Napolitano, C., Pasqualetti, P., Sergeant, J. A., et al. (2018). The influence of generalized anxiety disorder on executive functions in children with ADHD. *Eur. Arch. Psychiatry Clin. Neurosci.* 268, 349–357. doi: 10.1007/s00406-017-0831-9

Mione, V., Canterini, S., Brunamonti, E., Pani, P., Donno, F., Fiorenza, M. T., et al. (2015). Both the COMT Val158Met single-nucleotide polymorphism and sex-dependent differences influence response inhibition. *Front. Behav. Neurosci.* 9:127. doi: 10.3389/fnbeh.2015.00127

Mirabella, G., Pani, P., and Ferraina, S. (2008). Context influences on the preparation and execution of reaching movements. *Cogn. Neuropsychol.* 25, 996–1010. doi: 10.1080/02643290802003216

Mohanty, A., Gitelman, D. R., Small, D. M., and Mesulam, M. M. (2008). The spatial attention network interacts with limbic and monoaminergic systems to modulate motivation-induced attention shifts. *Cereb. Cortex* 18, 2604–2613. doi: 10.1093/cercor/bhn021

Montanari, R., Giamundo, M., Brunamonti, E., Ferraina, S., and Pani, P. (2017). Visual salience of the stop-signal affects movement suppression process. *Exp. Brain Res.* 235, 2203–2214. doi: 10.1007/s00221-017-4961-0

Mulder, M. J., Wagenmakers, E.-J., Ratcliff, R., Boekel, W., and Forstmann, B. U. (2012). Bias in the brain: a diffusion model analysis of prior probability and potential payoff. *J. Neurosci.* 32, 2335–2343. doi: 10.1523/JNEUROSCI.4156-11.2012

Olivito, G., Brunamonti, E., Clausi, S., Pani, P., Chiricozzi, F. R., Giamundo, M., et al. (2017). Atrophic degeneration of cerebellum impairs both the reactive and the proactive control of movement in the stop signal paradigm. *Exp. Brain Res.* 235, 2971–2981. doi: 10.1007/s00221-017-5027-z

Padmala, S., Bauer, A., and Pessoa, L. (2011). Negative emotion impairs conflict-driven executive control. *Front. Psychol.* 2:192. doi: 10.3389/fpsyg.2011.00192

Padmala, S., and Pessoa, L. (2010). Interactions between cognition and motivation during response inhibition. *Neuropsychologia* 48, 558–565. doi: 10.1016/j.neuropsychologia.2009.10.017

Palmer, J., Huk, A. C., and Shadlen, M. N. (2005). The effect of stimulus strength on the speed and accuracy of a perceptual decision. *J. Vis.* 5, 1–404. doi: 10.1167/5.5.1

Pani, P., Di Bello, F., Brunamonti, E., D'Andrea, V., Papazachariadis, O., and Ferraina, S. (2014). Alpha- and beta-band oscillations subserve different processes in reactive control of limb movements. *Front. Behav. Neurosci.* 8:383. doi: 10.3389/fnbeh.2014.00383

Pani, P., Giamundo, M., Giarrocco, F., Mione, V., Fontana, R., Brunamonti, E., et al. (2022). Neuronal population dynamics during motor plan cancellation in nonhuman primates. *Proc. Natl. Acad. Sci. U. S. A.* 119:e2122395119. doi: 10.1073/pnas.2122395119

Pani, P., Giarrocco, F., Giamundo, M., Montanari, R., Brunamonti, E., and Ferraina, S. (2018). Visual salience of the stop signal affects the neuronal dynamics of controlled inhibition. *Sci. Rep.* 8:14265. doi: 10.1038/s41598-018-32669-8

Pani, P., Menghini, D., Napolitano, C., Calcagni, M., Armando, M., Sergeant, J. A., et al. (2013). Proactive and reactive control of movement are differently affected in attention deficit hyperactivity disorder children. *Res. Dev. Disabil.* 34, 3104–3111. doi: 10.1016/j.ridd.2013.06.032

Pessoa, L., and Engelmann, J. B. (2010). Embedding reward signals into perception and cognition. *Front. Neurosci.* 4:17. doi: 10.3389/fnins.2010.00017

Ramautar, J., Kok, A., and Ridderinkhof, K. J. B.cognition (2004). Effects of stop-signal probability in the stop-signal paradigm: the N2/P3 complex further validated. *Brain Cogn.* 56, 234–252. doi: 10.1016/j.bandc.2004.07.002

Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychol. Bull.* 86, 446–461. doi: 10.1037/0033-2909.86.3.446

Ratcliff, R. (1985). Theoretical interpretations of the speed and accuracy of positive and negative responses. *Psychol. Rev.* 92, 212–225. doi: 10.1037/0033-295X.92.2.212

Ratcliff, R. (1988). Continuous versus discrete information processing modeling accumulation of partial information. *Psychol. Rev.* 95, 238–255. doi: 10.1037/0033-295x.95.2.238

Ratcliff, R. (2002). A diffusion model account of response time and accuracy in a brightness discrimination task: fitting real data and failing to fit fake but plausible data. *Psychon. Bull. Rev.* 9, 278–291. doi: 10.3758/bf03196283

Ratcliff, R., and McKoon, G. (2008). The diffusion decision model: theory and data for two-choice decision tasks. *Neural Comput.* 20, 873–922. doi: 10.1162/neco.2008.12-06-420

Rosell-Negre, P., Bustamante, J. C., Fuentes-Claramonte, P., Costumero, V., Benabarre, S., and Barros-Loscertales, A. (2014). Reward anticipation enhances brain activation during responseinhibition. *Cogn. Affect. Behav. Neurosci.* 14, 621–634. doi: 10.3758/s13415-014-0292-9

Scangos, K. W., and Stuphorn, V. (2010). Medial frontal cortex motivates but does not control movement initiation in the countermanding task. *J. Neurosci.* 30, 1968–1982. doi: 10.1523/jneurosci.4509-09.2010

Schall, J. D., Palmeri, T. J., and Logan, G. D. (2017). Models of inhibitory control. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 372:20160193. doi: 10.1098/rstb.2016.0193

Scheres, A., Oosterlaan, J., and Sergeant, J. A. (2001). Response inhibition in children with DSM-IV subtypes of AD/HD and related disruptive disorders: the role of reward. *Child Neuropsychol.* 7, 172–189. doi: 10.1076/chin.7.3.172.8746

Schevernels, H., Bombeke, K., Van der Borght, L., Hopf, J. M., Krebs, R. M., and Boehler, C. N. (2015). Electrophysiological evidence for the involvement of proactive and reactive control in a rewarded stop-signal task. *NeuroImage* 121, 115–125. doi: 10.1016/j.neuroimage.2015.07.023

Schwarz, G. (1978). Estimating the dimension of a model. *Ann. Stat.* 6, 461–464. doi: 10.1214/aos/1176344136

Stoppel, C. M., Boehler, C. N., Strumpf, H., Heinze, H. J., Hopf, J. M., and Schoenfeld, M. A. (2011). Neural processing of reward magnitude under varying attentional demands. *Brain Res.* 1383, 218–229. doi: 10.1016/j.brainres.2011.01.095

Thomson, D. R., Besner, D., and Smilek, D. (2015). A resource-control account of sustained attention: evidence from mind-wandering and vigilance paradigms. *Perspect. Psychol. Sci.* 10, 82–96. doi: 10.1177/1745691614556681

van Boxtel, G. J. M., van der Molen, M. W., Jennings, J. R., and Brunia, C. H. M. (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biol. Psychol.* 58, 229–262. doi: 10.1016/S0301-0511(01)00117-X

Vandekerckhove, J., and Tuerlinckx, F. (2007). Fitting the Ratcliff diffusion model to experimental data. *Psychon. Bull. Rev.* 14, 1011–1026. doi: 10.3758/BF03193087

Vandekerckhove, J., and Tuerlinckx, F. (2008). Diffusion model analysis with MATLAB: a DMAT primer. *Behav. Res. Methods* 40, 61–72. doi: 10.3758/BRM.40.1.61

Verbruggen, F., Aron, A. R., Band, G. P. H., Beste, C., Bissett, P. G., Brockett, A. T., et al. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *elife* 8:e46323. doi: 10.7554/eLife.46323

Verbruggen, F., Chambers, C. D., Lawrence, N. S., and McLaren, I. P. (2017). Winning and losing: effects on impulsive action. *J. Exp. Psychol. Hum. Percept. Perform.* 43, 147–168. doi: 10.1037/xhp0000284

Verbruggen, F., Logan, G. D. J. N., and Reviews, B. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neurosci. Biobehav. Rev.* 33, 647–661. doi: 10.1016/j.neubiorev.2008.08.014

Verbruggen, F., and McLaren, R. (2018). Effects of reward and punishment on the interaction between going and stopping in a selective stop-change task. *Psychol. Res.* 82, 353–370. doi: 10.1007/s00426-016-0827-5

Vince, M. A. (1948). The intermittency of control movements and the psychological refractory period. *Br. J. Psychol. Gen. Sect.* 38, 149–157. doi: 10.1111/j.2044-8295.1948.tb01150.x

Voss, A., Rothermund, K., and Voss, J. (2004). Interpreting the parameters of the diffusion model: an empirical validation. *Mem. Cogn.* 32, 1206–1220. doi: 10.3758/bf03196893

Wagenmakers, E. J., van der Maas, H. L., Dolan, C. V., and Grasman, R. P. (2008). EZ does it! Extensions of the EZ-diffusion model. *Psychon. Bull. Rev.* 15, 1229–1235. doi: 10.3758/pbr.15.6.1229

Wilbertz, T., Deserno, L., Horstmann, A., Neumann, J., Villringer, A., Heinze, H.-J., et al. (2014). Response inhibition and its relation to multidimensional impulsivity. *Neuroimage* 103, 241–248. doi: 10.1016/j.neuroimage.2014.09.021

Zandbelt, B. B., Bloemendaal, M., Neggers, S. F., Kahn, R. S., and Vink, M. J. H. B. M. (2013). Expectations and violations: delineating the neural network of proactive inhibitory control. *Hum. Brain Mapp.* 34, 2015–2024. doi: 10.1002/hbm.22047

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The implicit preference evaluation for the ceramic tiles with different visual features: Evidence from an event-related potential study

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Background: Ceramic tiles are popular because of their various forms, and they are often used to decorate the environment. However, few studies have applied objective methods to explore the implicit preference and visual attention of people toward ceramic tile features. Using event-related potential technology can provide neurophysiological evidence for the study and applications of tiles.

Materials and methods: This study explored the influence of pattern, lightness, and color system factors of ceramic tiles on the preferences of people using a combination of subjective questionnaires and event-related potential (ERP) technology. Twelve different conditions of tiles (2×3×2) were used as stimuli. EEG data were collected from 20 participants while they watched the stimuli. Subjective preference scores and average ERPs were analyzed using analysis of variance and correlation analysis.

Results: (1) Pattern, lightness, and color system factors significantly affected the subjective preference scores for tiles; the unpatterned tiles, light-toned tiles, and warm-colored tiles received higher preference scores. (2) The preferences of people for different features of tiles moderated ERP amplitudes. (3) The light-toned tiles with a high preference score caused a greater N100 amplitude than the medium-toned and dark-toned tiles; and the patterned tiles and warm-colored tiles with low preference scores induced greater P200 and N200 amplitudes.

Discussion: In the early stage of visual processing, light-toned tiles attracted more attention, possibly because of the positive emotional effects related to the preference. The greater P200 and N200 elicited by the patterned and neutral-colored tiles in the middle stage of visual processing indicates that patterned and neutral-colored tiles attracted more attention. This may be due to negativity bias, where more attention is allocated to negative stimuli that people strongly dislike. From the perspective of cognitive processes, the results indicate that the lightness of ceramic tiles is the factor that people first detect, and the visual processing of pattern and color system factors of ceramic tiles belong to a higher level of visual processing. This study provides a new perspective and relevant information for assessing the visual characteristics of tiles for environmental designers and marketers involved in the ceramic tiles industry.

KEYWORDS

event-related potentials, implicit preference, ceramic tiles, visual features, N100, P200, N200

1. Introduction

As common decorative materials, tiles are widely used in both private and public environments. For example, ceramic tiles are the most popular materials for interior floor decoration (China Building Sanitary Ceramics Association, 2021). Tiles are not only representative of fashion but also provide a decorative environment through a combination of patterns, colors, and other design features (Albors-Garrigós et al., 2009). In daily life, people's contact with ceramic tiles depends mainly on their vision (Artacho et al., 2020). Therefore, the design of tiles is primarily focused on the visual aspects. Some studies have correlated the visual features of design with human preferences (Mugge and Schoormans, 2012; Guo et al., 2019). For example, Agost and Vergara (2014) have found through questionnaires that the meaning and emotions (e.g., Well-being, calm, nervous.) contained in tiles with different features can influence the preferences of people. However, there are few studies on the preferences of tiles, especially on physiological responses (Chen and Cheng, 2022). Studying the preferences of people for tiles with different characteristics can help designers further improve the human experience.

Preference refers to how much people like a product (Zajonc and Markus, 1982; Roberts, 2007) and is crucial to the study of industrial design (Park et al., 2005). The preferences of people include an evaluation of the esthetic quality of the design. The object that people prefer often leads to a pleasant experience, whereas the object they do not prefer may lead to a negative experience (Palmer et al., 2013). Assessing the preferences of people for products can help improve product design and make products succeed in the competitive market (Macdonald et al., 2009; Orsborn and Cagan, 2009). Product form affects user preferences and plays an important role in purchasing decisions (Guo et al., 2016). The theory of Kansei engineering connects the formal characteristics of product design with the preferences of people and converts emotional preferences into words to guide product design (Nagamachi, 2002). Several important achievements have been made depending on Kansei Engineering. However, the commonly used methods, such as questionnaires and interviews, may not be able to obtain physiological evidence related to the preference (Ding et al., 2016). In recent years, many researchers have studied product preferences by evaluating the degree of preference for a specific product design appearance through physiological measurement methods (Wang et al., 2012; Ma et al., 2015). Research on preferences has gradually turned to more concretization. For example, Ma et al. (2015) found through an event-related potential (ERP) study that architectures with low preference scores attracted attention in the middle stage of visual processing. People's preferred appearance of robots may attract attention in the early stages of visual processing (Guo et al., 2022). Therefore, specific experiments need to be conducted. In real life, most people do not make conscious preference judgments after seeing tiles; therefore, this study focused on people's implicit preferences for different types of tiles. To avoid the influence of participant intention, this study chose an implicit preference assessment task (Wang et al., 2012).

Research on the preferences of tiles has received some attention. Serrano et al. (2013) found that participants' satisfaction scores with the tiles significantly increased when they changed the tiles to their preferred type in an virtual reality research. Through a questionnaire survey, Agost and Vergara (2014) found that light-toned tile floors could bring people a happier sense of a bright and spacious environment compared to dark-toned tile floors. Therefore, this study evaluates the preference for tile floors with different features from the aspect of appearance. In a previous study, we found that different tile preferences could modulate neural activity. Specifically, the like-tiles induced more brain activity than dislike-tiles in the early visual stage. After that, the disliked-tiles induced more brain activity than the like-tiles in the middle and late visual stages (Chen and Cheng, 2022). Nevertheless, people may have different experiences with different tile types. For example, light-toned tiles bring people feelings of pleasure and relaxation (Agost and Vergara, 2014). Previous studies have shown that different levels of preference for tiles trigger differences in ERPs (Chen and Cheng, 2022). However, the preference and neural responses that people generate for tiles with different features are still unknown. Exploring the esthetic preferences and neural responses of ceramic tiles with different visual characteristics can help designers and researchers to understand people's perceptions of ceramic tiles. Furthermore, the perception information about different tiles can help designers improve the design effect according to specific needs. Artacho et al. (2020) found through questionnaires that pattern, lightness, and color are the most important factors in terms of the human visual perception of tiles, thus identifying the three factors of tiles (pattern, lightness, and color) in this study. In contrast to our previous study (Chen and Cheng, 2022), the tiles in this study were applied to the indoor environment rather than presented as a single tile to make the participants feel more realistic. Furthermore, this study explores the influence of factors such as pattern, lightness, and color system.

In terms of research methods, most previous researchers have often used questionnaire as a quantitative research tool. Questionnaires are advantagesous because they afford a large sample size and can collect a large amount of information. However, participants' responses are not always recorded instantly, and some responses may differ from their actual experiences, and the development of neurophysiology provides a more objective method of visual perception research for investigating people's feelings (Ding et al., 2016; Zhang, 2020). In terms of neurophysiological measurement, La Parra-Hernandz et al. conducted a study using electromyogram (EMG) and galvanic skin reflex (GSR) techniques and found that different tiles could cause changes in arousal but not in valence (Laparra-Hernández et al., 2009). Nevertheless, some researchers have found that participants' age, gender, body temperature, skin humidity, and respiratory rate tend to affect GSR results, leading to difficulties in comparing GSR results (Guo et al., 2019). In addition, the environment can significantly affect experimental results. Some researchers have used real environments for their experiments (Artacho et al., 2020). However, real environments require many resources, and interference factors in realistic experimental environments can affect research results. Therefore, this study was conducted in a laboratory setting.

ERP recorded by electroencephalography (EEG) has the advantages of high time precision and no trauma to participants, and it can be used for physiological measurements, which cannot be achieved by questionnaires or interviews (Daliri, 2013; Zeng et al., 2013; Jiang et al., 2018; Hou and Yang, 2021). Previous neurological studies on visual perception have indicated that human visual processing is usually related to mechanisms such as perception, attention, memory, reward, and emotional processing (Beudt and Jacobsen, 2015; Righi et al., 2017). The ERP technique performs well in measuring visual perception of stimuli (Bayer and Schacht, 2014; Lin et al., 2015). These results were obtained by studying the characteristics of different ERP components such as N100, P200, and N200.

Some early and middle ERP components can reveal attentional resource allocation (Song and Zhao, 2012). The N100 (a negative-going electrical potential, usually peaking around 100 ms after stimulation) is sensitive to low-level visual features and reveals the attentional allocation in perceptual processing (Luck et al., 2000; Vogel and Luck, 2000). Regarding P200 (a positive-going electrical potential that peaks around 100–200 ms after stimulation), many researchers have pointed out that it is correlated to visual perception (de Tommaso et al., 2008; Handy et al., 2010), and reveals the attentional allocation (Kosonogov et al., 2019). The N200 is related to automatic stimulus recognition, the formation of higher-order cognitive processes, and selective attention (Ernst et al., 2013; Li et al., 2013).

Emotion is a critical factor that affects people's perceptions (Rolls, 2017). It strongly determines attractive and repulsive behaviors (Damasio and Carvalho, 2013; Righi et al., 2014). The cognitive process of esthetic preference involves the participation of emotions (Chatterjee, 2004; Brown et al., 2011). In affect-based assessments, preference is correlated with emotion (positive/pleasant or negative/unpleasant), which can produce different distributions of attention that are reflected in the amplitudes of the ERP components (Pessoa, 2008; Guo et al., 2022). Many researchers have demonstrated that a preference judgment for a design can influence attention formation and ERP amplitude (Handy et al., 2010; Beudt and Jacobsen, 2015; Cao et al., 2021).

For the tiles, in a previous ERP study, we found that the preference factor modulated the ERP amplitudes. For example, the N100 elicited by like-tiles is larger than that elicited by dislike-tiles (Chen and Cheng, 2022). In a previous study, ceramic tiles were divided into two categories (like-tiles or dislike-tiles). However, there are many types of tiles; therefore, the preferences of people toward different tile features (pattern, lightness, and color system factors) need to be explored. In addition, Guo et al. (2022) found that preferred robot appearances can induce greater N100 amplitudes than non-preferred robot appearances. Therefore, Hypothesis 1 was proposed. H1: The features of tiles (pattern, lightness, and color system factors) that people prefer elicit larger N100 amplitudes than those of tiles that people do not prefer.

Many studies have found that design preference can influence attentional allocation and P200 amplitudes (Righi et al., 2017; Chen and Cheng, 2022). For example, in a previous ERP study, we found that dislike-tiles elicited a larger P200 than like-tiles did in the posterior region of the brain (Chen and Cheng, 2022). Wang et al. (2012) found through an ERP study that P200 amplitudes can be effectively modulated by the preference of people for pendant design, and that ugly pendants induced larger P200 amplitudes. Ma et al. (2015) found that the architectures with low esthetic experience scores induced larger P200 amplitudes than those with high esthetic experience scores. In another ERP study on the preference for Chinese characters, Li et al. (2015) found that the preference factor significantly modulated the P200 amplitudes in the parietal and occipital regions. Thus, Hypothesis 2 was proposed. H2: The features of tiles that people do not prefer elicit a larger P200 amplitude than those elicited by prefer tile features in the parietal and occipital regions.

It has been demonstrated that N200 is associated with visual assessment (Folstein and Van Petten, 2008). In a study on preferences, N200 is considered an indicator of consumer preference (Vogel and Machizawa, 2004). In addition, many researchers have found that people's preferred products triggered smaller N200 amplitudes in the frontal electrodes (de Tommaso et al., 2008; Telpaz et al., 2015; Goto et al., 2017). For example, Telpaz et al. (2015) found in product preference studies that a product with the highest preference score elicited the smallest N200. In contrast, the product with the lowest preference score elicited the highest N200. Goto et al. found that the N200 induced in the Fz electrode could predict people's preferences relatively accurately (Goto et al., 2019). Therefore, Hypothesis 3 was proposed. H3: The features of tiles that people do not prefer elicit larger N200 amplitudes than those of tiles that people prefer in the frontal region.

This paper explores the preferences of people for different tile features, and how different features of the tile will affect cognitive processes (allocation of attention). To address these hypotheses, this study was organized into two research questions as follows:

1. Do different tile features lead to differences in subjective preferences?
2. Do different tile features cause differences in the ERP component amplitudes (N100, P200, and N200)?

Therefore, we conducted ERP experiments and used subjective questionnaires to explore the differences in the preferences of people with different tile features. At the time of the prevalence of COVID-19, studying the preferences of people for tile features may help designers effectively enhance their design so as to improve the experience of people working and living indoors.

2. Methods

2.1. Participants

We used G*Power 3.1 software to calculate the sample size. When α was 0.05 and the power (1-β) was 0.95, a minimal total sample size of 18 was required to detect a medium effect size of 0.25. Based on similar ERP researches (Beudt and Jacobsen, 2015; Guo et al., 2019; Chen and Cheng, 2022), we selected 20 undergraduates (11 females and 9 males, 18–31 years old, average age 22.5) as participants in the present study. All the participants were right-handed and had normal visual or corrected visual acuity. To avoid the health problem of participants affecting the results of the study, we asked clinicians to inspect participants for a history of neurological and psychiatric disorders, autoimmune disease, major depression, and mild cognitive impairment. None of the participants in this study had a history of brain injury, systemic disease, rheumatic disease, or autoimmune disease. In addition, all the participants were asked to rest well and not take stimulants or psychotropic drugs before the experiment. After the experiment, each participant was paid 80 CNY.

2.2. Stimuli

Gao et al. (2019) found in the environmental research that no significant differences between the experience of field investigation and that of images, which confirms that images can be used in experimental research as stimuli on environmental perception. A previous study also demonstrated that experimental studies could be conducted using neuroscience techniques with 2D picture stimulation of tiles (Chen and Cheng, 2022). Therefore, pictures of the tiles were used as the stimuli. In an event-related potential study, Wan et al. (2021) classified the lightness of stimuli into light, medium, and dark levels, and found that the lightness factor can modulate brain activity. However, the effect of tile brightness on brain activity is still unknown. In terms of color, Zhang et al. (2020) pointed out that tiles with neutral and warm color systems are the most common in the tiles market. In terms of pattern, Zhang et al. (2020) pointed out that tiles on the market are usually divided into patterned and unpatterned types. Therefore, this present study classified the lightness of tiles into three levels: light-toned, medium-toned, and dark-toned (Wan et al., 2021). The three levels of lightness were differentiated according to the brightness level of the ceramic tile color. For example, white and beige tiles are considered light-toned, gray and yellow-brown tiles are medium-toned, and black and dark brown tiles are dark-toned. The color factor is divided into two levels: neutral-colored and warm-colored (Zhang et al., 2020). The pattern factor is divided into two levels: patterned and unpatterned (Zhang et al., 2020). The pattern of the ceramic tile is composed of a decorated texture on its surface. When the surface of the ceramic tile is decorated with points, lines, and planes, it is regarded as a patterned ceramic tile. When the surface of the ceramic tile is not decorated with points, lines, and planes, it is regarded as a unpatterned tile. It should be emphasized that the pattern of tiles described here is flat and two-dimensional; therefore, it does not need to be perceived through touch. In summary, 12 different tile conditions (two levels of pattern factor × three levels of lightness factor × two levels of color system factor) were applied in this study, with two tiles of each condition for a total of 24 tiles (Figure 1). The purpose of using two tiles per condition was to avoid people's preference for a single tile, thus influencing the results of each type. Stimulus pictures were rendered using 3Dmax software. A neutral room was used as the environment to analyze the preferences for different tiles. No furniture or decoration was added to the room to avoid distractions. The resolution of the images was uniformly set to 1,280 × 768 pixels and was displayed on a 15.6-inch LCD screen (1,280 × 768, 60 Hz).

2.3. Procedure

The main purpose of this experiment was to explore the differences in implicit preferences and automatic attentional allocation caused by different features of ceramic tiles. Therefore, we used a modified oddball paradigm (Ma et al., 2018; Guo et al., 2019; Chen and Cheng, 2022) in which participants were asked to look at different pictures of tile floors without making a decision. Pictures containing tile floors were presented as frequent non-target stimuli, and landscape pictures were presented as rare target stimuli. All the participants sat 60 cm from the front of the computer screen to view the stimulus pictures with a viewing angle of approximately 32.9° × 18.5° (width × height). The ERP task was programmed and presented using E-prime 2.0, and each picture of the 12 types of tiles was repeated 40 times. Stimuli were presented randomly to eliminate the order effect, as shown in Figure 2. First, a 3-min countdown was used to facilitate participants' relaxation, and then a plus sign appeared to help participants focus on the center of the picture, followed by the alternating presentation of the stimuli. Each image was displayed for 800 ms, followed by a gray screen for 1,200 ms to return the participants' visual perception to baseline. After the ERP experiment, each participant was asked to complete a questionnaire that reflected their subjective preferences for each stimulus. Each experiment lasted about 40 min, with three breaks in between.

2.4. Subjective questionnaire

Subjective questionnaires are typically used to measure the preferences for different tiles. Wang et al. (2012) asked participants to

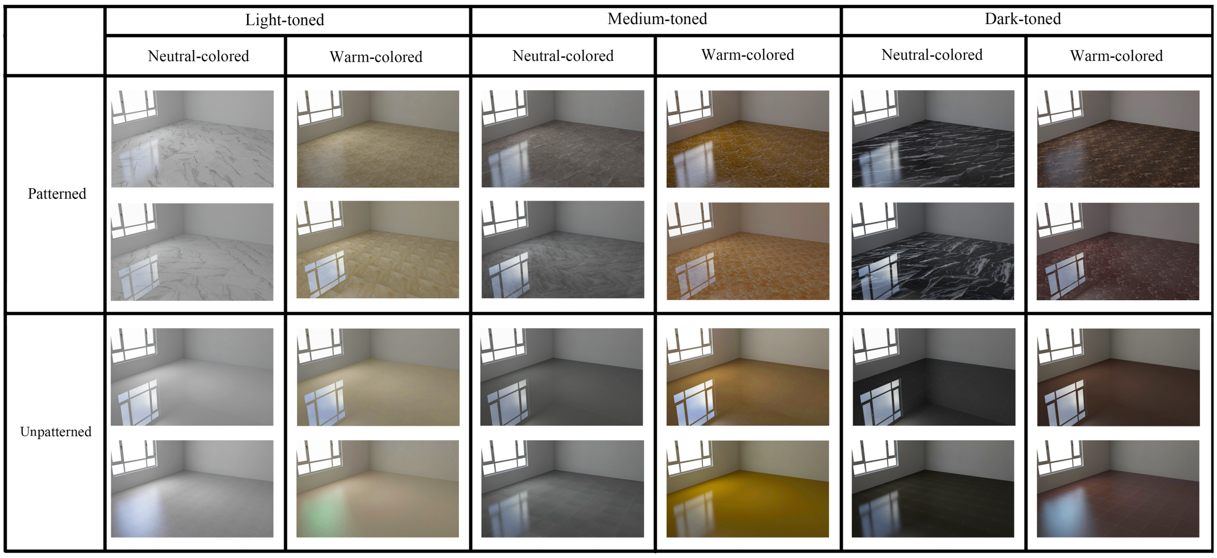

FIGURE 1
Stimuli samples of 12 different types of tiles.

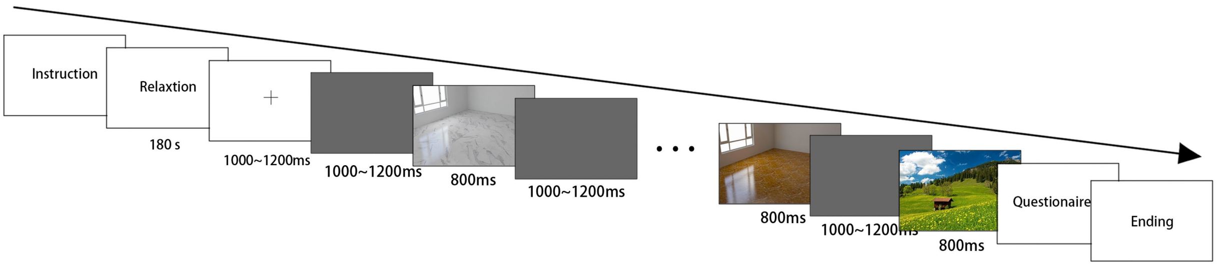

FIGURE 2
Task paradigm with the timing of presentation.

evaluate their degree of preference for pendant design to collect product preferences using a 7-point Likert scale. de Tommaso et al. (2008) asked participants to rate the appearance of experimental stimuli to assess the level of stimulus preference using a 10-point Likert scale. Therefore, this study used a questionnaire to measure the preferences of people for different tiles. The question was: "From the aspect of appearance preference, do you like or dislike the tiles?" The indicator was divided into two: like and dislike. Participants were asked to rate the esthetic preference of different tiles separately on a 9-point Likert scale, ranging from 1 to 9, where 1 indicates intensely disliked and 9 indicates intensely liked.

2.5. Electrophysiological recording and analysis

A SMARTING PRO EEG system (32 electrodes) was used to continuously record EEG signals in this study. According to an extended version of the international 10–20 electrode placement system (Figure 3), the electrodes were located at 32 standard positions [Fp1/2, Fpz, F3/4, F7/8, Fz, Fc1/2, Fc6, C3/4, T7/8, Cz, Cp1/2, Cp5/6, P3/4, P7/8, Pz, O1/2, Oz, vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG), M1/2]. The midpoint of Fz and Fpz was used as the ground electrode, and the reference electrodes (M1 and M2) were placed at the bilateral ear lobes. The VEOG was placed at the infraorbital region of the right eye, and the HEOG was placed at the outer canthi of the left eye. The impedance of each electrode was less than 5kΩ. After recording, an offline pretreatment was conducted using the EEGLAB toolbox. The procedure was divided into the following steps: 1. Remove useless electrodes (eye electrodes); 2. Filter at 0.1 ~ 30 Hz; 3. Segment processing (−200 ms ~ 800 ms); 4. Re-reference with the average of the earlobe electrodes; 5. Independent component analysis (ICA); 6. Manually identification and deletion of artifacts; and 7. Stack and average ERPs. Stimulation of each condition was repeated at least 60 times in the data retained after pretreatment.

Based on previous studies (Chatterjee and Vartanian, 2014), the N100 amplitudes at the electrodes of the frontal (Fz, F3, and F4), central (Cz, C3, and C4), parietal (Pz, P3, and P4), and occipital (Oz, O1, and O2) regions were included in the statistical analysis. Previous studies have shown that the parietal and occipital regions are usually chosen for the analysis of P200 (Guo et al., 2022; Liu et al., 2022). In addition, the waveform plots and topographic maps elicited by the pattern, lightness, and color system factors in this experiment showed that the P200 amplitudes elicited in the frontal and central regions were not obvious. Therefore, the P200 amplitudes in the parietal and occipital regions (Pz, P3, P4, Oz, O1, and O2) were chosen for analysis. For the N200, many authoritative studies have shown that the N200 component is mainly evident at the frontal and central electrodes (Folstein and Van Petten, 2008; Telpaz et al., 2015). Moreover, combined with the waveform plots of our experiment, the N200 amplitudes on parietal and occipital electrodes were not obvious. Therefore, we chose the frontal and central regions (Fz, F3, F4, Cz, C3, and C4) for analysis. The time window was taken as the period of time around the peak of each grand average ERP (Chen and Cheng, 2022). For the N100, the amplitudes in the frontal, central, parietal, and occipital regions were used for analysis in a time window of 80–130 ms. For the P200, the amplitudes in the parietal and occipital regions were used for analysis in a time window of 200–260 ms. For the N200, the amplitudes in the frontal and central regions were used for analysis in a time window of 260–330 ms. The average amplitude of each time window was used as the dependent variable for repeated-measures ANOVA. Each ANOVA included four independent variables: lightness (light-toned, medium-toned, or dark-toned), pattern (patterned or unpatterned), color system (neutral-or warm-colored system), and electrode (frontal, central, parietal, or occipital regions). Pearson correlation analysis was used to compare the subjective preference scores and ERP amplitudes.

All statistical analyses were conducted using SPSS Statistics 25 for statistical significance testing and were considered statistically significant at $p < 0.05$. The analyzed data in SPSS were corrected using Greenhouse–Geisser.

3. Results

The goal of this study was to investigate the preferences of people for different tile features. The results of subjective evaluation (preference) and ERP amplitudes (N100, P200, and N200) are reported below.

3.1. Subjective evaluation

Repeated-measures ANOVA showed that pattern [$F\,(1,19) = 4.455$, $p = 0.048$, partial $\eta^2 = 0.19$], lightness [$F\ (2,38) = 32.188$, $p < 0.001$, partial $\eta^2 = 0.629$], and color system [$\mathrm{F}\ (1,19) = 16.125$, $p = 0.001$, partial $\eta^2 = 0.459$] had significant effects on preference ratings.

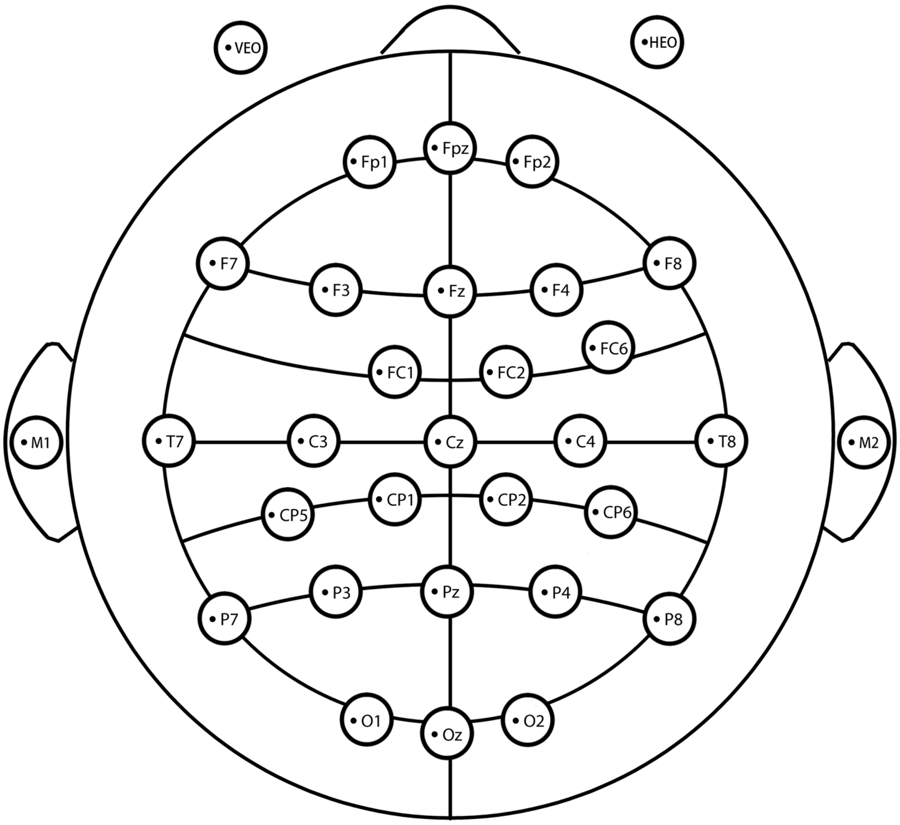

FIGURE 3
A diagram of the electrodes used in the experiment.

Participants preferred unpatterned tiles (mean = 5.042, SD = 0.209) over patterned tiles (mean = 4.458., SD = 0.233). The preference rating score of light-toned tiles (mean = 6.075, SD = 0.298) was higher than that of medium-toned tiles (mean = 4.638, SD = 0.253) and dark-toned tiles (mean = 3.537, SD = 0.195). The preference score of warm-colored tiles (mean = 5.158, SD = 0.193) was higher than that of neutral-colored tiles (mean = 4.342, SD = 0.209). Table 1 presents the details of the ANOVA results.

TABLE 1 ANOVA of subjective preference scores for the different features of tiles.

Factors	*F*	*P*	Partial η^2	Levels	Preference score	
					Mean	SD
Pattern	4.455	0.048	0.19	Patterned	4.458	0.233
				Unpatterned	5.042	0.209
Lightness	32.188	<0.001	0.629	Light-toned	6.075	0.298
				Medium-toned	4.638	0.235
				Dark-toned	3.537	0.195
Color system	16.125	0.001	0.459	Neutral-colored	4.342	0.209
				Warm-colored	5.158	0.193

3.2. Event-related potentials

Repeated-measures ANOVA showed that the lightness factor of tiles had a significant effect on the N100 (80–130 ms) amplitudes in the frontal, central, parietal and occipital regions [*F* (2, 38) = 4.218, $p = 0.024$, partial $\eta^2 = 0.182$]. There was no significant effect of pattern [*F* (1, 19) = 0.578, $p = 0.456$, partial η2 = 0.03] or color system [F (1, 19) = 1.157, $p = 0.296$, partial $\eta^2 = 0.057$] factors. The interaction between lightness, pattern, color system and electrode factors was insignificant [*F* (2, 38) = 3.206, $p = 0.053$, partial η2 = 0.144]. The electrode factor had no significant effect on N100 [*F* (11, 209) = 1.938, $p = 0.134$, partial $\eta^2 = 0.093$]. The mean N100 amplitude elicited by the light-toned tiles (mean = −0.9, SD = 0.186) was lower than that elicited by the medium-toned tiles (mean = −0.579, SD = 0.156) and dark-toned tiles (mean = −0.7, SD = 0.15). The results of the Pearson correlation analysis showed a significant negative correlation between the mean value of the subjective preference scores and the mean N100 amplitudes ($r = -0.607$, $p = 0.005$). Table 2 presents more details of the ANOVA results. The grand average waveforms and topography map caused by the different lightness levels of the tiles are shown in Figure 4.

For P200 (200–260 ms), repeated-measures ANOVA showed that the pattern factor [*F* (1, 19) = 17.198, $p = 0.001$, partial $\eta^2 = 0.475$] and color system [*F* (1, 19) = 5.891, $p = 0.025$, partial $\eta^2 = 0.237$] factors had significant effects on P200 in the parietal and occipital regions. There

TABLE 2 ANOVA of ERP amplitudes for the different features of tiles.

ERP	Region	Factors	*F*	*P*	Partial η^2	Levels	Preference score	
							Mean	SD
N100	Frontal, central, parietal, and occipital	Ligntness	4.218	0.024	0.182	Light-toned	−0.9	0.186
						Medium-toned	−0.579	0.156
						Dark-toned	−0.7	0.15
P200	Parietal and occipital	Pattern	17.198	0.001	0.475	Patterned	2.96	0.61
						Unpatterned	2.141	0.523
		Color system	5.891	0.025	0.237	Neutral-colored	2.715	0.58
						Warm-colored	2.386	0.547
N200	Frontal	Pattern	10.059	0.005	0.346	Patterned	−1.521	0.321
						Unpatterned	−0.886	0.244
		Color system	11.324	0.003	0.373	Neutral-colored	−1.462	0.272
						Warm-colored	−0.945	0.283
	Central	Pattern	6.361	0.021	0.251	Patterned	−0.469	0.24
						Unpatterned	−0.089	0.201

was no significant effect of the lightness factor [F (2, 38) = 0.876, *p* = 0.423, partial η^2 = 0.044] on the P200 amplitudes. The interaction between the pattern, lightness, and color system factors was not significant [F (2, 38) = 0.038, *p* = 0.961, partial η^2 = 0.002]. The electrode factor had no significant effect on P200 [*F* (5, 95) = 1.325, *p* = 0.275, partial η^2 = 0.065]. The mean P200 amplitude that elicited by patterned tiles (mean = 2.96, SD = 0.61) was higher than that elicited by unpatterned tiles (mean = 2.141, SD = 0.523). The mean P200 amplitude that elicited by neutral-colored tiles (mean = 2.715, SD = 0.58) was higher than that elicited by warm-colored tiles (mean = 2.386, SD = 0.547). There was a significant negative correlation between the mean value of the subjective preference scores and the mean P200 amplitudes (*r* = −0.629, *p* = 0.003). The grand average waveforms and topography map caused by different pattern levels of tiles are shown in Figure 5. The grand average waveforms and topography map caused by different color system levels of tiles are shown in Figure 6.

For N200 (260–330 ms), repeated-measures ANOVA showed significant effects of pattern [*F* (1, 19) = 9.134, *p* = 0.007, partial η^2 = 0.325] and color system [*F* (1, 19) = 6.195, *p* = 0.022, partial η^2 = 0.246] factors on the frontal and central regions. There was no significant effect of the lightness factor [*F* (2, 38) = 0.06, *p* = 0.936, partial η2 = 0.003]. There was no significant interaction between the pattern, lightness, and color system factors [*F* (1, 19) = 0.81, *p* = 0.537, partial η^2 = 0.041]. The electrode factor had a significant effect on N200 [*F* (5, 95) = 22.974, *p* < 0.001, partial η^2 = 0.547]. The pattern factor induced significant effects on the N200 amplitudes in the frontal [F (1, 19) = 10.059, *p* = 0.005, partial η^2 = 0.346] and central [F (1, 19) = 6.361, *p* = 0.021, partial η^2 = 0.251] regions. The color system factor induced significant effects on the N200 amplitudes in the frontal region [F (1, 19) = 11.324, *p* = 0.003, partial η^2 = 0.373], but had an insignificant effect on the N200 amplitudes of the central region [*F* (1, 19) = 0.936, *p* = 0.345, partial η^2 = 0.047]. The mean N200 amplitude in the frontal region that elicited by patterned tiles (mean = −1.521, SD = 0.321) was lower than that elicited by unpatterned tiles (mean = −0.886, SD = 0.244). The mean N200 amplitude in the central region that elicited by patterned tiles (mean = −0.469, SD = 0.24) was lower than that elicited by unpatterned tiles (mean = −0.089, SD = 0.201). The mean N200 amplitude in the frontal region that induced by neutral-colored tiles (mean = −1.462, SD = 0.272) was lower than that induced by the warm-colored tiles (mean = −0.945, SD = 0.283). There was a significant positive correlation between the mean value of subjective preference scores and mean N200 amplitudes in the frontal and central regions (*r* = 0.688, *p* = 0.001).

4. Discussion

This study applied a combination of ERP and self-reporting methods to study the preferences of people for different features of tiles, and the subjective preferences and neural responses of people for different ceramic tiles were collected.

The results showed that light-toned tiles that people preferred elicited larger N100 amplitudes. N100 is sensitive to brightness and reflects automatic attentional resource allocation (Anllo-Vento and Hillyard, 1996; Vogel and Luck, 2000). Based on these studies, the light-toned tiles induced the greatest N100 amplitude in the parietal and occipital regions in our study, possibly indicating that the light-toned tiles attracted more attentional resources than the medium-toned and dark-toned tiles in the early stage of visual processing. Many studies have revealed that the preference judgment for the appearance of a design could influence attention formation and ERP amplitudes (Wang et al., 2012; Chen and Cheng, 2022; Guo et al., 2022; Liu et al., 2022). The preference formation theory points out that the appearance of objects that people prefer can attract users and have a positive influence (Zajonc and Markus, 1982). In addition, some researchers have found that not only does bright stimulus cause a larger difference in N100 amplitude compared to dim stimuli, but the N100 latency induced by bright stimuli is significantly shorter than that induced by dim stimuli (Carillo-de-la-Peña et al., 1999; Johannes et al., 2003). However, there was no significant difference in the N100 latency between light-toned, medium-toned and dark-toned tiles in this study. Therefore, the differences in the N100 components in our experiment may not be induced by changes in stimulus brightness

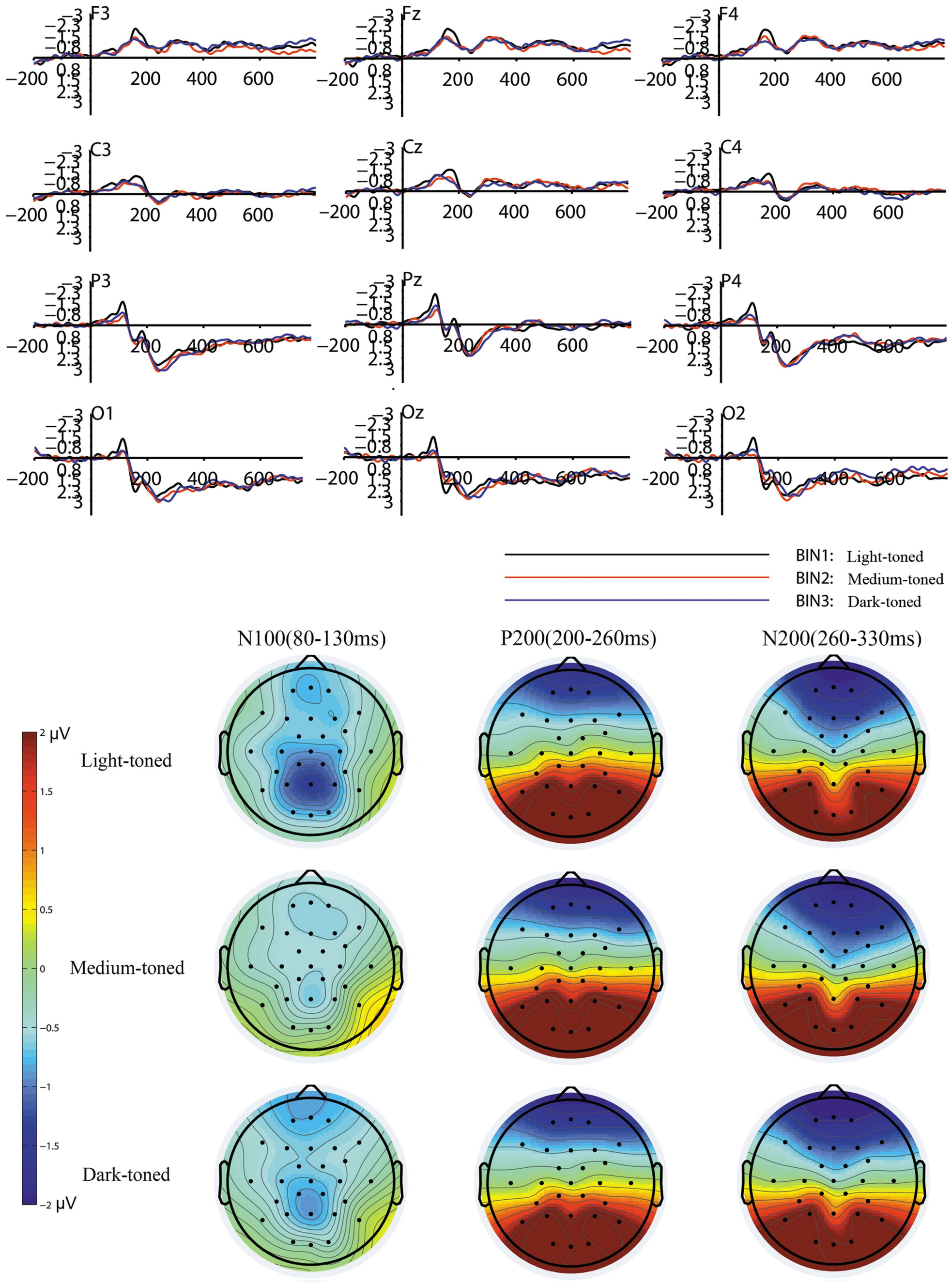

FIGURE 4
The grand averaged waveforms and topography map for the three conditions of the lightness factor.

intensity, but rather by the preference-related attention allocation. Thus, the positive influence of preference prompts people to pay more attention to the preferred stimulus during early visual processing stages and is reflected in the larger N100 amplitude, which is consistent with previous studies (Handy et al., 2010; Guo et al., 2022). The result demonstrating that the light-toned tiles with the highest preference scores induced the largest N100 amplitudes and the negative correlation between preference scores and N100 amplitude supported the view that the tile features that people preferred can induce a greater N100 than those that are not preferred. These results support H1. Another interpretation is that N100 may reflect emotions induced by stimuli, as Keil et al. (2001) pointed out in a previous study. Agost and Vergara (2014) pointed out that the emotion contained in the tiles can influence the preferences for tiles. Although the difference in N100 amplitude caused by dark-and medium-tone tiles was insignificant, both light-and dark-toned tiles induced larger N100 than medium-toned tiles, confirming the view that both pleasant and unpleasant stimuli trigger larger N100 than neutral stimuli (Keil et al., 2001). The N100 induced by light-toned tiles is the largest, that may be because the pleasure induced by light-toned tiles is strong, and the unpleasant feelings induced by dark-toned tiles is not strong. This result is consistent with the study by Agost and Vergara that people

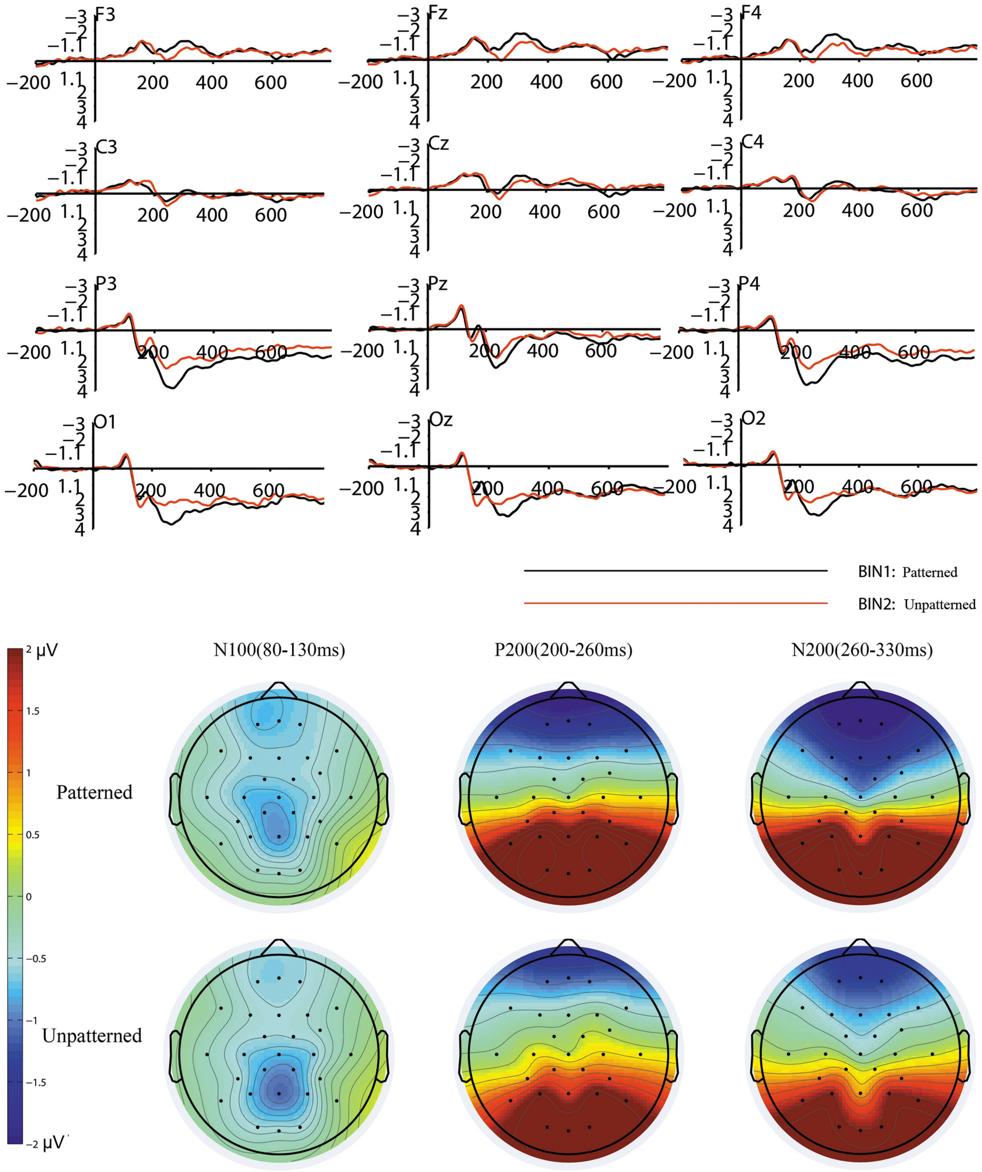

FIGURE 5
The grand averaged waveforms and topography map for the two conditions of the pattern factor.

preferred light-toned tiles because light-toned tiles make the environment feel more spacious, bright, and comfortable (Agost and Vergara, 2014). In terms of temporal order, the pattern and color system did not induce a difference in the N100 amplitudes, indicating that the first thing that the participants could distinguish might be the lightness factor of the tiles. The lag of the differences in the amplitude generated by the pattern and color system factors may indicate that these two factors require more time to differentiate and are related to higher-order cognitive processes.

The ANOVA results revealed that the patterned and neutral-colored tiles with low preference scores elicited larger P200 values in the parietal and occipital regions. P200 is associated with higher-order perceptual processing and attention allocation (Herbert et al., 2006; Yuan et al., 2007; de Tommaso et al., 2008). Many researchers have suggested that the P200 amplitude in the posterior brain region indicates a larger allocation of automatic attentional resources to negative stimuli (Dennis and Chen, 2007; Lin et al., 2018). This phenomenon may be caused by the negativity bias that stimuli are automatically processed to be more emotionally arousing when they make people feel unpleasant and then attract people's automatic attention (Righi et al., 2017). In neurological studies of product design, many studies have found that an increase in P200 amplitude correlates with the negativity bias that the non-preferred designs evoke significantly greater P200 than those elicited by preferred designs (Wang et al., 2012; Ma et al., 2015; Chen and Cheng, 2022). This is also confirmed by the results of our correlation analysis; when people's preference value is lower, the P200 amplitude is larger. According to the interpretation of the negativity bias and previous studies (Wang et al., 2012; Ma et al., 2015; Chen and Cheng, 2022), patterned and neutral-colored tiles induced greater P200, which may be due to the automatic negativity bias in which the preferential processing of negative stimuli affects attention allocation (Cacioppo and Berntson,

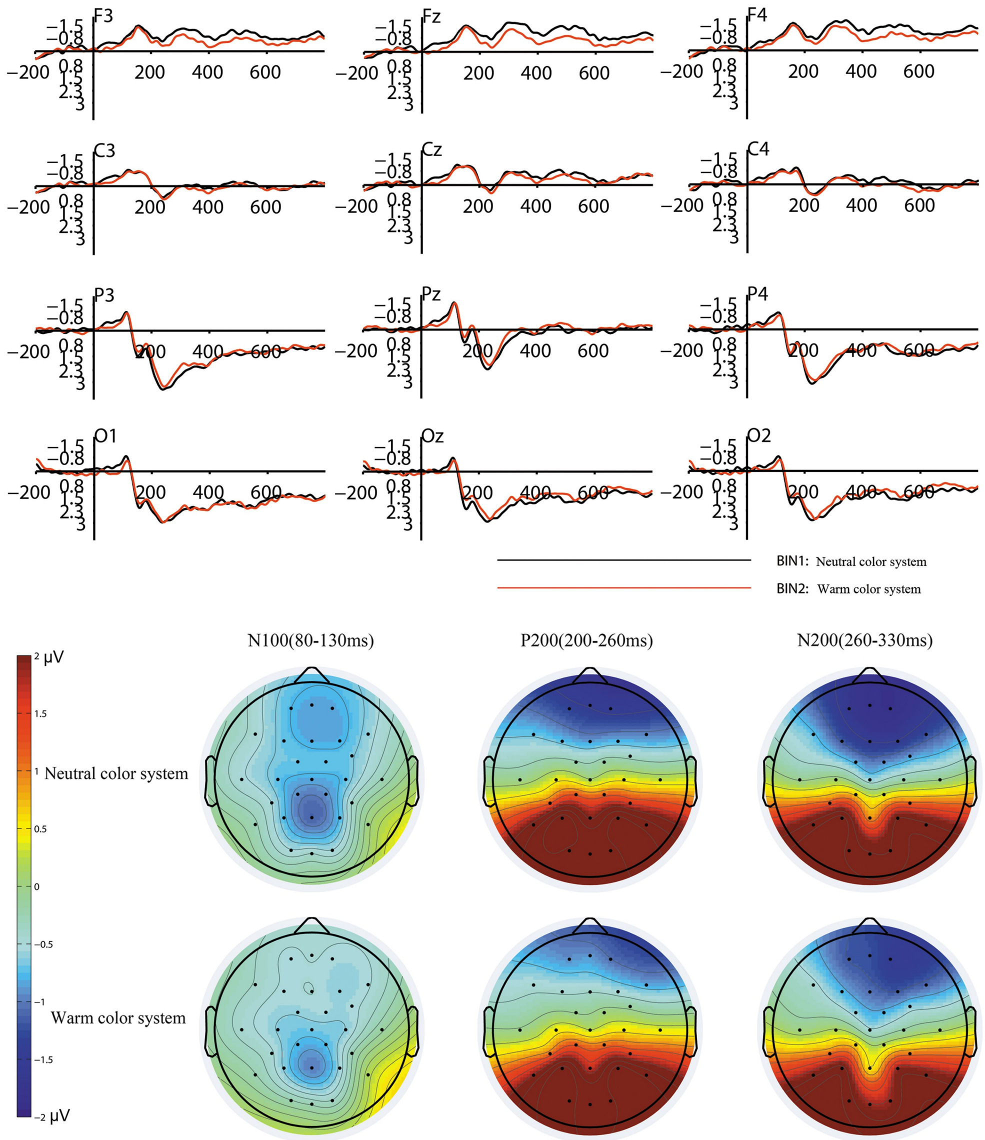

FIGURE 6
The grand averaged waveforms and topography map for the two conditions of the color system factor.

1994; Simpson et al., 2000). Therefore, we suggest that patterned and neutral-colored tiles that people do not prefer attract more attentional resources. These results support H2. The dark-toned tiles did not cause a larger P200 amplitude. This may be because the unpleasant feelings induced by the dark-toned tiles are not strong, which is also reflected in the N100 amplitude. Patterned tiles are preferred less than unpatterned tiles, which may be because the unpatterned tiles look cleaner and neater (Agost and Vergara, 2014). Jonauskaite et al. found that people prefer neutral colors less, which may be because neutral colors appear to be less chromatic and tend to be more negative (Jonauskaite et al., 2019). Therefore, we suggested that participants preferred warm tones, possibly because warm tones are usually associated with positivity and can create a warm and cozy perception of the environment. In addition, the difference in the amplitudes of the P200 induced by the pattern and color system factors confirms the previous view that people's discrimination against these two factors takes more time than lightness factors and is a higher-order cognitive process.

Following P200, patterned and neutral-colored tiles with low preference scores induced a greater N200 in the frontal region. Many studies have confirmed that preference can moderate N200 amplitudes and that low-preferred stimuli can elicit higher N200 amplitudes (de Tommaso et al., 2008; Telpaz et al., 2015; Goto et al., 2017; Lin et al., 2018). In this study, the positive correlation between preference scores and N200 amplitudes indicated that the features of tiles with higher preference scores elicited a smaller negative N200 deflection. The results are consistent with the conclusions of the preference prediction model proposed by Telpaz et al. (2015) and Goto et al. (2017), which showed that the N200 can predict the preferences of people. This phenomenon may be related to a negativity bias (Cacioppo and Berntson, 1994; Simpson et al., 2000; Dennis and Chen, 2007). Olofsson et al. (2008) pointed out that unpleasantness induced by stimuli could elicit greater N200 than pleasant stimuli in the anterior cingulate cortex. Thus, we suggest that the non-preferred tiles (patterned and neutral tiles) induced greater N200 amplitudes, reflecting a negative stimulus-driven attentional response, which is consistent with prior studies (Olofsson et al., 2008; Ma et al., 2010; Walker et al., 2011; Ding et al., 2017). These results support H3.

5. Conclusion

The goal of this study is to investigate the preferences of people for different tiles. Light-toned tiles with high preference induced greater N100 amplitudes than medium-toned and dark-toned tiles; the patterned and neutral-colored tiles with low preference induced greater P200 and N200 amplitudes. From a sequential point of view, the late appearance of neural response differences induced by the pattern and color system factors compared to the lightness factors may indicate that the lightness of tiles is the first factor to be distinguished. The visual processing of the pattern and color system factors of tiles belongs to a higher visual cognitive process that requires more time to distinguish. From the perspective of the allocation of attentional resources, the results indicate that in the early stage of visual processing (N100), the features of the tiles that people preferred (light-toned) attracted more attention, whereas in the middle stage of visual processing (P200 and N200), disliked features of the tiles (patterned and neutral-colored) attracted more attention. The correlation between preference scores and ERPs further validates the feasibility of using ERP techniques to measure the preferences for tiles. In terms of theoretical implications, this study reports the relationship between the preferences of people for different tile features and ERPs, which offers a new perspective for the study of neuro-esthetics and neurodesign. From a practical perspective, this study found that people prefer unpatterned, light-toned, and warm-colored tiles. This provides references for interior designers, environmental designers, and other relevant people. This study can provide researchers with a better understanding of the preferences for different tiles and help designers choose appropriate tiles for varied environments.

6. Limitations and future research

The study had three main limitations. First, although the number of participants in our experiment reached the minimum standard required for this study, including more participants would be preferable. Therefore, we will recruit more participants in future studies. Second, most of the participants were young students, and the preferences of different age groups may vary. Therefore, future studies should recruit multiple age groups. In addition, LPP correlates with the perceptual evaluation of a stimulus and may reflect the top-down allocation of motivational attention to emotional stimuli (Hou and Lu, 2018). However, the preference judgment in our study was implicit, and we aimed to explore the automatic attentional allocation induced by different tile features. During the ERP experiment, participants did not consciously evaluate the preferences for each stimulus. The lack of conscious judgment may explain why our experimental stimuli did not elicit significant differences in the LPP amplitudes. Behavioral data also contains a lot of useful information; hence, we will collect behavioral data about the preference judgment of people in future studies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the ethics committee of Jingdezhen Third People's Hospital, China (LL2022003), and followed the Declaration of Helsinki. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JC was involved in study design, execution of experimental procedures, data analysis, and manuscript drafting and revision. BH was involved in manuscript revision. HZ was involved in study design. JW participated in the execution of part of the experimental procedures. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Publisher's note

References

Agost, M. J., and Vergara, M. (2014). Relationship between meanings, emotions, product preferences andpersonal values. Application to ceramic tile floorings. *Appl. Ergon.* 45, 1076–1086. doi: 10.1016/j.apergo.2014.01.008

Albors-Garrigós, J., Hervas-Oliver, J. L., and Márquez, P. (2009). Internet and mature industries. Its role in the creation of value in the supply chain. The case of tile ceramic manufacturers and distributors in Spain. *Int. J. Inf. Manag.* 29, 476–482. doi: 10.1016/j.ijinfomgt.2009.03.005

Anllo-Vento, L., and Hillyard, S. A. (1996). Selective attention to the color and direction of moving stimuli: electrophysiological correlates of hierarchical feature selection. *Percept. Psychophys.* 58, 191–206. doi: 10.3758/BF03211875

Artacho, M. A., Alcantara, E., and Martinez, N. (2020). Multisensory analysis of consumer-product interaction during ceramic tile shopping experiences. *Multisens. Res.* 33, 213–249. doi: 10.1163/22134808-20191391

Bayer, M., and Schacht, A. (2014). Event-related brain responses to emotional words, pictures, and faces - a cross-domain comparison. *Front. Psychol.* 5, 1–10. doi: 10.3389/fpsyg.2014.01106

Beudt, S., and Jacobsen, T. (2015). On the role of mentalizing processes in aesthetic appreciation: an ERP study. *Front. Hum. Neurosci.* 9, 1–13. doi: 10.3389/fnhum.2015.00600

Brown, S., Gao, X., Tisdelle, L., Eickhoff, S. B., and Liotti, M. (2011). Naturalizing aesthetics: brain areas for aesthetic appraisal across sensory modalities. *NeuroImage* 58, 250–258. doi: 10.1016/j.neuroimage.2011.06.012

Cacioppo, J. T., and Berntson, G. G. (1994). Relationship between attitudes and evaluative space: a critical review, with emphasis on the separability of positive and negative substrates. *Psychol. Bull.* 115, 401–423. doi: 10.1037//0033-2909.115.3.401

Cao, Y., Zhang, Y., Ding, Y., Duffy, V. G., and Zhang, X. (2021). Is an anthropomorphic app icon more attractive? *Evid. Neuroergonomom. Appl. Ergon.* 97:103545. doi: 10.1016/j.apergo.2021.103545

Carillo-de-la-Peña, M., Holguín, S. R., Corral, M., and Cadaveira, F. (1999). The effects of stimulus intensity and age on visual-evoked potentials (VEPs) in normal children. *Psychophysiology* 36, 693–698. doi: 10.1017/S0048577299980435

Chatterjee, A. (2004). Prospects for a cognitive neuroscience of visual aesthetics. *Bull. Psychol. Arts* 4, 56–60. doi: 10.1037/e514602010-003

Chatterjee, A., and Vartanian, O. (2014). Neuroaesthetics. *Trends Cogn. Sci.* 18, 370–375. doi: 10.1016/j.tics.2014.03.003

Chen, J., and Cheng, Y. (2022). The relationship between aesthetic preferences of people for ceramic tile design and neural responses: an event-related potential study. *Front. Hum. Neurosci.* 16, 1–13. doi: 10.3389/fnhum.2022.994195

China Building Sanitary Ceramics Association (2021). Blockbuster! The 2021 world tile forum was held, and the authoritative data of global tile was released. available at: http://www.cbmf.org/BMI/zx/_465637/7126169/index.html. (accessed December 10, 2021).

Daliri, M. R. (2013). Kernel earth Mover's distance for EEG classification. *Clin. EEG Neurosci.* 44, 182–187. doi: 10.1177/1550059412471521

Damasio, A., and Carvalho, G. B. (2013). The nature of feelings: evolutionary and neurobiological origins. *Nat. Rev. Neurosci.* 14, 143–152. doi: 10.1038/nrn3403

de Tommaso, M., Pecoraro, C., Sardaro, M., Serpino, C., Lancioni, G., and Livrea, P. (2008). Influence of aesthetic perception on visual event-related potentials. *Conscious. Cogn.* 17, 933–945. doi: 10.1016/j.concog.2007.09.003

Dennis, T. A., and Chen, C. C. (2007). Neurophysiological mechanisms in the emotional modulation of attention: the interplay between threat sensitivity and attentional control. *Biol. Psychol.* 76, 1–10. doi: 10.1016/j.biopsycho.2007.05.001

Ding, Y., Guo, F., Hu, M., and Cao, Y. (2017). Using event related potentials to investigate visual aesthetic perception of product appearance. *Hum. Factor Ergon. Man.* 27, 223–232. doi: 10.1002/hfm.20704

Ding, Y., Guo, F., Zhang, X., Qu, Q., and Liu, W. (2016). Using event related potentials to identify a user's behavioural intention aroused by product form design. *Appl. Ergon.* 55, 117–123. doi: 10.1016/j.apergo.2016.01.018

Ernst, L. H., Ehlis, A. C., Dresler, T., Tupak, S. V., Weidner, A., and Fallgatter, A. J. (2013). N1 and N2 ERPs reflect the regulation of automatic approach tendencies to positive stimuli. *Neurosci. Res.* 75, 239–249. doi: 10.1016/j.neures.2012.12.005

Folstein, J. R., and Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology* 070915195953001–070070915195953. doi: 10.1111/j.1469-8986.2007.00602.x

Gao, T., Liang, H., Chen, Y., and Qiu, L. (2019). Comparisons of landscape preferences through three different perceptual approaches. *Int. J. Environ. Res. Public Health* 16, 1–13. doi: 10.3390/ijerph16234754

Goto, N., Lim, X. L., Shee, D., Hatano, A., Khong, K. W., Buratto, L. G., et al. (2019). Can brain waves really tell if a product will be purchased? Inferring consumer preferences from single-item brain potentials. *Front. Integr. Neurosci.* 13, 1–13. doi: 10.3389/fnint.2019.00019

Goto, N., Mushtaq, F., Shee, D., Lim, X. L., Mortazavi, M., Watabe, M., et al. (2017). Neural signals of selective attention are modulated by subjective preferences and buying decisions in a virtual shopping task. *Biol. Psychol.* 128, 11–20. doi: 10.1016/j.biopsycho.2017.06.004

Guo, F., Ding, Y., Wang, T., Liu, W., and Jin, H. (2016). Applying event related potentials to evaluate user preferences toward smartphone form design. *Int. J. Ind. Ergon.* 54, 57–64. doi: 10.1016/j.ergon.2016.04.006

Guo, F., Jiang, J.-Y., Tian, X.-H., and Chen, J.-H. (2019). Applying event-related potentials to measure perceptual experience toward the navigation Interface of a Mobile game for improving the design. *Symmetry (Basel).* 11:710. doi: 10.3390/sym11050710

Guo, F., Li, M., Chen, J., and Duffy, V. G. (2022). Evaluating users' preference for the appearance of humanoid robots via event-related potentials and spectral perturbations. *Behav. Inf. Technol.* 41, 1381–1397. doi: 10.1080/0144929X.2021.1876763

Handy, T. C., Smilek, D., Geiger, L., Liu, C., and Schooler, J. W. (2010). ERP evidence for rapid hedonic evaluation of logos. *J. Cogn. Neurosci.* 22, 124–138. doi: 10.1162/jocn.2008.21180

Herbert, C., Kissler, J., Junghöfer, M., Peyk, P., and Rockstroh, B. (2006). Processing of emotional adjectives: evidence from startle EMG and ERPs. *Psychophysiology* 43, 197–206. doi: 10.1111/j.1469-8986.2006.00385.x

Hou, G., and Lu, G. (2018). Semantic processing and emotional evaluation in the traffic sign understanding process: evidence from an event-related potential study. *Transport. Res. F-Traf.* 59, 236–243. doi: 10.1016/j.trf.2018.08.020

Hou, G., and Yang, J. (2021). Measuring and examining traffic sign comprehension with event-related potentials. *Cogn. Technol. Work* 23, 497–506. doi: 10.1007/s10111-020-00632-1

Jiang, J., Correa, C. M., Geerts, J., and van Gaal, S. (2018). The relationship between conflict awareness and behavioral and oscillatory signatures of immediate and delayed cognitive control. *NeuroImage* 177, 11–19. doi: 10.1016/j.neuroimage.2018.05.007

Johannes, S., Munte, T. F., Heinze, H. J., and Mangun, G. R. (2003). Luminance and spatial attention effects on early visual processing. *Cogn. Brain Res.* 2, 189–205. doi: 10.1016/0926-6410(95)90008-X

Jonauskaite, D., Althaus, B., Dael, N., Dan-Glauser, E., and Mohr, C. (2019). What color do you feel? Color choices are driven by mood. *Color. Res. Appl.* 44, 272–284. doi: 10.1002/col.22327

Keil, A., Müller, M. M., Gruber, T., Wienbruch, C., Stolarova, M., and Elbert, T. (2001). Effects of emotional arousal in the cerebral hemispheres: a study of oscillatory brain activity and event-related potentials. *Clin. Neurophysiol.* 112, 2057–2068. doi: 10.1016/S1388-2457(01)00654-X

Kosonogov, V., Martinez-Selva, J. M., Carrillo-Verdejo, E., Torrente, G., Carretié, L., and Sanchez-Navarro, J. P. (2019). Effects of social and affective content on exogenous attention as revealed by event-related potentials. *Cogn. Emot.* 33, 683–695. doi: 10.1080/02699931.2018.1486287

Laparra-Hernández, J., Belda-Lois, J. M., Medina, E., Campos, N., and Poveda, R. (2009). EMG and GSR signals for evaluating user's perception of different types of ceramic flooring. *Int. J. Ind. Ergon.* 39, 326–332. doi: 10.1016/j.ergon.2008.02.011

Li, R., Qin, R., Zhang, J., Wu, J., and Zhou, C. (2015). The esthetic preference of Chinese typefaces - an event-related potential study. *Brain Res.* 1598, 57–65. doi: 10.1016/j.brainres.2014.11.055

Li, Y., Zhong, W., Chen, Q., and Mo, L. (2013). Object detection is completed earlier than object categorization: evidence from LRP and N200. *Psychophysiology* 50, 1255–1262. doi: 10.1111/psyp.12131

Lin, M. H., Cross, S. N. N., Jones, W. J., and Childers, T. L. (2018). Applying EEG in consumer neuroscience. *Eur. J. Mark.* 52, 66–91. doi: 10.1108/EJM-12-2016-0805

Lin, H., Jin, H., Liang, J., Yin, R., Liu, T., and Wang, Y. (2015). Effects of uncertainty on ERPs to emotional pictures depend on emotional valence. *Front. Psychol.* 6, 1–11. doi: 10.3389/fpsyg.2015.01927

Liu, W., Cao, Y., and Proctor, R. W. (2022). The roles of visual complexity and order in first impressions of webpages: an ERP study of webpage rapid evaluation. *Int. J. Hum. Comput. Interact.* 38, 1345–1358. doi: 10.1080/10447318.2021.2002044

Luck, S. J., Woodman, G. F., and Vogel, E. K. (2000). Event-related potential studies of attention. *Trends Cogn. Sci.* 4, 432–440. doi: 10.1016/S1364-6613(00)01545-X

Ma, Q., Hu, L., and Wang, X. (2015). Emotion and novelty processing in an implicit aesthetic experience of architectures: evidence from an event-related potential study. *Neuroreport* 26, 279–284. doi: 10.1097/WNR.0000000000000344

Ma, Y., Jin, J., Yu, W., Zhang, W., Xu, Z., and Ma, Q. (2018). How is the neural response to the Design of Experience Goods Related to personalized preference? An implicit view. *Front. Neurosci.* 12, 1–8. doi: 10.3389/fnins.2018.00760

Ma, Q., Wang, K., Wang, X., Wang, C., and Wang, L. (2010). The influence of negative emotion on brand extension as reflected by the change of N2: a preliminary study. *Neurosci. Lett.* 485, 237–240. doi: 10.1016/j.neulet.2010.09.020

Macdonald, E., Gonzalez, R., and Papalambros, P. (2009). The construction of preferences for crux and sentinel product attributes. *J. Eng. Design.* 20, 609–626. doi: 10.1080/09544820802132428

Mugge, R., and Schoormans, J. P. L. (2012). Product design and apparent usability. The influence of novelty in product appearance. *Appl. Ergon.* 43, 1081–1088. doi: 10.1016/j.apergo.2012.03.009

Nagamachi, M. (2002). Kansei engineering as a powerful consumer-oriented technology for product development. *Appl. Ergon.* 33, 289–294. doi: 10.1016/S0003-6870(02)00019-4

Olofsson, J. K., Nordin, S., Sequeira, H., and Polich, J. (2008). Affective picture processing: an integrative review of ERP findings. *Biol. Psychol.* 77, 247–265. doi: 10.1016/j.biopsycho.2007.11.006

Orsborn, S., and Cagan, J. (2009). Multiagent shape grammar implementation: automatically generating form concepts according to a preference function. *J. Mech. Des.* 131, 1210071–12100710. doi: 10.1115/1.4000449

Palmer, S. E., Schloss, K. B., and Sammartino, J. (2013). Visual aesthetics and human preference. *Annu. Rev. Psychol.* 64, 77–107. doi: 10.1146/annurev-psych-120710-100504

Park, H. J., Economou, A., and Papalambros, P. (2005). "Hermes: A computational tool for proportional Studies in design," in *Learning from the Past a Foundation for the Future: Conference Proceedings of Caadfutures*, 2005.

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nat. Rev. Neurosci.* 9, 148–158. doi: 10.1038/nrn2317

Righi, S., Gronchi, G., Pierguidi, G., Messina, S., and Viggiano, M. P. (2017). Aesthetic shapes our perception of every-day objects: an ERP study. *New Ideas Psychol.* 47, 103–112. doi: 10.1016/j.newideapsych.2017.03.007

Righi, S., Orlando, V., and Marzi, T. (2014). Attractiveness and affordance shape tools neural coding: insight from ERPs. *Int. J. Psychophysiol.* 91, 240–253. doi: 10.1016/j.ijpsycho.2014.01.003

Roberts, M. N. (2007). *Complexity and aesthetic preference for diverse visual stimuli*. (Doctoral), Palma, Spain: Universitat de les Illes Balear.

Rolls, E. T. (2017). Neurobiological foundations of aesthetics and art. *New Ideas Psychol.* 47, 121–135. doi: 10.1016/j.newideapsych.2017.03.005

Serrano, B., Botella, C., Baños, R. M., and Alcañiz, M. (2013). Using virtual reality and mood-induction procedures to test products with consumers of ceramic tiles. *Comput. Human Behav.* 29, 648–653. doi: 10.1016/j.chb.2012.10.024

Simpson, J. R., Öngür, D., Akbudak, E., Conturo, T. E., Ollinger, J. M., Snyder, A. Z., et al. (2000). The emotional modulation of cognitive processing: an fMRI study. *J. Cogn. Neurosci.* 12, 157–170. doi: 10.1162/089892900564019

Song, S. S., and Zhao, G. J. (2012). Expression of physiological sensation of anatomical patterns in wood: an event-related brain potential study. *Bio Resour.* 7, 5593–5610. doi: 10.15376/biores.7.4.5593-5610

Telpaz, A., Webb, R., and Levy, D. J. (2015). Using EEG to predict consumers' future choices. *J. Mark. Res.* 52, 511–529. doi: 10.1509/jmr.13.0564

Vogel, E. K., and Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology* 37, 190–203. doi: 10.1017/S0048577200981265

Vogel, E. K., and Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature* 428, 748–751. doi: 10.1038/nature02447

Walker, S., O'Connor, D. B., and Schaefer, A. (2011). Brain potentials to emotional pictures are modulated by alexithymia during emotion regulation. *Cogn. Affect. Behav. Neurosci.* 11, 463–475. doi: 10.3758/s13415-011-0042-1

Wan, Q., Li, X., Zhang, Y., Song, S., and Ke, Q. (2021). Visual perception of different wood surfaces: an event-related potentials study. *Ann. For. Sci.* 78, 1–18. doi: 10.1007/s13595-021-01026-7

Wang, X., Huang, Y., Ma, Q., and Li, N. (2012). Event-related potential P2 correlates of implicit aesthetic experience. *Neuroreport* 23, 862–866. doi: 10.1097/WNR.0b013e3283587161

Yuan, J., Zhang, Q., Chen, A., Li, H., Wang, Q., Zhuang, Z., et al. (2007). Are we sensitive to valence differences in emotionally negative stimuli? Electrophysiological evidence from an ERP study. *Neuropsychologia* 45, 2764–2771. doi: 10.1016/j.neuropsychologia.2007.04.018

Zajonc, R. B., and Markus, H. (1982). Affective and cognitive factors in preferences. *J. Consum. Res.* 9:123. doi: 10.1086/208905

Zeng, J., Zou, Y., and Zhang, Q. (2013). Social competition factor influences the neural response to rewards: an ERP study. *Brain Res.* 1501, 12–20. doi: 10.1016/j.brainres.2013.01.030

Zhang, X. (2020). The influences of brand awareness on consumers' cognitive process: an event-related potentials study. *Front. Neurosci.* 14, 1–7. doi: 10.3389/fnins.2020.00549

Zhang, X. Y., Luo, H., Long, H. R., Huang, S., Zhou, Y., Yi, N., et al. (2020). Design color scheme of black and white gray in the application of tile products. *Foshan Ceramics.* 30, 44–46.

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The binding of negative emotional stimuli with spatial information in working memory: A possible role for the episodic buffer

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Introduction: Remembering where negative events occur has undeniable adaptive value, however, how these memories are formed remains elusive. We investigated the role of working memory subcomponents in binding emotional and visuo-spatial information using an emotional version of the object relocation task (EORT).

Methods: After displaying black rectangles simultaneously, emotional pictures (from the International Affective Pictures System) appeared sequentially over each rectangle. Participants repositioned the rectangles as accurately as possible after all stimuli had disappeared. During the EORT encoding phase, a verbal trail task was administered concurrently to selectively interfere with the central executive (CE). The immediate post-encoding administration of an object feature-report task was used to interfere with the episodic buffer (EB).

Results: Only the EB-interfering task prevented the emotion-enhancing effect of negative pictures. The latter effect was not observed with a concurrent executive task.

Discussion: Overall, our findings suggest that pre-attentive automatic processes are primarily involved in binding emotional and visuo-spatial information in the EB.

KEYWORDS

working memory, attention, object-relocation task, emotional valence, arousal

1. Introduction

Places in which negative experiences were encountered are usually well remembered. It is known that the emotional content of an experience facilitates consolidation processes, enhancing explicit long-term memories of that event (Richter-Levin and Akirav, 2003). However, the mechanism by which emotional stimuli are encoded and bound to spatial information in working memory remains unclear. We recently demonstrated that superimposing emotionally charged images on objects (black rectangles) that had to be relocated improved visuo-spatial memory for object position. Interestingly, this enhancing effect was only significant when both emotionally charged and neutral stimuli were presented during the same encoding trial. When all the presented images were unpleasant (negative valence), or when half of the images were pleasant (positive valence) and the other half were unpleasant, the effect of emotion vanished. These findings suggested that the emotional content of stimuli only affected memory for object position when neutral and emotional stimuli competed with one another (Costanzi et al., 2019).

Several studies support the competition hypothesis, suggesting that when information is initially processed, arousal prioritizes the processing of emotional stimuli through bottom–up perceptual salience and top–down relevance (Mather and Sutherland, 2011). Christianson (1992) hypothesized that negative stimuli processing occurs along a temporal continuum involving two stages: (i) a pre-attentive processing phase, assumed to be fast, unconscious, and independent of attentional resources, and (ii) a post-stimulus elaboration, a controlled process that occurs once attention has been directed to the emotional stimulus. Previous studies highlighted the central role of attention in processing emotional stimuli, by narrowing the focus of attention during encoding and facilitating their processing in memory systems (Nummenmaa et al., 2006; Riggs et al., 2011; Huntsinger, 2013; Kennedy et al., 2020). For example, Kensinger et al. (2007) found that when participants were presented with a complex visual scene that included a negatively arousing object placed on an otherwise non-emotional background, they remembered the negative arousing objects better than the neutral ones, and remembered the backgrounds presented with negative arousing objects worse than those presented with neutral ones. More recently, Kennedy et al. (2020) showed a performance impairment in a rotation detection task if an emotional picture appeared shortly before the rotated picture, confirming the existence of the typical "emotion-induced blindness" (Kennedy et al., 2020). Together these results suggest that the emotional content of visual stimuli can capture attentional resources when presented in both task-relevant and irrelevant conditions.

Despite this evidence, the role of attention in encoding emotional stimuli remains quite controversial. Several pieces of evidence show that memory recall for negative, but not for neutral and positive, pictures is unaffected by the administration of a concurrent attention-demanding task (divided attention condition), suggesting that the formation of negative valenced memories is largely dependent on automatic processes (Kern et al., 2005; Talmi et al., 2007; Migita et al., 2011). On the other hand, Pottage and Schaefer (2012) found that performance in a concurrent visual attention-demanding task mediated the enhancement of memory for affective information, suggesting that visual attentional processes play an important role in the encoding of emotional memories (Pottage and Schaefer, 2012). In a similar vein, Rossi-Arnaud et al. (2018) found a significant target-related advantage for all types of stimuli, regardless of their emotional valence, when investigating the attentional boost effect in the recognition of emotional pictures. Authors suggested that attention-dependent processes are involved in the encoding of emotional stimuli (Rossi-Arnaud et al., 2018). Finally, Kang et al. (2014) found that a divided attention condition impaired recognition of neutral and negative non-arousing words but not of negative-arousing ones, suggesting that negative valenced words can be encoded by either automatic or controlled processes, depending on the arousal level of the stimuli (Kang et al., 2014).

It is worth noting that the studies discussed so far have only considered memory for visual and verbal information, not for spatial information. To the best of our knowledge, only one study investigated the involvement of attentional mechanisms in processing emotional stimuli in visuo-spatial working memory. González-Garrido et al. (2015) combined an event-related potential (ERP) analysis with a behavioral study in which participants had to encode the position of neutral and emotional faces. They found that the amplitude of P2, an ERP component linked to attentional allocation, was higher for emotional than for neutral faces, and that emotional faces were better relocated than neutral ones. They suggested that visuo-spatial working memory relied on a domain-general attention-based mechanism, whereby the maintenance of spatial to-be-remembered locations might be influenced by the emotional content of the stimuli. It is important to note, however, that in the González-Garrido et al. (2015) study attentional control was not specifically manipulated and the emotional stimuli used in the behavioral task were only happy faces.

In the present study, we decided to investigate the role of different working memory subcomponents in binding negative stimuli, incidentally encoded, to the locations in which they were presented. According to Baddeley (2012) model of working memory, four main subcomponents have to be considered: the phonological loop (PL), responsible for rehearsal and temporary storage of verbal information; the visuo-spatial sketchpad (VSSP), which maintains visual and spatial information; the central executive (CE), a general-domain attentional module that controls ongoing processes; and the episodic buffer (EB), which binds information coming from different sources (Baddeley et al., 2012).

Here, we specifically target the roles of the CE and EB. The CE is a domain-general process that allows attentional resources to be allocated to the encoding of presented stimuli. Interfering with this process during encoding prevents exogenous information from entering the working memory system (Baddeley et al., 2012). The EB is a more recent addition to the working memory model and appears to be a later object-based storage process (Baddeley et al., 2011). Although tasks that assess its function are still being developed, there is increasing evidence that tasks requiring the binding of different features of stimuli (e.g., different visual features, like shape and color, color and position, different aspects of a geometric shape, and so on) require EB activity (see Nobre et al., 2013 for a review). Recently, Gao et al. (2017) found that administering a secondary feature reporting task during the working memory maintenance phase selectively disrupted binding while sparing memory for constituent features in a change detection task. These results suggested that EB is an independent storage buffer fueled by object-based attention (Gao et al., 2017). As concerns the role of EB in processing emotional information, although largely unexplored, it has been hypothesized that emotional valence may be rapidly detected and may act on information in the EB at both explicit and implicit levels (Baddeley, 2013). Mikels et al. (2008), for example, found that administering an affective interfering task, but not a cognitive one, impaired emotional working memory in an affective delayed-response task. The authors suggested that the EB may include a domain-specific component specialized in the active maintenance of emotional information.

We hypothesize that if a domain-general attention-based mechanism is involved in encoding the locations of negative-related objects, then a divided-attention condition should prevent the emotion-enhancing effect on spatial memory. To test this hypothesis, we used a dual task paradigm to interfere with the CE (verbal trail task; Fürst and Hitch, 2000) during the encoding phase of an emotional version of the object-relocation task (EORT; Costanzi et al., 2019). Negative pictures with high or low arousal levels and neutral pictures were used to investigate whether arousal modulates the switch between automatic and controlled processes in encoding emotional pictures. Moreover, the role of the EB was assessed by administering an object feature-report task (Gao et al., 2017)–known to interfere with the maintenance of bound visual information (e.g., colors and shapes) more than with the maintenance of single features–immediately after the EORT encoding phase. If the position of stimuli was bound with their emotional content in the EB, we would expect the object feature-report task to selectively interfere with the enhancing effect of emotional valence on memory for object location, while sparing memory for the single features (i.e., memory for both object locations and pictures' identity).

2. Materials and methods

2.1. Participants, materials, and procedures

University students (197, of whom 152 females; age: 24.94 ± 3.77) voluntarily participated. All were Italian native speakers with normal or corrected-to-normal vision. The entire procedure was in accordance with the Helsinki Declaration and was approved by LUMSA University Ethical Committee.

In Experiment 1, EORT was run on a PC with a 17″ LCD monitor using a software programmed in Python. Because of COVID-19 pandemic restrictions, Experiments 2 and 3 were conducted online in a Google Meet virtual lab. Experimental tasks were run using jsPsych library (de Leeuw, 2015). In all experiments, the general procedure was alike to Costanzi et al. (2019). The EORT started with a 1000 ms fixation point, followed by a 1000 ms presentation of eight black rectangles in an array (165 × 128 px, 72 dpi). Four neutral and four negative pictures from the International Affective Picture System (IAPS; Lang et al., 2008) sequentially appeared superimposed, one at a time, on each rectangle (1000 ms; ISI: 250 ms). Participants were not informed about their occurrence. In Experiment 1, neutral and negative pictures differed in valence [neutral: 4.7 ± 0.25; negative: 3.1 ± 0.26; $t_{(6)} = 8.85$, $p < 0.001$] and arousal [neutral: 2.5 ± 0.17; negative: 5.7 ± 0.25; $t_{(6)} = 12.34$, $p < 0.0001$]. In Experiments 2 and 3, neutral and negative pictures differed in valence [neutral: 4.7 ± 0.32; negative: 3.5 ± 0.25; $t_{(6)} = 5.57$, $p < 0.001$] but not in arousal [neutral: 3.7 ± 0.18; negative: 3.8 ± 0.21; $t_{(6)} = 0.41$, $p = 0.79$].[1][1] The images selected from the IAPS were simple photos depicting a single focal element and a stable background, with the exception of #9427 (Experiment 1) and #2590 (Experiments 2 and 3), which depicted negative complex scenes with multiple elements and an undefined background. Since neutral IAPS images are typically simpler in composition than negative ones (e.g., Marin et al., 2016), we also controlled for the visual complexity of the selected pictures. The following parameters were computed for each image and used as indexes of visual complexity: (i) the number of bytes and (ii) the number of blocks obtained with a quadratic tree decomposition (Gabrieli et al., 2022). This was computed with the pyaesthetics package,[2] by setting 40 px as the minimum size and 10 as the minimum standard deviation for a block to be split. The statistical analyses of visual complexity (t-test) revealed no significant differences between neutral and negative pictures across all experiments—in Experiment 1: $t_{(6)} = -0.16$, $p = 0.88$ and $t_{(6)} = 0.34$, $p = 0.74$ for bytes and blocks number, respectively; in Experiments 2 and 3: $t_{(6)} = 1.06$, $p = 0.33$ and $t_{(6)} = -0.48$, $p = 0.65$ for bytes and blocks number, respectively.

In the test phase, all the black rectangles re-appeared at the bottom of the screen and participants had to relocate them as accurately as possible, using touchpad/mouse (**Figure 1**). Displacement error (dependent variable) was the distance in pixel between the center of the originally positioned object and the center of the closest relocated object.

Three hours after the test, participants were administered (i) an object-relocation task (ORT) which used pictures built by scrambling pixels of different colors in order to assess spatial working memory span, and (ii) a memory test for the incidentally learned pictures presented during the initial EORT. For the latter task, participants in Experiment 1 had to verbally describe the pictures (free recall). In Experiments 2 and 3, to facilitate online data collection, a two-alternative-forced-choice recognition task was used.

In Experiment 1, participants were randomly assigned to one of two experimental conditions (**Figure 1A**): (i) The CE-interference group ($n = 29$, 18 females) performed a concurrent verbal trail task: the experimenter provided a starting letter-day pair, and participants were required to continue the sequence with subsequent letter-day pairs (e.g., F-Sunday, G-Monday, etc.) until the encoding phase ended. (ii) The control group ($n = 29$, 18 females) performed only the EORT.

Experiment 2 (CE-interference group $n = 30$, 23 females; control group $n = 26$, 19 females) was similar to Experiment 1, with the exception that neutral and negative pictures were matched in terms of arousal.

In Experiment 3 participants were randomly assigned to one of two experimental conditions (**Figure 1B**): (i) The EB-interference group ($n = 42$, 39 females) performed an object feature-report task immediately after the EORT encoding phase. A blank screen

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[1] IAPS pictures were selected by considering valence (from unpleasant to pleasant) and arousal (from calm to exciting) evaluated on a 9-point scale.
In study 1, pictures were:
- Neutral: *#7035* (4.98; 2.66), *#7060* (4.43; 2.55), *#7110* (4.55; 2.27), *#7491* (4.82; 2.39).
- Negative: *#1220* (3.47; 5.57), *#6244* (3.09; 5.68), *#9427* (2.89; 5.5), *#9630* (2.96; 6.06).

In studies 2 and 3, pictures were:
- Neutral: *#2214* (5.01; 3.46), *#2484* (5; 3.75), *#7011* (4.52; 3.81), *#7290* (4.37; 3.87).
- Negative: *#2590* (3.26; 3.93), *#2722* (3.47; 3.52), *#7078* (3.79; 3.69), *#9110* (3.76; 3.98).

Valence and arousal values are reported for each picture in parentheses.

[2] https://github.com/Gabrock94/pyaesthetics

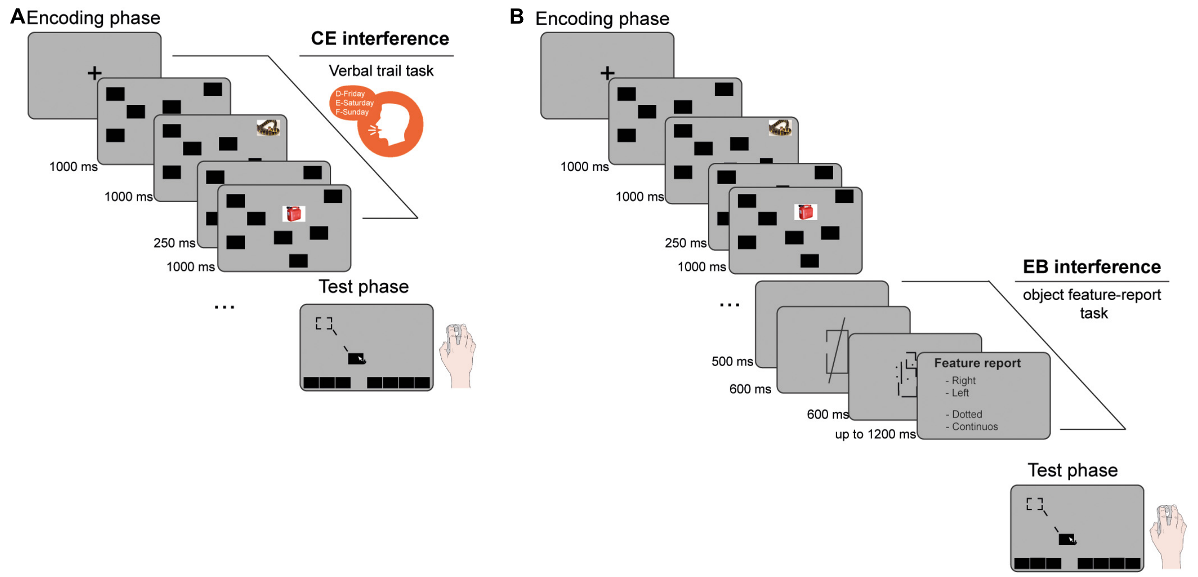

FIGURE 1
Schematic representations of the experimental procedures. **(A)** In Experiment 1 and 2 the concurrent administration of a verbal-trail task during the encoding phase of the emotional object relocation task (EORT) was used to interfere with the central executive (CE). **(B)** In Experiment 3, an object feature report-task immediately after the encoding phase of the EORT was used to interfere with the episodic buffer (EB).

(500 ms) was followed by a box-line stimulus formed with a square and an overlapping line oriented at 82° anti-clockwise to the horizontal plane. The entire stimulus was 360 × 396 px, lasted 600 ms and was placed in the center of the screen. The square presented a gap on either the right or the left vertical side, whereas the line could be solid or dashed. Following a mask of a random pattern of dots and lines (600 ms), participants had to report which side of the square presented the gap and how the line was. The EORT test phase began after an additional 500 ms of blank interval. (ii) The control group (n = 41, 34 females) watched the box-line stimulus but participants were explicitly instructed to ignore it.

2.2. Data analysis

In all experiments the displacement error was calculated as the distance (expressed in pixel) between the center of the originally positioned object and the center of the closest relocated object. The proportion of correctly recognized and/or recalled pictures was considered as an index for picture memory performance.

Two- or three-way ANOVAs and t-test were performed when appropriate on displacement error and on picture memory performance. Simple regressions analyses were also performed by considering picture memory performance as a predictor and displacement error as a criterion. All statistical analyses were performed with SPSS v.23 and GraphPad Prism (8.0.4) considering alpha = 0.05.

3. Results

In Experiments 1 and 2, two-way ANOVAs (2 × 2) were carried out on displacement errors, considering the experimental groups (CE-interference and control) as a between-subject factor and valence (negative and neutral) as a within-subject factor. In both experiments, significant main effects emerged for interference [Experiment 1: $F_{(1,56)} = 9.079$, $p = 0.0039$, η_p^2 0.14; Experiment 2: $F_{(1,54)} = 6.806$, $p = 0.0117$, η_p^2 0.11] and valence [Experiment 1: $F_{(1,56)} = 9.219$, $p = 0.0036$, η_p^2 0.14; Experiment 2: $F_{(1,54)} = 7.752$, $p = 0.0074$, η_p^2 0.13], while the interactions were not significant [Experiment 1: $F_{(1,56)} = 0.1331$, $p = 0.7166$, η_p^2 0.002; Experiment 2: $F_{(1,54)} = 0.1726$, $p = 0.6794$, η_p^2 0.003]. These results indicated that although CE interference reduced spatial working memory performance, perhaps increasing the cognitive load, emotional-related objects were better relocated than neutral-related ones in all experimental conditions (see Figures 2A, B). In both experiments, performance in ORT with scramble pictures did not differ among groups, indicating that the effect of interference on EORT performance cannot be ascribed to differences in spatial working memory span ($p > 0.05$; data not shown). Moreover, participants who underwent the CE interference showed high level of performance in the verbal trial task (96.8% ± 7.3 of correctness in Experiment 1 and 97.4% ± 6.7 in Experiment 2), indicating that the concurrent interfering task was effectively performed while encoding the EORT. Interfering with CE impaired memory for pictures in both experiments [Experiment 1: $F_{(1,56)} = 12.76$, $p = 0.0007$, η_p^2 0.18; Experiment 2: $F_{(1,54)} = 21.80$, $p < 0.0001$, η_p^2 0.3], whereas negative valence increased later retrieval only when arousal levels differed between negative and neutral pictures [Experiment 1: $F_{(1,56)} = 20.93$, $p < 0.0001$, η_p^2 0.27; Experiment 2: $F_{(1,54)} = 1.84$, $p = 0.18$, η_p^2 0.03].

In Experiment 3, two-way ANOVA (2 × 2) on displacement errors (Figure 2C) with groups (EB-interference and control) as a between subject factor and valence (negative and neutral) as a within subject factor, revealed a significant effect for the interaction [$F_{(1,81)} = 5.93$, $p = 0.017$, η_p^2 0.07], but neither for

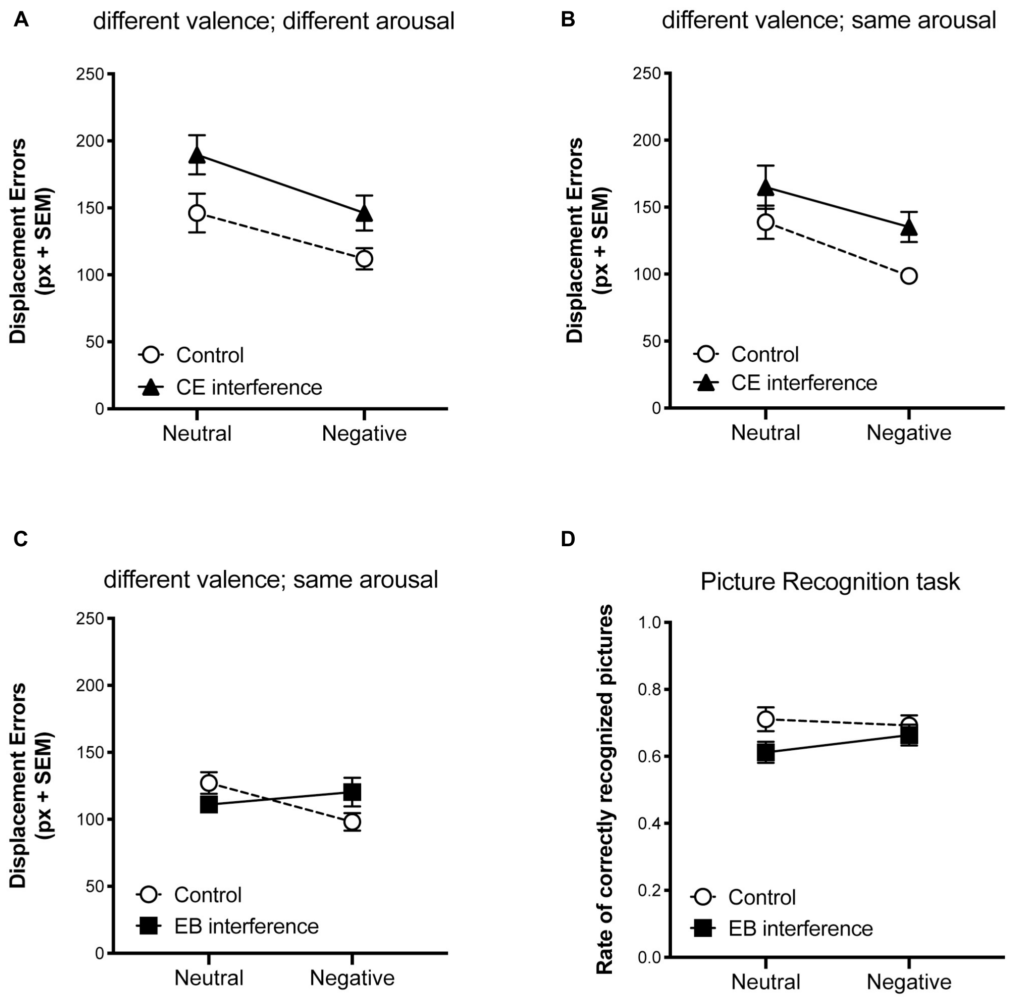

FIGURE 2

Effect of interfering tasks on visuo-spatial working memory performance in the EORT. Mean displacement errors obtained in controls and in and central executive (CE interference) suppression conditions **(A)** when negative pictures presented during the encoding phase of the EORT were more arousing than neutrals and **(B)** when negative and neutral pictures had similar levels of arousal. **(C)** Mean displacement errors obtained in controls and episodic buffer (EB interference) suppression condition. **(D)** Rate of correctly recognized pictures presented during the encoding phase of the EORT in controls and episodic buffer (EB interference) suppression condition. Vertical bars represent SEM.

group [$F_{(1,81)} = 0.144$, $p = 0.7051$, η_p^2 0.002], nor for valence [$F_{(1,81)} = 1.57$, $p = 0.21$, η_p^2 0.02]. *Post-hoc* analyses (Bonferroni's multiple comparisons test) showed that negative-related objects were better relocated than neutral ones in the control group [$t_{(40)} = 2.59$, $p = 0.01$, η_p^2 0.14], but not in the EB interference group [$t_{(41)} = 0.84$, $p = 0.4$, η_p^2 0.017]. Also in this experiment, performances in ORT with scramble pictures did not differ between groups [$t_{(81)} = 1.02$; $P = 0.31$]. Moreover, participants who underwent the EB interference showed a high rate (82.4% ± 24.4.) of correct responses in the object feature-report task.

The two-way ANOVA carried out on recognition performance (Figure 2D) did not reveal any significant effects [group: $F_{(1,81)} = 3.84$, $p = 0.053$, η_p^2 0.04; valence: $F_{(1,81)} = 1.23$, $p = 0.27$, η_p^2 0.01; interaction: $F_{(1,81)} = 0.27$, $p = 0.6$, η_p^2 0.003].

A further regression analysis was performed by considering recognition performance as a predictor and displacement error as a criterion. We hypothesized that if attention-demanding processes modulate the binding of emotional pictures to spatial position, a significant correlation between memory for pictures and spatial working memory performance should be observed. Regression analyses performed on the results of Experiments 2 and 3 did not reveal any significant relation between the two variables in controls ($R^2 = 0.01$, $p = 0.41$ for neutral picture condition and $R^2 = 0.004$, $p = 0.59$ for negative picture condition), in the CE-interference group ($R^2 = 0.01$, $p = 0.86$ for neutral picture condition and $R^2 = 0.003$, $p = 0.34$ for negative picture condition), and EB-interference group ($R^2 = 0.004$, $p = 0.68$ for neutral picture condition and $R^2 = 0.04$, $p = 0.21$ for negative picture condition) (Figure 3). These results indicate that the relocation performance was unrelated to the explicit memory of pictures and suggest that the effect of negative pictures on spatial working memory is independent of attentional control.

To directly compare the effects of CE and EB interferences on single picture memory, we compared recognition accuracy between Experiment 2 and 3 participants. Three-way ANOVA (2 × 2 × 2) with valence (negative and neutral) as a within-subjects factor, and experiment (2 and 3) and group (control and interference) as between-subjects factors revealed significant main effects for

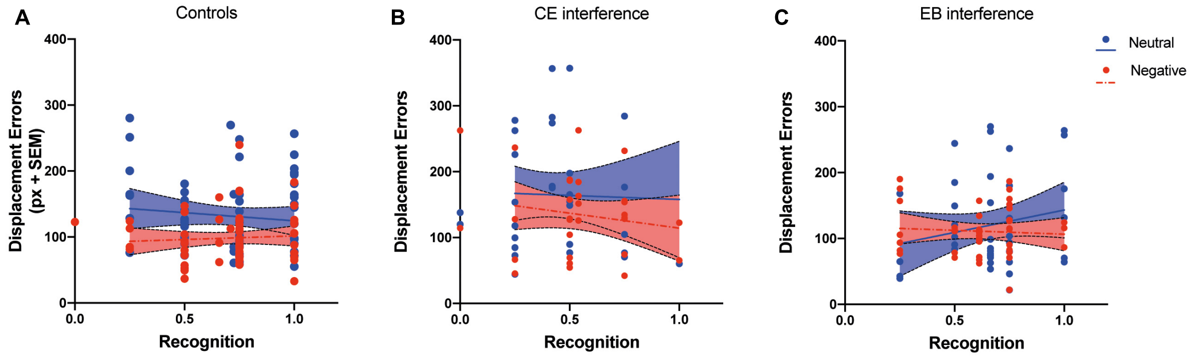

FIGURE 3
Relationship between the rate of correctly recognized pictures (Recognition) and the displacement errors in Experiments 2 and 3. Separate regression analyses for negative and neutral pictures were performed for controls **(A)**, CE-interference **(B)**, and EB-interference **(C)** groups.

both experiment [$F_{(1,135)} = 7.0$, $p < 0.01$, η_p^2 0.05] and group [$F_{(1,135)} = 26.98$, $p < 0.001$, η_p^2 0.17] as well as a significant interaction between the two factors [$F_{(1,135)} = 8.65$, $p < 0.01$, η_p^2 0.06]. Bonferroni's-corrected t-tests confirmed that interfering with the CE impaired memory for pictures compared to controls [$t_{(55)} = -5.23$, $p < 0.001$, η_p^2 0.33], whereas interfering with the EB did not impact subsequent recognition performance compared to controls [$t_{(82)} = 1.77$, $p = 0.08$, η_p^2 0.03]. Accordingly, recognition accuracy was lower in the CE-interference group than in EB-interference group [$t_{(71)} = -4.05$, $p < 0.001$, η_p^2 0.19], whereas no difference emerged between the control groups of the two experiments [$t_{(66)} = 0.02$, $p = 0.83$, $\eta_p^2 < 0.01$].

Overall, this pattern of results indicates that interfering with the CE does not affect binding of negative pictures and spatial locations in working memory. Instead, interfering with EB activity selectively disrupted the binding. In contrast, when investigating memory for single pictures the opposite pattern emerged: interfering with the CE, but not with the EB, impaired later recognition performance.

Given the imbalance between the number of female and male participants in our experiments, gender was added as a covariate to all analyses reported above to test for the potential confounding effects of gender, following Schneider's procedure for mixed designs experiments (Schneider et al., 2015). The results of the ANCOVA coincided in all experiments with those of ANOVA.

4. Discussion

The role of different working memory subcomponents in binding emotional and spatial information was investigated using an emotional version of the object relocation task (EORT). Results of Experiments 1 and 2 revealed that interfering with the CE during the encoding phase did not prevent the enhancing effect of incidentally presented negative pictures on object location memory. Although the CE interference impaired overall spatial working memory performance, negative-related objects were better relocated than neutral ones, regardless of the arousal level of negative pictures. These findings suggest that general attention-based mechanisms are not involved in binding emotional information to the location of objects.

On the other hand, the comparison of picture memory performance between Experiments 1 and 2 showed that the recollection of single images was impaired when domain-general attention resources were diverted from encoding. This pattern of results is in line with the known effect of divided attention during the encoding phase on subsequent recognition performance (e.g., Craik et al., 1996; Kang et al., 2014). Interestingly, in Experiment 1 negative high-arousing pictures were better remembered than neutral low-arousing one. No differences emerged in Experiment 2 where the arousal levels of both negative and neutral pictures were kept constant. This pattern of results is consistent with our previous findings that valence, rather than arousal, is involved in the prioritization of emotional stimuli in working memory access (Costanzi et al., 2019). It is also in line with theories proposing a primary role for arousal in the consolidation process of emotional memories (McGaugh, 2004; Mather and Sutherland, 2011).

In experiment 3 we found that interfering with the EB (i) completely and specifically prevented the emotion-enhancing effect exerted by negative pictures on spatial working memory performance, (ii) did not affect relocation performance of neutral-related objects–which was comparable to the control group, and (iii) did not affect recognition memory for both neutral and negative pictures presented during the EORT encoding phase. Moreover, the picture recognition accuracy of the EB-interference group (Experiment 3) was higher than the accuracy of the CE-interference group (Experiment 2). These results further support the idea that EB plays a key role in maintaining the bound representations of stimuli in working memory, whereas it does not influence memory for single features (Gao et al., 2017).

Findings from regression analyses revealed that spatial working memory performance of both control and interference groups did not correlate with memory for pictures. Although these analyses do not reveal any causal link between the two variables, the lack of a significant correlation suggests that the superior recall of the locations of negative pictures cannot be ascribed to explicit memory for those pictures.

Altogether, the findings of the present study suggest that automatic processes are primarily involved in modulating the emotion-enhancing effect of negative pictures on spatial working memory for object positions. For the present purposes, automatic processes can be considered as the opposite of domain-general attention-based processes, considering the latter as conscious mechanisms that drive the focus of attention. In this respect, interfering with attention-based processes means diverting conscious resources away from the main task (Schneider et al., 1982).

This interpretation appears to be consistent with several psychophysiological and behavioral studies showing that emotional stimuli are rapidly encoded through the activation of pre-attentive mechanisms that facilitate memory formation (Kern et al., 2005; Tamietto and De Gelder, 2010; Carretié, 2014; Arend et al., 2015; Kragel et al., 2021). From a psychophysiological standpoint, a main role for the subcortical regions (e.g., amygdala, pulvinar, basal ganglia, and superior colliculus) in prioritizing the selection of emotional stimuli in working memory has been proposed (Tamietto and De Gelder, 2010; Arend et al., 2015; Kragel et al., 2021). In particular, neuroimaging and lesion studies suggested that pulvinar is involved in both working memory and emotional information processing (Soto et al., 2007; Grecucci et al., 2010; Rotshtein et al., 2011; Kragel et al., 2021). Patients with lesions of the rostral part of pulvinar showed an impairment in spatial attention and visual filtering tasks, but not in emotional processing tasks, while patients with lesions of the medial part of pulvinar were impaired in emotional processing, but not in attention functions (Ward et al., 2002, 2005, 2007; Arend et al., 2008). Interestingly, neuroimaging studies reported a specific involvement of the medial pulvinar in working memory (Soto et al., 2007; Grecucci et al., 2010; Rotshtein et al., 2011). Based on these findings, a unique role for medial pulvinar in binding emotionally relevant stimuli with information held in working memory has been envisaged (Arend et al., 2015). More recently Kragel et al. (2021) found a selective role for the collicular-pulvinar-amygdala pathway in mediating the unconscious affective responses to visual stimuli (Kragel et al., 2021). These findings add new evidence to behavioral studies, indicating that the processing of emotional information is often prioritized and independent of attentional resources (Carretié et al., 2004; Vuilleumier, 2005; Tamietto and De Gelder, 2010).

From a behavioral point of view, Phillips et al. (2008) found that performance accuracy in a two-choice discrimination task requiring participants to decide whether two emotions were the same or different was relatively unaffected by the administration of a concurrent task taxing working memory capacity, supporting the hypothesis that the encoding of emotional stimuli is automatic and does not require attentional resources (Phillips et al., 2008; Tsouli et al., 2017). In discussing how the emotional valence of stimuli might be processed in working memory tasks, several pieces of evidence suggested the existence of dedicated subcomponent. Mikels et al. (2008) found that an emotional, but not a cognitive, interfering task impaired emotional working memory performance, suggesting that working memory may include a domain-specific component specialized in the processing of emotional information. Along the same lines, Baddeley et al. (2012) proposed the existence of a dedicated "hedonic detector," which automatically assesses the emotional values of incoming sensory stimuli. This process modulates how information is selected, represented, and stored in working memory (Baddeley, 2007; Baddeley et al., 2012; Ribeiro et al., 2018). In his seminal work, Baddeley (2007) hypothesized that the hedonic detector evaluates the valence of incoming stimuli by setting a neutral point based on one's mood. As a result, inducing a negative mood leads to a more negative assessment of stimuli that must be processed in working memory (Baddeley et al., 2012). Ribeiro et al. (2018) extended Baddeley's hypothesis by pointing out that the "hedonic detector" would explain the impact that emotional stimuli processing might have on working memory performance. Our results support the idea that the hedonic detector can automatically reveal the valence of the emotional stimuli processed by working memory. We also envisage the hedonic detector being integrated in the working memory model through a direct connection with the EB.

General attention-demanding processes can certainly modulate the enhancing effect of emotional pictures on working memory, especially when participants are instructed to pay attention to emotional stimuli relevant for solving the working memory task (Kensinger and Corkin, 2003; Schupp et al., 2007; Ziaei et al., 2014). After all, the EB can be also fueled by the CE through attention-based mechanisms (Baddeley et al., 2010; Gao et al., 2017). However, we believe that the valence of emotional stimuli—revealed by the hedonic detector—may automatically tag the location of objects retained in the EB, leading to a better memory for that location. This interpretation is also consistent with findings showing that conditions requiring binding are less sensitive to attention-demanding concurrent tasks than conditions requiring retention of single features, such as color or shape (Baddeley et al., 2010).

Alternatively, since in our experiments we interfere with CE by administering an attention-demanding task during the encoding phase of EORT, attentional control may be required in binding emotional and spatial information in a later stage of information processing (i.e., during the maintenance or retrieval phases). However, previous results have shown that interfering with attentional mechanisms after the encoding phase of visuo-spatial working memory tasks has little impact on feature binding memory (Johnson et al., 2008; Delvenne et al., 2010; Zhang et al., 2012). Another caveat when interpreting our findings is the different domains of the interfering tasks: verbal for CE and visual for EB. It is possible that the different modalities in which the interfering tasks were administered influenced our results. However, because the CE-mediated attention that we interfered with in Experiments 1 and 2 is assumed to be domain-general (Allen et al., 2006; Gao et al., 2017), we would expect similar results when presenting a secondary task with a different modality. Indeed, there is evidence showing that the concurrent administration of two attention-demanding tasks (dual-task condition) taxing different sensory modalities (i.e., visual and verbal) lead to an interference because the two tasks depend on the activation of the same brain areas (involved in domain-general attention processing: Klingberg, 1998; Loose et al., 2003). Regarding EB, administering either auditory or visual secondary tasks in the maintenance phase of a visual working memory task impaired memory for binding (Zokaei et al., 2014). In addition, the administration of a visual object feature-reporting task affected the binding of verbal to visual information (Gao et al., 2017). These results suggest that EB activity in maintaining bound representations may be inhibited regardless of the modality (i.e., verbal or visual) with which the secondary task is presented. We therefore conclude that differences in the modality (i.e., verbal vs. visual) and/or in the phase (encoding vs. maintenance) in which the interfering tasks were administered may have had negligible effects on the results obtained in the present study. However, future experiments would be necessary to better assess the effect of domain- and phase-specific interference in modulating the binding of spatial and emotional information.

Richter-Levin and Akirav (2003) suggested that emotional stimuli may trigger subcortical neuromodulatory systems, which in turn can modulate (tag) the synaptic activity of neurons in other brain regions. This "emotional tagging" would affect memory formation by influencing the sorting of important stimuli among less important ones (Richter-Levin and Akirav, 2003). Coherently with the "emotional tagging" hypothesis, we propose that the emotional content of stimuli operates in the early phase of information processing, allowing emotional-related stimuli to be prioritized in accessing the working memory system, through the connection between the hedonic detector and EB. As a result, memory for the location of the emotional stimulus improves. This interpretation of our findings may provide a neurobiological and cognitive explanation for affective working memory, though further research is needed to confirm this hypothesis.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by CERS, LUMSA University. Date of approval: December 10, 2019. The patients/participants provided their written informed consent to participate in this study.

Author contributions

BC and MC developed the idea for this study and drafted the manuscript. BC, AE, PS, AS, VC, CR-A, and MC contributed conception and designed the study. BC and AE collected the data and organized the database. BC, AE, CR-A, VC, and MC analyzed and interpreted data. PS and AS contributed to the discussion of content-related issues and to the critical revision of the article and wrote sections of the manuscript. MC and CR-A wrote the final version of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

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Conflict of interest

Publisher's note

References

Allen, R. J., Baddeley, A. D., and Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *J. Exp. Psychol.* 135, 298–313.

Arend, I., Henik, A., and Okon-Singer, H. (2015). Dissociating emotion and attention functions in the pulvinar nucleus of the thalamus. *Neuropsychology* 29:191.

Arend, I., Rafal, R., and Ward, R. (2008). Spatial and temporal deficits are regionally dissociable in patients with pulvinar lesions. *Brain* 131, 2140–2152. doi: 10.1093/brain/awn135

Baddeley, A. (2007). *Working Memory, Thought, And Action*, Vol. 45. Oxford: OuP Oxford, doi: 10.1093/acprof:oso/9780198528012.001.0001

Baddeley, A. (2012). Working memory: theories, models, and controversies. *Ann. Rev. Psychol.* 63, 1–29. doi: 10.1146/annurev-psych-120710-100422

Baddeley, A. (2013). Working memory and emotion: Ruminations on a theory of depression. *Rev. Gen. Psychol.* 17, 20–27. doi: 10.1037/a0030029

Baddeley, A., Allen, R. J., and Hitch, G. (2010). Investigating the episodic buffer. *Psychol. Belg.* 50, 223–243.

Baddeley, A., Allen, R. J., and Hitch, G. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia* 49, 1393–1400.

Baddeley, A., Banse, R., Huang, Y. M., and Page, M. (2012). Working memory and emotion: Detecting the hedonic detector. *J. Cogn. Psychol.* 24, 6–16.

Carretié, L. (2014). Exogenous (automatic) attention to emotional stimuli: a review. *Cogn. Affect. Behav. Neurosci.* 14, 1228–1258. doi: 10.3758/s13415-014-0270-2

Carretié, L., Hinojosa, J. A., Martín-Loeches, M., Mercado, F., and Tapia, M. (2004). Automatic attention to emotional stimuli: neural correlates. *Hum. Brain Mapp.* 22, 290–299.

Christianson, S. A. (1992). "Remembering emotional events: Potential mechanisms," in *The Handbook of Emotion and Memory: Research and Theory*, ed. S. A. Christianson (Hillsdale, NJ: Lawrence Erlbaum Associates Inc).

Costanzi, M., Cianfanelli, B., Saraulli, D., Lasaponara, S., Doricchi, F., Cestari, V., et al. (2019). The effect of emotional valence and arousal on visuo-spatial working memory: incidental emotional learning and memory for object-Location. *Front. Psychol.* 19:2587. doi: 10.3389/fpsyg.2019.02587

Craik, F. I., Govoni, R., Naveh-Benjamin, M., and Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *J. Exp. Psychol.* 125, 159–180.

de Leeuw, J. R. (2015). jsPsych: A JavaScript library for creating behavioral experiments in a web browser. *Behav. Res. Methods* 47, 1–12. doi: 10.3758/s13428-014-0458-y

Delvenne, J. F., Cleeremans, A., and Laloyaux, C. (2010). Feature bindings are maintained in visual short-term memory without sustained focused attention. *Exp. Psychol.* 57, 108–116. doi: 10.1027/1618-3169/a000014

Fürst, A. J., and Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Mem. Cogn.* 28, 774–782. doi: 10.3758/bf03198412

Gabrieli, G., Bornstein, M. H., Setoh, P., and Esposito, G. (2022). Machine learning estimation of users' implicit and explicit aesthetic judgments of web-pages. *Behav. Inform. Technol.* 1–11.

Gao, Z., Wu, F., Qiu, F., He, K., Yang, Y., and Shen, M. (2017). Bindings in working memory: The role of object-based attention. *Attent. Percept. Psychophys.* 79, 533–552.

González-Garrido, A. A., López-Franco, A. L., Gómez-Velázquez, F. R., Ramos-Loyo, J., and Sequeira, H. (2015). Emotional content of stimuli improves visuospatial working memory. *Neurosci. Lett.* 585, 43–47. doi: 10.1016/j.neulet.2014.11.014

Grecucci, A., Soto, D., Rumiati, R. I., Humphreys, G. W., and Rotshtein, P. (2010). The interrelations between verbal working memory and visual selection of emotional faces. *J. Cogn. Neurosci.* 22, 1189–1200. doi: 10.1162/jocn.2009.21276

Huntsinger, J. R. (2013). Does emotion directly tune the scope of attention? *Curr. Direct. Psychol. Sci.* 22, 265–270. doi: 10.1177/0963721413480364

Johnson, J. S., Hollingworth, A., and Luck, S. J. (2008). The role of attention in the maintenance of feature bindings in visual short-term memory. *J. Exp. Psychol.* 34, 41–55.

Kang, C., Wang, Z., and Wei Lü, S. A. (2014). Immediate emotion-enhanced memory dependent on arousal and valence: The role of automatic and controlled processing. *Acta Psychol.* 150, 153–160. doi: 10.1016/j.actpsy.2014.05.008

Kennedy, B. L., Huang, R., and Mather, M. (2020). Age differences in emotion-induced blindness: Positivity effects in early attention. *Emotion* 20, 1266–1278. doi: 10.1037/emo000064

Kensinger, E. A., Garoff-Eaton, R. J., and Schacter, D. L. (2007). Effects of emotion on memory specificity: Memory trade-offs elicited by negative visually arousing stimuli. *J. Mem. Lang.* 56, 575–591.

Kensinger, E. A., and Corkin, S. (2003). Effect of negative emotional content on working memory and long-term memory. *Emotion* 3, 378–393. doi: 10.1037/1528-3542.3.4.378

Kern, R. P., Libkuman, T. M., Otani, H., and Holmes, K. (2005). Emotional stimuli, divided attention, and memory. *Emotion* 5, 408–417. doi: 10.1037/1528-3542.5.4.408

Klingberg, T. (1998). Concurrent performance of two working memory tasks: potential mechanisms of interference. *Cereb. Cortex* 8, 593–601.

Kragel, P. A., Čeko, M., Theriault, J., Chen, D., Satpute, A. B., Wald, L. W., et al. (2021). A human colliculus-pulvinar-amygdala pathway encodes negative emotion. *Neuron* 109, 2404–2412. doi: 10.1016/j.neuron.2021.06.001

Lang, P. J., Bradley, M. M., and Cuthbert, B. N. (2008). "International Affective Picture System (IAPS): Instruction manual and affective ratings," in *Technical Report A-8. Gainesville: The Center for Research in Psychophysiology*, (Gainesville, FL: University of Florida).

Loose, R., Kaufmann, C., Auer, D. P., and Lange, K. W. (2003). Human prefrontal and sensory cortical activity during divided attention tasks. *Hum. Brain Mapp.* 18, 249–259.

Marin, M. M., Lampatz, A., Wandl, M., and Leder, H. (2016). Berlyne revisited: Evidence for the multifaceted nature of hedonic tone in the appreciation of paintings and music. *Front. Hum. Neurosci.* 10:536. doi: 10.3389/fnhum.2016.00536

Mather, M., and Sutherland, M. R. (2011). Arousal-biased competition in perception and memory. *Perspect. Psychol. Sci.* 6, 114–133.

McGaugh, J. L. (2004). The amygdala modulates the consolidation of memories of emotionally arousing experiences. *Annu. Rev. Neurosci.* 27, 1–28.

Migita, M., Otani, H., Libkuman, T. M., and Sheffert, S. M. (2011). Preattentive processing, poststimulus elaboration, and memory for emotionally arousing stimuli. *J. Gen. Psychol.* 138, 260–280. doi: 10.1080/00221309.2011.604364

Mikels, J. A., Reuter-Lorenz, P. A., Beyer, J. A., and Fredrickson, B. L. (2008). Emotion and working memory: evidence for domain-specific processes for affective maintenance. *Emotion* 8:256. doi: 10.1037/1528-3542.8.2.256

Nobre, A. D. P., Rodrigues, J. D. C., Sbicigo, J. B., Piccolo, L. D. R., Zortea, M., Duarte Junior, S., et al. (2013). Tasks for assessment of the episodic buffer: A systematic review. *Psychol. Neurosci.* 6, 331–343. doi: 10.1080/09297049.2015.1085500

Nummenmaa, L., Hyöna, J., and Calvo, M. G. (2006). Eye movement assessment of selective attentional capture by emotional pictures. *Emotion* 6, 257–268. doi: 10.1037/1528-3542.6.2.257

Phillips, L. H., Channon, S., Tunstall, M., Hedenstrom, A., and Lyons, K. (2008). The role of working memory in decoding emotions. *Emotion* 8:184.

Pottage, C. L., and Schaefer, A. (2012). Visual attention and emotional memory: recall of aversive pictures is partially mediated by concurrent task performance. *Emotion* 12, 33–38. doi: 10.1037/a0024574

Ribeiro, F., Albuquerque, P. B., and dos Santos, F. H. (2018). Relations between emotion and working memory: Evidence from behavioural and psychophysiological studies. *Psicol. Estudo* 23:35734. doi: 10.1016/j.psyneuen.2005.04.014

Richter-Levin, G., and Akirav, I. (2003). Emotional tagging of memory formation–in the search for neural mechanisms. *Brain Res. Brain Res. Rev.* 43, 247–256. doi: 10.1016/j.brainresrev.2003.08.005

Riggs, L., McQuiggan, D. A., Farb, N., Anderson, A. K., and Ryan, J. D. (2011). The role of overt attention in emotion-modulated memory. *Emotion* 11, 776–785. doi: 10.1037/a0022591

Rossi-Arnaud, C., Spataro, P., Costanzi, M., Saraulli, D., and Cestari, V. (2018). Divided attention enhances the recognition of emotional stimuli: evidence from the attentional boost effect. *Memory* 26, 42–52. doi: 10.1080/09658211.2017.1319489

Rotshtein, P., Soto, D., Grecucci, A., Geng, J. J., and Humphreys, G. W. (2011). The role of the pulvinar in resolving competition between memory and visual selection: a functional connectivity study. *Neuropsychologia* 49, 1544–1552. doi: 10.1016/j.neuropsychologia.2010.12.002

Schneider, B. A., Avivi-Reich, M., and Mozuraitis, M. (2015). A cautionary note on the use of the Analysis of Covariance (ANCOVA) in classification designs with and without within-subject factors. *Front. Psychol.* 6:474. doi: 10.3389/fpsyg.2015.00474

Schneider, W., Dumais, S. T., and Shiffrin, R. M. (1982). Automatic/Control Processing and Attention.

Schupp, H. T., Stockburger, J., Codispoti, M., Junghöfer, M., Weike, A. I., and Hamm, A. O. (2007). Selective visual attention to emotion. *J. Neurosci.* 27, 1082–1089. doi: 10.1523/JNEUROSCI.3223-06.2007

Soto, D., Humphreys, G. W., and Rotshtein, P. (2007). Dissociating the neural mechanisms of memory-based guidance of visual selection. *Proc. Natl. Acad. Sci. U.S.A.* 104, 17186–17191. doi: 10.1073/pnas.0703706104

Talmi, D., Schimmack, U., Paterson, T., and Moscovitch, M. (2007). The role of attention and relatedness in emotionally enhanced memory. *Emotion* 7, 89–102. doi: 10.1037/1528-3542.7.1.89

Tamietto, M., and De Gelder, B. (2010). Neural bases of the non-conscious perception of emotional signals. *Nat. Rev. Neurosci.* 11, 697–709. doi: 10.1038/nrn2889

Tsouli, A., Pateraki, L., Spentza, I., and Nega, C. (2017). The effect of presentation time and working memory load on emotion recognition. *J. Psychol. Cogn.* 2, 61–66. doi: 10.1007/BF03380088

Vuilleumier, P. (2005). How brains beware: neural mechanisms of emotional attention. *Trends Cogn. Sci.* 9, 585–594. doi: 10.1016/j.tics.2005.10.011

Ward, R., Calder, A. J., Parker, M., and Arend, I. (2007). Emotion recognition following human pulvinar damage. *Neuropsychologia* 45, 1973–1978.

Ward, R., Danziger, S., and Bamford, S. (2005). Response to visual threat following damage to the pulvinar. *Curr. Biol.* 15, 571–573. doi: 10.1016/j.cub.2005.01.056

Ward, R., Danziger, S., Owen, V., and Rafal, R. (2002). Deficits in spatial coding and feature binding following damage to spatiotopic maps in the human pulvinar. *Nat. Neurosci.* 5, 99–100. doi: 10.1038/nn794

Zhang, W., Johnson, J. S., Woodman, G. F., and Luck, S. J. (2012). "Features and conjunctions in visual working memory," in *From Perception to Consciousness: Searching with Anne Treisman, 5*, eds J. Wolfe and L. Robertson (New York, NY: Oxford Series in Visual Cognition).

Ziaei, M., Peira, N., and Persson, J. (2014). Brain systems underlying attentional control and emotional distraction during working memory encoding. *Neuroimage* 87, 276–286. doi: 10.1016/j.neuroimage.2013.10.048

Zokaei, N., Heider, M., and Husain, M. (2014). Attention is required for maintenance of feature binding in visual working memory. *Q. J. Exp. Psychol.* 67, 1191–1213.

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Attentional capture by fearful faces requires consciousness and is modulated by task-relevancy: A dot-probe EEG study

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In the current EEG study, we used a dot-probe task in conjunction with backward masking to examine the neural activity underlying awareness and spatial processing of fearful faces and the neural processes for subsequent cued spatial targets. We presented face images under different viewing conditions (subliminal and supraliminal) and manipulated the relation between a fearful face in the pair and a subsequent target. Our mass univariate analysis showed that fearful faces elicit the N2-posterior-contralateral, indexing spatial attention capture, only when they are presented supraliminally. Consistent with this, the multivariate pattern analysis revealed a successful decoding of the location of the fearful face only in the supraliminal viewing condition. Additionally, the spatial attention capture by fearful faces modulated the processing of subsequent lateralised targets that were spatially congruent with the fearful face, in both behavioural and electrophysiological data. There was no evidence for nonconscious processing of the fearful faces in the current paradigm. We conclude that spatial attentional capture by fearful faces requires visual awareness and it is modulated by top-down task demands.

KEYWORDS

spatial attention, awareness, fearful faces, EEG, mass univariate analysis, multivariate pattern analysis

1. Introduction

Fearful expressions communicate information to other individuals regarding our perception of the environment. Specifically, we may express fear in response to dangerous events or threat. Therefore, fearful faces are usually perceived as indicators of negative events and they tend to attract our attention easily (Pourtois et al., 2004; Schupp et al., 2004). It has been reported that emotional faces including fearful faces can be detected faster and they elicit stronger neural activity, compared to neutral faces (for a review see Schindler and Bublatzky, 2020), even when people are unaware of them (Vuilleumier, 2005; Tamietto and De Gelder, 2010; Qiu et al., 2022c).

With regards to attentional capture, it has been shown that the presence of a fearful face can enhance the processing of a subsequent stimulus. Such modulatory effects of fearful faces on subsequent targets have been mainly examined using the dot-probe paradigm (e.g., Torrence and Troup, 2018). In this paradigm, a pair of face stimuli is presented before a lateralised target stimulus. The lateralised target can be presented in the same spatial location as the emotional face that precedes it (the congruent condition), or at the location opposite to the emotional face (the incongruent condition). The response to the lateralised target is measured, and the differences between congruent and incongruent conditions can be used as an index of spatial attention to the preceding faces. Previous research has repeatedly shown that a target (e.g., a dot or a letter) can be detected faster (Carlson and Reinke, 2008, 2010; Torrence et al., 2017) or discriminated more accurately (Pourtois et al., 2004) when it follows the emotional face in the spatially congruent condition, compared to when it is spatially incongruent to the emotional face (but see van Rooijen et al., 2017).

Neural imaging studies have provided supporting evidence for these behavioural observations. For example, in a dot-probe experiment using electroencephalography (EEG) recording, Carlson and Reinke (2010) presented participants with pairs of faces as the cues and a lateralised dot as the target. At the behavioural level, they found that participants' reaction time towards dots in the congruent condition was shorter than the incongruent condition. Additionally, the neural activity, indexed by event-related potentials (ERPs), at posterior electrodes were found to be enhanced by a lateralised fearful face compared to a neutral face. The magnitude of the increase in the ERPs, in particular the face-sensitive N170, positively correlated with the reaction time difference between congruent and incongruent trials. These results were taken to suggest that fearful faces attracted spatial attention and facilitated task performance for congruent targets. However, to show that fearful faces indeed modulate attention to the subsequent targets, it would have been more compelling to show that fearful faces alter the neural response to the subsequent targets. The target-related ERPs were not reported in the study (Carlson and Reinke, 2010), leaving it an open question how attention to fearful faces modulates neural activity for the targets.

In an object-substitution masking study by Giattino et al. (2018), face and house images were used as cueing stimuli, presented subliminally (for 17 ms) and subsequently masked. Participants were required to detect a target rectangle that was either validly or invalidly cued. It was found that the participants' ability to detect the cue stimuli was no different from chance-level guessing (Giattino et al., 2018). However, participants' early neural activity (i.e., P1) in response to the target stimuli was enhanced when the targets were validly cued, even in trials where participants reported not being aware of the preceding cue. This cue validity effect was also found in the behavioural data such that participants localised the targets faster and more accurately in the congruent condition, even when participants were not aware of the cues (Giattino et al., 2018). Thus, in the absence of awareness of face cues, the spatial information about them was processed to a level where it modulated the neural responses to the subsequent stimuli.

In a series of backward masking experiments, we analysed ERPs for fearful faces presented in face pairs with different visibility (subliminal and supraliminal viewing conditions; Qiu et al., 2022a, 2023). We used 16 ms of presentation time in the subliminal viewing condition, as opposed to 33 ms which was used in Carlson and Reinke (2010), for a stronger impeding effect on visual awareness (Milders et al., 2008). Our results showed that fearful faces can attract spatial attention by eliciting an N2-posterior-contralateral (N2pc), only when the faces were presented above the awareness threshold (266 ms; supraliminal viewing) and when they were relevant to participants' tasks (Qiu et al., 2022a). Although subliminal fearful faces did not elicit an N2pc, some fear-related non-spatial enhancement effect is present in the data (Qiu et al., 2022d). We then ask whether any of the fear-related effects are sustained and can modulate the neural response to stimuli presented after the faces (i.e., modulate target-related EEG signals). Importantly, we ask whether any of the effects require visual awareness, or they can occur as nonconscious processes.

To answer these questions, in the current study, we used a dot-probe task together with the backward masking technique. Specifically, pairs of faces were presented either briefly (for 16 ms) or for a longer time (166 ms) and immediately backward masked. A following lateralised dot either appeared on the same side as the fearful face (congruent) or on the side opposite to it (incongruent). In one half of the experiment, the participants were required to respond to the target dots as well as the faces that preceded them, whereas in the other half of the experiment, participants were instructed to ignore the faces.

For the face stimuli, we expected to find an N2pc for the fearful face only in the supraliminal viewing condition, replicating our previous finding (Qiu et al., 2022a). For the target dot stimuli, we expected dots in the congruent conditions to be detected faster than the incongruent condition. We predicted that the early ERPs (e.g., P1) for congruent dots would be enhanced compared to incongruent dots. Further, if fearful faces can be processed nonconsciously, such cue validity effect should be observed in both supraliminal and subliminal face presentations. Data were also analysed with a multivariate approach to examine neural patterns associated with the variables of interest (i.e., fearful face location, congruency) which may not be revealed in univariate ERP analyses.

2. Materials and methods

2.1. Participants

We determined the sample size in MorePower (Campbell and Thompson, 2012) using an effect size from a previous study with a similar design ($\eta_p{}^2 = 0.22$; Carlson and Reinke, 2008). A minimum of 24 participants were required for a significant main effect of congruency in reaction time in a 3(fearful-face-dot congruency: congruent, incongruent, control) x 2(face-visibility: subliminal, supraliminal) x 2(face-relevancy: relevant, irrelevant) design with an effect size of 0.22 (power = 0.9, two-tailed alpha = 0.05). Thirty-one participants were recruited and were compensated with either course credits or $40 AUD. Data from five participants were excluded after data pre-processing (see below). Therefore, 26 participants constituted the final sample ($M_{age} = 21.9$, $SD_{age} = 2.1$, 8 males, 18 females). This study was approved by the University of Queensland ethics committee.

2.2. Apparatus and experimental stimuli

The experiment was programmed and run in PsychoPy 3 (Peirce et al., 2019) and all stimuli were presented on a 24-inch ASUS LCD monitor (resolution: 1920 × 1,080 pixels) placed 70 cm away from the participant's eyes.

Face stimuli were obtained from the Radboud Face Database (Langner et al., 2010). We used fearful and neutral face images from 10 different models (five females and five males). Non-face information including hair was removed by cutting the face images into oval shapes (6.5°x 5.1 in visual angle; see Figure 1A). The mask stimuli were created by scrambling the neutral face images for each

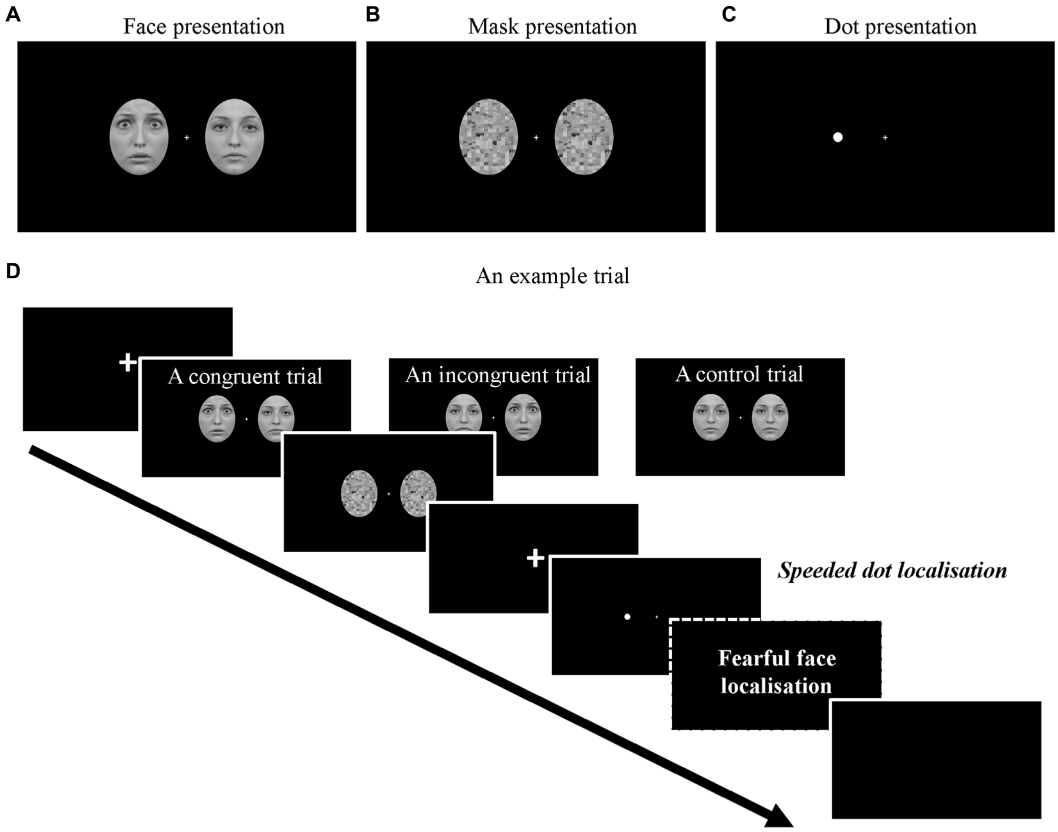

FIGURE 1
Examples of **(A)** the face images (Fearful-on-left) and **(B)** mask images. **(C)** An example of the lateralised target dot (Dot-on-left). **(D)** The full sequence of a trial. Note that the fearful face localisation task was only required in the face-relevant conditions.

model using the Scramble Filter tool[1] such that each mask image consisted of 208 randomly scrambled squares (4.4 mm x 4.4 mm each), see Figure 1B. In this experiment, we used a bilateral presentation of faces and mask stimuli. Each lateralised stimulus was presented 4.1° (in visual angle) away from a central fixation on the screen. The possible face combinations included (a) fearful face on the left and neutral face on the right (fearful-face-on-left), (b) neutral face on the left and fearful face on the right (fearful-face-on-right), and (c) two neutral faces.

A white disc (a dot) extending 0.25°x 0.25 in visual angle was used as the target stimulus in the current dot-probe paradigm (Figure 1C). The distance between the centre of the dot and the central fixation was 4.1° in visual angle.

All images were rendered black-and-white and were presented on a black screen. Image editing was performed in Adobe Photoshop (version 22.4.0).

2.3. Procedure

As shown in Figure 1D, at the start of each trial, a fixation screen was presented with a variable duration between 500–800 ms. Then, a pair of face stimuli appeared for either 16 ms (subliminal) or 166 ms (supraliminal), immediately followed by a pair of mask stimuli for either 166 ms or 16 ms, making the total duration of faces and masks the same across conditions. Afterwards, a fixation screen was presented for 66 ms (Torrence et al., 2017) and was followed by a lateralised dot presented either on the left or the right side of the screen for 750 ms. In a small proportion of the trials (360 trials in total), there was no dot following the mask (baseline condition). The baseline trials were introduced for us to obtain clean dot-related ERPs (see Data analysis). Upon the onset of the dot presentation (or the blank screen in the baseline condition), participants were required to correctly localise the dot as quickly as possible (left arrow key = dot on left; right arrow key = dot on right; both keys = no dot) with their right hand. If no response was made within 1,000 ms after the onset of the dot, a prompt “Too slow!” would be presented on the screen.

There were two types of blocks in the experiment: face-relevant and face-irrelevant blocks. In the face-relevant blocks, participants were instructed to first perform the dot localisation task. Then, they were required to indicate on which side of the screen they saw a fearful face (Q key = fearful face on left; E key = fearful face on right; W = no fearful face/two neutral faces) with their left hand. In the face-irrelevant blocks, participants were instructed to respond only to the dots and ignore the faces. That is, they only needed to perform the speeded dot localisation task in these blocks. Each of the face combinations was presented equiprobably in all conditions, and the

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[1] http://telegraphics.com.au/sw/product/scramble

dot presentations were manipulated orthogonally to the face presentations.

There were three conditions regarding the location of the fearful face and the lateralised dot in each trial: *congruent* condition, where the fearful face and the subsequent dot were presented on the same side of the screen, *incongruent* condition, where they were presented on different sides of the screen and the *control* condition where the two neutral faces were presented before the dot.

There were 16 blocks of 1,200 trials (including 360 baseline trials) in total with short breaks provided between blocks. Participants completed eight face-relevant blocks in either the first half or the second half of the experiment and completed the eight face-irrelevant blocks in the other half of the experiment. This order was determined randomly by the experimental programme for each participant.

2.4. EEG data recording and pre-processing

Raw continuous EEG was recorded at 1024 Hz using the BioSemi ActiveTwo system (Biosemi, Amsterdam, Netherlands). Sixty-four electrodes were placed according to the international 10–20 system location. Horizontal electrooculogram (EOG) was recorded with two bipolar electrodes. Vertical EOG was recorded with an external electrode placed below participants' left eye. Recordings were referenced online to the CMS/DRL electrodes.

Pre-processing of the EEG data was performed with EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). We interpolated electrodes that produced noise throughout the experiment. Signals were re-sampled to 512 Hz offline, filtered from 0.1 to 30 Hz and notch-filtered at 50 Hz to remove line noise. All signals were then re-referenced to the average of all electrodes. EEG data were segmented into epochs with a time window of 600 ms from the onset of the faces and the dots, respectively for the face-related analyses and for the dot-related analyses, using a pre-stimulus baseline (−100 to 0 ms). Independent component analysis was performed on the epoched data to identify and remove eye-blink and eye-movement components in the signals. After eye-related components were removed, epochs containing other artefacts were detected and removed on a trial-by-trial basis through visual inspection. Consequently, data from five participants were excluded for further analyses due to the limited number of epochs remaining (i.e., fewer than 40 trials for each condition of interest). On average, 91% epochs were kept for the remaining participants ($N = 26$).

2.5. Data analysis

At the behavioural level, we examined the reaction time data from the speeded dot localisation task with a repeated-measures ANOVA. We only used reaction time data from the task-correct trials and excluded datapoints identified as outliers from an outlier cheque (i.e., beyond 3rd quartile +1.5*interquartile) for each participant. We did not analyse the accuracy data for the dot localisation task because the accuracy was near ceiling (percent correct: $M = 0.96$, $SD = 0.03$). For the fearful face localisation task, we examined the accuracy data with a paired-samples t-test. All behavioural data analyses were performed in IBM SPSS Statistics 27.

For the EEG data, we separately examined the face-related signals and dot-related signals, using both a univariate approach and a multivariate method.

2.5.1. Mass univariate analysis (ERP analysis)

We conducted ERP analyses using the factorial mass univariate analysis toolbox (Fields and Kuperberg, 2020) and the mass univariate analysis toolbox (for pairwise comparisons; Groppe et al., 2011).

Because we were interested in the early visual processing of the stimuli, posterior electrodes were selected as regions of interest. Only lateral electrodes were included in ERP analyses due to the lateralised stimulus configuration. As a result, the electrodes of interest are P3/4, P5/6, P7/8, P9/10, PO3/4, PO7/8 and O1/2. For significant difference testing, we performed the cluster-based permutation test (10,000 permutations) on all time-points within the epoch (0-600 ms), with a family-wise α level of 0.05. Electrodes were considered as spatial neighbours if adjacent electrodes were within 3.3 cm from each other (Mean spatial neighbours = 2.9; cluster inclusion $p < 0.05$). Follow-up comparisons were conducted using the cluster-based permutation t-tests (two-tailed family-wise $\alpha = 0.05$).

For the analyses on the face-related signals, because we were interested in ERP components that are calculated as difference waves between lateral electrodes (i.e., N2pc), we collapsed the left and right electrodes and retained the information about the relation between the location of the fearful face and electrodes. Specifically, in the two fearful-face-present conditions, signals were relabelled based on whether they were contralateral or ipsilateral to the fearful face. For the neutral faces condition, the average signals between the left and right electrodes were calculated.

For the analyses on the dot-related signals, we first subtracted signals in the dot-absent baseline trials from the dot-present trials to remove effects from the preceding face stimuli. Specifically, the ERPs time-locked to the dot onset from the baseline condition would be subtracted from the ERPs from the experimental condition (i.e., dot-present) that was preceded by the same face combination (e.g., fearful-on-left). Then, we averaged signals from the left and right electrodes. Analyses were performed on the average baseline-subtracted ERPs.

2.5.2. Multivariate pattern analysis

We also examined the data with a multivariate approach using the CoSMoMVPA toolbox (Oosterhof et al., 2016) and LIBSVM (Chang and Lin, 2011). We used a radial kernel support vector machine on each time point to find the decision boundary that discriminated between patterns of two conditions of interest using signals across 16 posterior electrodes (P3/4, P5/6, P7/8, P9/10, PO3/4, PO7/8, O1/2, POz, and Oz). Then, data were spatially filtered with surface Laplacian (Kayser and Tenke, 2006) and temporally smoothed with a Gaussian-weighted running average of 20 ms. Classification was performed on each time point and 4 neighbouring time points to avoid the overfitting issue (Grootswagers et al., 2017). Single-trial data were partitioned into 10 chunks and the two classification targets were equally likely to occur in each chunk. Following a leave-one-out procedure, each classifier at each time point was trained on data from nine chunks and tested on the remaining chunk. Decoding accuracies of all iterations were then averaged at each time point for each participant. Statistical significance testing was conducted using one-sample t-tests (against chance-level decoding performance at 50%). The t statistics were corrected for multiple comparisons using Threshold-Free Cluster Enhancement (TFCE) and Monte Carlo-based permutations (Oosterhof et al., 2016). Briefly, a null distribution was acquired through flipping the sign of the statistics across time points for a random half of participants, iteratively for 10,000 times. The observed TFCE statistic at each time point was considered significant if its value was larger than the 95th percentile of the null distribution (i.e., $p < 0.05$ for a one-tailed test; Smith and Nichols, 2009).

For the face-related signals, we decoded the spatial location of the fearful face (fearful-face-on-left vs. fearful-face-on-right) for each condition of face-visibility (collapsing across face-relevancy), and decoded the fearful face location for each condition of face-relevancy (collapsing across face-visibility). All signals were time-locked to the face onset.

For the dot-related signals, we performed decoding of fearful-face-dot congruency (congruent vs. incongruent) across all conditions and also separately for the face-subliminal and face-supraliminal conditions. All signals were time-locked to the dot onset.

3. Results

3.1. Behavioural data

3.1.1. Fearful face localisation task

A paired-samples t-test on the accuracy data (percent correct) for the fearful face localisation task revealed that the fearful face was more accurately localised in the supraliminal condition ($M = 0.74$, $SD = 0.19$) than the subliminal condition ($M = 0.34$, $SD = 0.02$), $t(25) = 10.51$, $p < 0.001$, $d = 2.06$. A one-sample t-test showed that the accuracy in the subliminal condition was not different from chance-level performance (0.33), $t(25) = 0.92$, $p = 0.368$.

3.1.2. Dot localisation task

A 3(fearful-face-dot congruency) x 2(face-visibility) x 2(face-relevancy) repeated-measures ANOVA on the reaction times (in seconds) revealed a significant main effect of face-visibility ($F(1, 25) = 28.05$, $p < 0.001$, $\eta_p^2 = 0.53$), a main effect of face-relevancy ($F(1, 25) = 92.63$, $p < 0.001$, $\eta_p^2 = 0.79$) and a significant interaction between the two, $F(1, 25) = 27.01$, $p < 0.001$, $\eta_p^2 = 0.52$. Specifically, participants were faster at localising the dot in the face-irrelevant condition ($M = 0.34$, $SD = 0.04$) than face-relevant condition ($M = 0.44$, $SD = 0.06$), and when the preceding faces were presented subliminally ($M = 0.38$, $SD = 0.04$) than when presented supraliminally ($M = 0.40$, $SD = 0.05$). The effect of face-relevancy was significant in both face-visibility conditions, $ps < 0.001$. However, the effect of face-visibility was significant only when the faces were task-relevant, $p < 0.001$. When participants did not need to attend to the faces, no difference was found between face-subliminal and face-supraliminal conditions, $p = 0.295$.

The interaction between face-visibility and congruency was also significant, $F(2, 50) = 22.92$, $p = 0.008$, $\eta_p^2 = 0.20$. Follow-up tests showed that, the effect of congruency was non-significant in the face-subliminal condition, $F(2, 50) = 1.33$, $p = 0.274$, but was significant in the face-supraliminal condition, $F(2, 50) = 3.98$, $p = 0.025$, $\eta_p^2 = 0.14$. As part of our planned comparisons, the levels of congruency were compared against each other in the face-supraliminal condition. We found that, the dot was localised significantly slower in the incongruent condition, compared to the congruent condition, $p = 0.023$, and the control condition, $p = 0.018$. The difference between congruent and control conditions was non-significant, $p = 0.508$. No other effect was significant, $Fs < 2.25$, $ps > 0.116$.

3.2. Mass univariate analysis

3.2.1. Face-related ERPs

For ERPs time-locked to the face stimuli, we collapsed the left and right electrodes to create the laterality variable which indicates the relation between the location of a fearful face and the electrodes. A 3(laterality based on the location of a fearful face: contralateral, ipsilateral, control) x 2(face-visibility: subliminal, supraliminal) x 2(face-relevancy: relevant, irrelevant) repeated-measures ANOVA revealed that all main effects were significant, $Fs > 3.19$, $ps < 0.001$. As shown in Figure 2A, ERPs were significantly more negative in the supraliminal compared to the subliminal condition between 113–281 ms (temporal peak: 215 ms) with a maximal effect at P9/10, and between 293–594 ms across all posterior electrodes. ERPs in the face-relevant condition were overall more negative than those in the face-irrelevant condition between 262–594 ms (temporal peak: 348 ms) with a maximal effect on P3/4, see Figure 2B. ERP waveforms are presented in Figure 2C.

All interaction effects were significant including the three-way interaction between laterality, face-visibility and face-relevancy, $Fs > 3.19$, $ps < 0.009$. Follow-up tests revealed that the effect of laterality was significant only in the supraliminal conditions. Thus, we compared three levels of laterality against each other in the supraliminal condition, separately for face-relevant and face-irrelevant conditions, using the cluster-based permutation t-tests.

When the supraliminally-presented faces were task-irrelevant, signals contralateral to the fearful face were more negative than ipsilateral signals between 203–297 ms at posterior electrode sites (temporal peak: 273 ms; spatial peak: P7/8; Figure 2D), reflecting an N2pc for the fearful face. Additionally, contralateral signals were more positive than signals in the control condition in a later time window spanning from 309 to 535 ms (temporal peak: 332 ms; spatial peak: PO7/8; Figure 2E).

When the supraliminally-presented faces were task-relevant, two negative clusters at posterior electrode sites were significant when comparing contralateral against ipsilateral signals: 176-387 ms (temporal peak: 262 ms; spatial peak: P7/8), again reflecting an N2pc for the target fearful face, and a later time window, 477-600 ms (temporal peak: 543 ms; spatial peak: P7/8), see Figure 2F. Contralateral signals were also more negative than signals in the control condition between 184–336 ms (temporal peak: 273 ms; spatial peak: P9/10; Figure 2G). One additional positive cluster was found when contrasting contralateral against control conditions: 402-484 ms (temporal peak: 453 ms; spatial peak: P3/4).

Importantly, the later negativity between 477–600 ms in the contralateral-ipsilateral contrast (Figure 2F) likely reflected the sustained posterior contralateral negativity (SPCN; Luria et al., 2016), an ERP marker associated with working memory consolidation for task-relevant fearful faces. Note that the SPCN was not found in the face-irrelevant condition (Figure 2D). The ERP waveforms are plotted in Figure 2H.

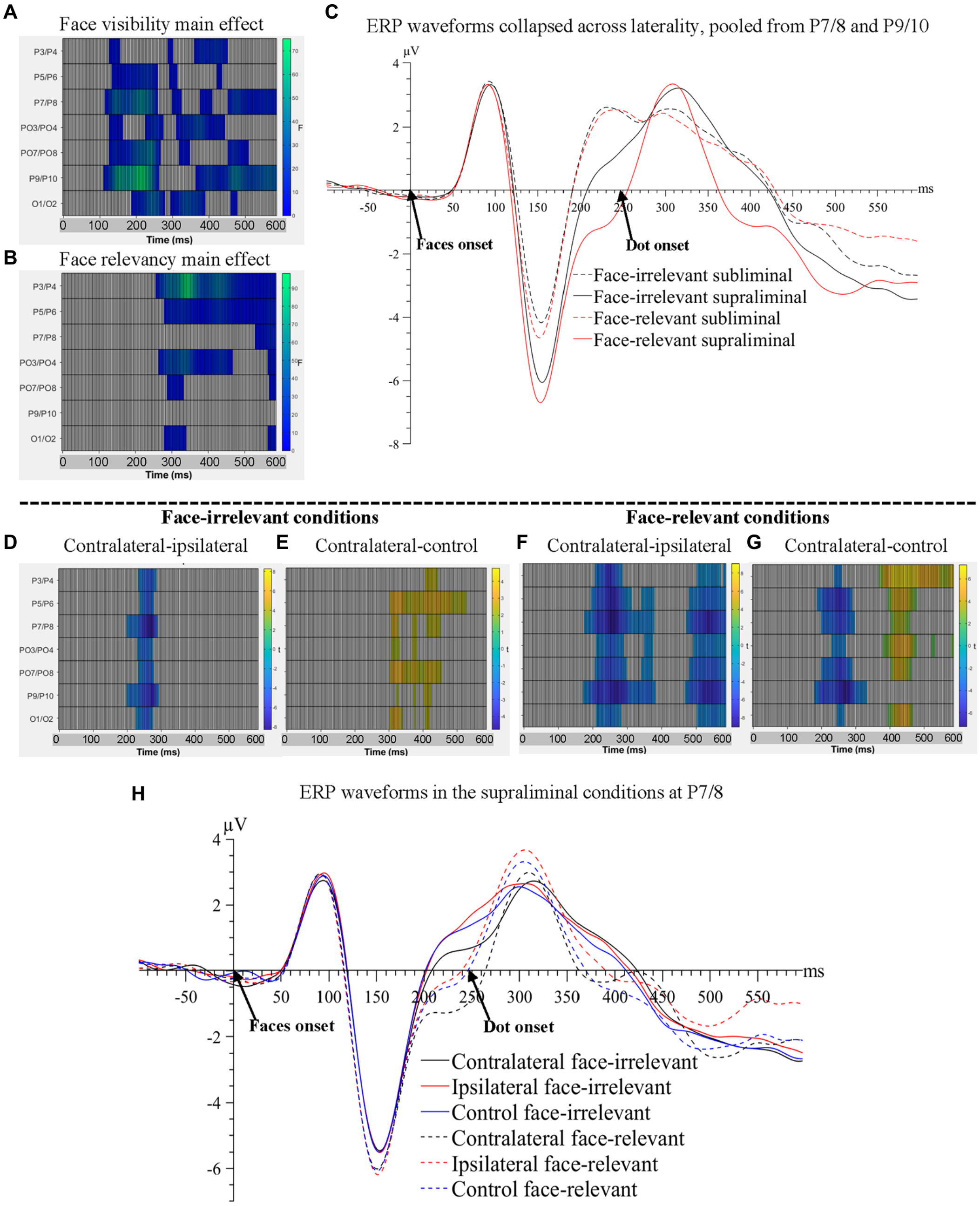

FIGURE 2
Raster plots for **(A)** the main effect of face-visibility and **(B)** the main effect of face-relevancy for face-related ERPs. **(C)** ERP waveforms collapsed across laterality conditions, pooled over P7/8 and P9/10, the two pairs of electrodes that showed the maximal main effect of face-visibility and the maximal interaction effect between face-visibility and face-relevancy. Raster plots for the contrasts between **(D)** contralateral and ipsilateral signals and between **(E)** contralateral and control signals, in the face-irrelevant conditions; between **(F)** contralateral and ipsilateral signals and between **(G)** contralateral and control signals, in the face-relevant conditions. **(H)** ERP waveforms for different conditions of laterality and face-relevancy in the supraliminal condition at electrodes P7/8, the pair that showed the maximal interaction effect between laterality and face-relevancy.

To summarise, starting from 113 ms post-face-onset, significant effects of all three variables of interest (face-visibility, face-relevancy and laterality) were found on the ERPs, encompassing time windows of the N2pc and the SPCN.

3.2.2. Dot-related ERPs

For ERPs time-locked to the target dots, because we did not have a hypothesis about the contralateral and ipsilateral signal differences, we averaged signals from the left and right electrodes, regardless of the spatial relation between the target and the electrodes (for a similar procedure see Giattino et al., 2018). A 3(fearful-face-dot congruency) x 2(face-visibility) x 2(face-relevancy) repeated-measures ANOVA. As shown in Figure 3, the main effects of face visibility and face-relevancy, and the interaction between the two were significant, $Fs > 4.26$, $ps < 0.028$.

To follow up the interaction effect between face-visibility and face-relevancy on the dot-related ERPs, we examined the differences

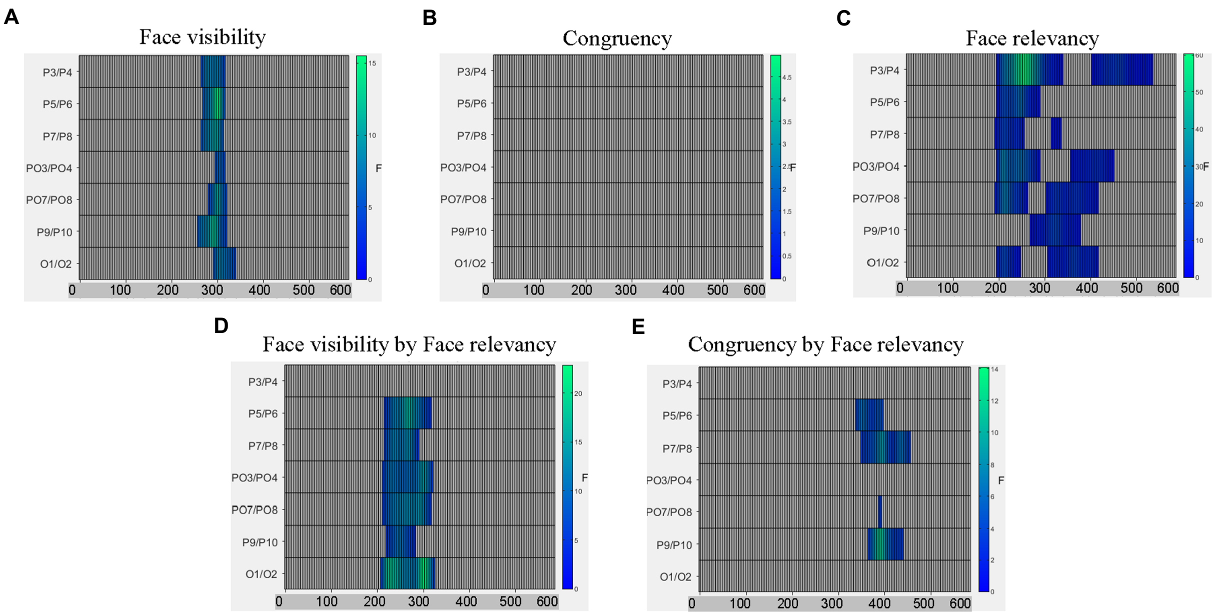

FIGURE 3
Raster plots for **(A)** the main effect of face visibility; **(B)** the non-significant main effect of congruency; **(C)** the main effect of face relevancy; **(D)** the interaction between face visibility and face relevancy; and **(E)** the interaction between congruency and face relevancy.

between the two face-relevancy conditions (face-irrelevant minus face-relevant), separately for when the faces were presented subliminally and when presented supraliminally.

When the preceding faces were presented subliminally, there was a significant negative cluster between 246–445 ms across electrodes P7/8, PO3/4, PO7/8, P9/10 and O1/2 with the maximal effect found on O1/2 (temporal peak: 316 ms), see Figure 4A. Therefore, the mid-latency N2 for dots in the face-relevant condition was smaller in this time window, compared to the face-irrelevant condition.

When the preceding faces were presented supraliminally, there was a significant positive cluster between 195–328 ms across all posterior electrodes with the maximal effect found on P3/4 (temporal peak: 266 ms). In a later time window of 324-445 ms, signals in the face-relevant condition continued to be attenuated, compared to face-irrelevant condition, see Figure 4B. Combined with the ERP waveforms (Figure 4C), it appears that the mid-latency ERPs (i.e., between 195–445 ms) for dots were attenuated overall by a pair of preceding task-relevant faces, especially when they were presented supraliminally (Figure 4C). This is consistent with our behavioural finding of a slower reaction time to the target dots in the face-relevant condition, compared to face-irrelevant condition.

From the omnibus analysis on dot-related signals, the main effect of congruency was not significant. However, the interaction between congruency and face-relevancy was significant (see Figure 3), $F = 3.22$, $p = 0.042$. A simple effect test revealed that the congruency effect was significant only in the face-relevant condition, $F = 3.18$, $p = 0.031$. As part of our planned comparisons, we compared levels of congruency (congruent, incongruent, control) against each other at each level of face visibility, in the face-relevant condition.

When the faces were presented subliminally, there were no significant differences in any of the comparison pairs. However, when the faces were presented supraliminally, signals in the incongruent condition were more negative than in the congruent condition between 258–383 ms (spatial peak: P9/10; temporal peak: 320 ms), see Figure 4D. Signals in the incongruent condition were also more negative than the control condition between 215–340 ms (spatial peak: P7/8; temporal peak: 270 ms), see Figure 4E. Combined with the ERP waveforms (Figure 4F), it appears that the P2 for the dots was smaller when they were presented spatially incongruent (opposite) to the preceding fearful face, compared to when they were presented at a spatially congruent location. Thus, it appears that the processing of a target dot was impaired when it was presented at an incongruent spatial location following a task-relevant and visible fearful face, and such impaired processing was accompanied by a slower reaction to the target dot behaviourally.

To summarise, modulations of all three variables (face-visibility, face-relevancy and congruency) were found on the mid-latency ERPs. Notably, the effect of congruency was significant only in the face-visible and face-relevant condition.

3.3. Multivariate pattern analysis

3.3.1. Decoding the spatial location of fearful faces

Using MVPA, we decoded the neural activity associated with the spatial locations of the fearful faces (fearful-face-on-left vs. fearful-face-on-right) in the subliminal and supraliminal conditions, separately, using signals time-locked to the onset of the face stimuli. The decoding was successful only in the supraliminal conditions (Figure 5A, left panel), with the accuracy significantly above chance level at ~53% ($SEM = 0.72$) between 270–289 ms. However, the decoding accuracy was at chance-level in the subliminal conditions (Figure 5B, left panel). These results were in line with the ERP results in showing that the spatial location of fearful faces was decodable only in conditions where participants were aware of the face stimuli.

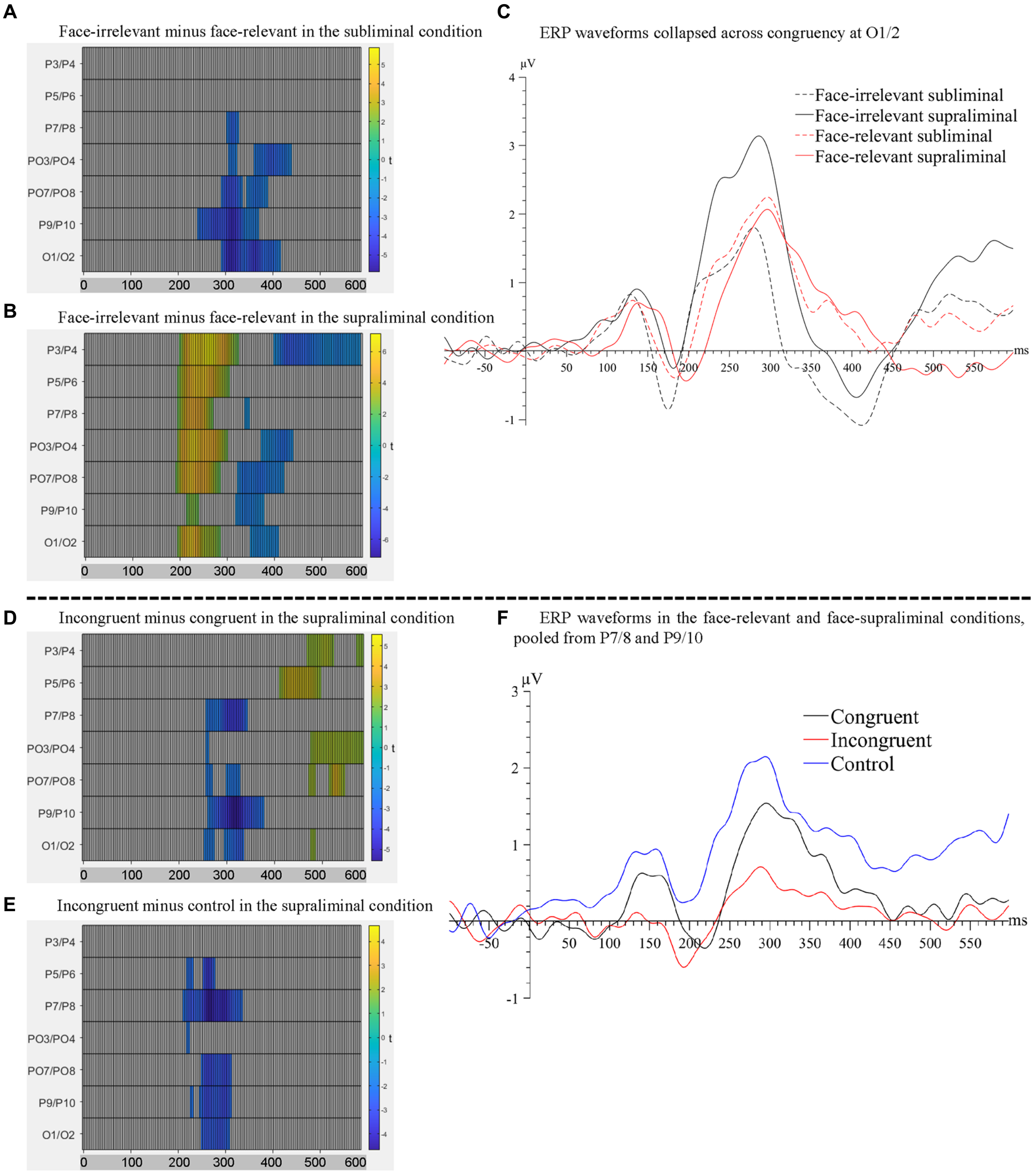

FIGURE 4
Raster plots for the contrasts between **(A)** face-irrelevant and face-relevant signals in the subliminal condition and between **(B)** face-irrelevant and face-relevant signals in the supraliminal condition. **(C)** ERP waveforms collapsed across congruency conditions at O1/2, the pair of electrodes showing the maximal interaction effect between face-relevancy and face-visibility. Raster plots for the contrasts between **(D)** incongruent and congruent signals and between **(E)** incongruent and control signals, in the supraliminal condition. **(F)** ERP waveforms for each congruency level in the face-relevant and face-supraliminal condition, pooled over P7/8 and P9/10.

We also decoded the spatial location of the fearful face separately in the task-relevant and task-irrelevant conditions, pooling over visibility. The decoding performance from both analyses was at chance-level throughout the entire epoch (Figures 5C,D, left panel), showing that the location of the fearful face was not decoded in either condition.

3.3.2. Decoding the relation between a fearful face and the subsequent stimulus

To examine if there was any neural pattern associated with the fearful-face-dot congruency, we decoded the neural activity between fearful-face-dot congruent and fearful-face-dot incongruent trials, using signals time-locked to the onset of the target dots. We performed the decoding first across all conditions and then separately for the face-subliminal and face-supraliminal conditions. No successful decoding of the fearful-face-dot relation was found overall (Figure 5A, right panel) or in the face-subliminal condition (Figure 5B, right panel). In the face-supraliminal condition, the decoding of congruency returned some significant results between −29 and 8 ms ($M_{accuracy}$ = 49%, SEM = 0.69) and between 123 and 150 ms ($M_{accuracy}$ = 50%, SEM = 0.57) (Figure 5C, right panel). Considering the

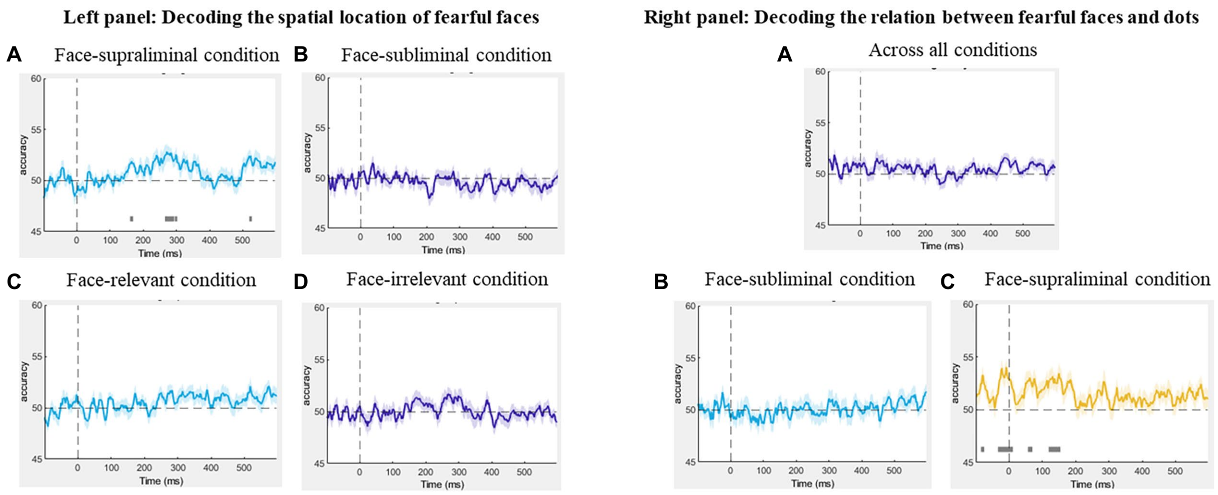

FIGURE 5
Left panel: Results of the decoding of spatial location of fearful faces in the **(A)** face-supraliminal condition, **(B)** face-subliminal condition, **(C)** face-relevant condition and **(D)** face-irrelevant condition. Right panel: Results of the decoding of the relation between fearful faces and the dots **(A)** across all conditions, **(B)** in the face-subliminal condition and **(C)** in the face-supraliminal condition.

near-chance decoding accuracies, we do not argue that there is very strong evidence for a successful decoding of congruency in the current analysis.

4. Discussion

Using the dot-probe paradigm with backward masked faces, we examined neural activity associated with the processing of fearful expressions, as well as subsequent visual targets.

From our mass univariate analysis on the dot-evoked signals, we found that, in the supraliminal face-relevant condition, mid-latency ERP signals were stronger for dots that appeared at the same locations as the fearful face (congruent condition), compared to when they were presented at locations opposite the fearful face (incongruent condition). Behaviourally, we found evidence for this cue validity effect, again only when the preceding face stimuli (cues) were presented supraliminally and when they were task-relevant. These results are consistent with numerous reports of the facilitatory effects of an emotional face on validly cued stimuli (for a review see Torrence and Troup, 2018). Crucially, this effect was not observed when the preceding faces were presented subliminally or when they were task-irrelevant. Therefore, the fearful face-related modulatory effect on subsequent stimuli requires conscious awareness of and top-down attention to the faces. In addition, our MVPA revealed a very low accuracy for congruency decoding. One potential reason for this could be that, in the MVPA, the baseline un-subtracted signals (dot-present ERPs) were used, and more noise introduced by neural patterns associated with the preceding face stimuli was present in the data, which resulted in a rather noisy and low decoding performance of the variable of interest (congruency).

Our second main finding is that supraliminally-presented fearful faces elicited an N2pc towards them, regardless of whether the faces were task-relevant or not. Whilst this finding is consistent to some existing research (e.g., Bar-Haim et al., 2005; Eimer and Kiss, 2007), inconsistent conclusions have been made in more recent studies including our own work (Lien et al., 2013; Zhou et al., 2020; Qiu et al., 2022a, 2023).

Although we failed to find an N2pc for task-irrelevant fearful faces in our previous experiments (Qiu et al., 2022a, 2023), our current findings do not contradict these previous findings. Specifically, task-relevancy was implemented *via* different methods across studies. The task-induced attentional load (Lavie et al., 2004; Lavie, 2005) varied largely between the current study and our previous ones, which could have led to two distinctly different conclusions. In our previous studies, the target non-face stimuli were superimposed onto the faces, and the onset of target stimuli was the same as the overlapping face images. Participants had to suppress the face information to accurately make a decision about the contrast-induced lines overlaid on the face images. Perhaps, the overall attentional load was higher in these previous studies, which could have prevented an N2pc from occurring (Qiu et al., 2022a, 2023). However, in the current face-irrelevant condition, the faces and the target stimuli were separated temporally by 66 ms. The competition between the faces and the targets is considered lower in the current paradigm, potentially allowing some processing of the task-irrelevant faces. As a result, an N2pc was evoked by the fearful face in the pair.

Additionally, when the faces were made task-relevant, we observed a SPCN, a marker for working memory maintenance, for the fearful face. This means that, in face-relevant conditions, the target fearful face was encoded and maintained in working memory, perhaps because this was necessary to produce a correct answer in the fearful face localisation task. However, when the requirement of attending to the fearful face was removed in the face-irrelevant condition, we no longer observed the neural processes associated with working memory (SPCN). These results are not surprising as the top-down suppression of task-irrelevant signals have been demonstrated extensively in the literature (e.g., Gaspelin and Luck, 2018; Liu et al., 2020; for a review see Luck et al., 2021). As explained, the temporal separation between the two pairs of stimuli (faces and target dots) may have allowed attention to shift to task-irrelevant fearful faces (i.e., N2pc). This is not incompatible with the "inhibitory mechanism" highlighted in this line of research where the inhibition was oftentimes exerted upon salient task-irrelevant stimuli presented simultaneously with the targets (Luck et al., 2021; for studies on face processing see Lien et al., 2013; Qiu et al., 2022a, 2023; Zhou et al., 2020). In the current data, signal suppression was perhaps present still, however it manifested as an absence of working memory consolidation for the task-irrelevant faces.

The task-relevancy of the faces also modulated the processing of the following target dot in the current paradigm. Specifically, a pair of task-relevant faces weakened the overall neural activity for the subsequent targets, regardless of the visibility of the faces. Perhaps, the dual task demands resulted in a higher attentional load in the face-relevant condition. Specifically, the task-relevant faces required a certain amount of the limited attentional or working memory resources (Xu and Chun, 2009; Ma et al., 2014) that are shared by neural processes for the target dots in close temporal proximity. Consequently, the strength of neural activity associated with the dots decreased as the preceding faces were processed more strongly in a task-relevant situation, compared to the face-irrelevant condition. Further, the decrease in dot-related ERPs was more evident when the faces were clearly visible (in the supraliminal condition) whereby the time range (200-400 ms) of this attenuation effect was larger than when the faces were presented subliminally (300-400 ms). It is likely that faces were more distracting when they were clearly visible, resulting in even stronger neural activity for the faces themselves, but further diminished ERPs for the subsequent dots. This finding is in line with our previous study using two rapid streams of visual presentations of faces, from which the amplitude of the N2pc towards a lateralised fearful face was found to decrease substantially when participants had to attend to another pair of faces presented immediately prior to it, compared to when the two face pairs were separated for longer (Qiu et al., 2022b).

Finally, and most importantly, no evidence was found for the nonconscious processing of fearful faces in the current paradigm. This was supported by both the univariate and multivariate analysis results, and through two indices of spatial attention (face-related signals and dot-related signals). Indeed, no N2pc for fearful faces was observed in the subliminal viewing condition, and the neural processes for the dots following subliminal face presentations were not modulated by the presence of a fearful face. Consistent with this, the MVPA decoding performance for the spatial location of the fearful faces was at chance-level when the faces were presented subliminally. Additionally, no successful decoding of congruency was found in the face-subliminal condition. Thus, in a bilateral presentation of face images, the spatial information about a lateralised fearful face cannot be processed without visual awareness. This finding is consistent with our recent studies (Qiu et al., 2022a, 2023) and several studies by other researchers (Koster et al., 2007; Gray et al., 2013; Hedger et al., 2019; Baier et al., 2022; Tipura and Pegna, 2022).

The majority of studies showing evidence for the nonconscious processing of fearful faces used central face presentations (e.g., Pegna et al., 2008, 2011; Del Zotto and Pegna, 2015). Faces presented laterally or more eccentric in the visual field are usually harder to detect, compared to faces presented at the centre of the visual field (Smith and Rossit, 2018; Papaioannou and Luck, 2020). Even when they are presented in a subliminal viewing condition, i.e., 16 ms (Pegna et al., 2008; Del Zotto and Pegna, 2015), some processing of fearful faces may occur for centrally presented faces, which may then result in a modulation of the ERPs. However, this modulation is not observed for lateralised faces, as shown by the current results, perhaps due to competition between the two similarly complex face stimuli in each presentation (Wirth and Wentura, 2018).

The use of bilateral presentations of faces in other studies on nonconscious emotion processing is however not rare (De Gelder et al., 2005; Koster et al., 2007; Carlson and Reinke, 2008, 2010; Bertini et al., 2013; Cecere et al., 2014; Hedger et al., 2019). For example, in Carlson and Reinke (2010), face pairs were presented for 33 ms in a backward masking experiment. It was found that the face-sensitive N170 for the masked fearful faces was enhanced, compared to masked neutral faces. However, as acknowledged by the authors themselves, there may be some conscious experience of the stimuli when they are presented for 33 ms (Carlson and Reinke, 2010; see also Pessoa et al., 2005), potentially accounting for the fear-related enhancement effect. In situations where visual awareness was more strongly impeded by either shorter presentation of faces in masking experiments (17 ms, Hedger et al., 2019; 14 ms, Koster et al., 2007) or in a continuous flash suppression procedure (Hedger et al., 2019), fearful faces did not attract spatial attention at the behavioural level. Our current EEG data complement the previous literature by showing that spatial attention was not captured by lateralised fearful faces presented subliminally (16 ms).

Another approach to investigate nonconscious emotion processing is testing patients with cortical blindness. Such patients usually experience a loss of visual awareness due to regional lesion(s) in the brain. Previous clinical studies have consistently shown that emotional faces can be processed even though the patients were incapable of detecting or reporting the stimuli (for a review see Celeghin et al., 2015). Specifically, in a bilateral presentation of face images, patients with hemifield blindness showed improved task performance on face stimuli (e.g., better emotion recognition) presented in their intact visual field when a fearful face was concurrently presented in the blind visual field, indicating some processing of the fearful face in the absence of awareness (De Gelder et al., 2005; Bertini et al., 2013; Cecere et al., 2014). This fear-related improvement on task performance was supported by electrophysical evidence (Cecere et al., 2014) as well as functional imaging evidence (De Gelder et al., 2005). However, whilst fearful faces can be processed (or "influence cognitive processing," Koster et al., 2007) nonconsciously, they do not necessarily attract spatial attention. Supporting this, in a patient with complete destruction of the primary visual cortex, Del Zotto et al. (2013) demonstrated that, whilst the presence of emotional faces, compared to neutral faces, facilitated the patient's task performance for subsequent sound stimuli, the spatial location of the emotional faces had no effect on the patient's behaviour (see supplementary data in Del Zotto et al., 2013).

Taken together, we conclude that, when not consciously detected, fearful faces do not attract spatial attention and they do not affect the processing of spatially contiguous stimuli. Although consciously seen fearful faces attract spatial attention and they modulate the neural processes for following stimuli, these processes are strongly modulated by attentional load. As part of the endeavour in understanding emotional face processing, the current results point to the importance of various conditions (i.e., awareness and task-relevancy) for attentional capture by fearful faces.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/54nw2/.

Ethics statement

The studies involving human participants were reviewed and approved by University of Queensland ethics committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ZQ and AP contributed to conception and design of the study. ZQ and JJ collected data and performed data processing. ZQ performed data analyses and wrote the first draft of the manuscript. ZQ, SB, and AP contributed to manuscript revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Baier, D., Kempkes, M., Ditye, T., and Ansorge, U. (2022). Do subliminal fearful facial expressions capture attention? *Front. Psychol.* 13:840746. doi: 10.3389/fpsyg.2022.840746

Bar-Haim, Y., Lamy, D., and Glickman, S. (2005). Attentional bias in anxiety: a behavioural and ERP study. *Brain Cogn.* 59, 11–22. doi: 10.1016/j.bandc.2005.03.005

Bertini, C., Cecere, R., and Làdavas, E. (2013). I am blind, but I "see" fear. *Cortex* 49, 985–993. doi: 10.1016/j.cortex.2012.02.006

Campbell, J. I., and Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behav. Res. Methods* 44, 1255–1265. doi: 10.3758/s13428-012-0186-0

Carlson, J. M., and Reinke, K. S. (2008). Masked fearful faces modulate the orienting of covert spatial attention. *Emotion* 8, 522–529. doi: 10.1037/a0012653

Carlson, J. M., and Reinke, K. S. (2010). Spatial attention-related modulation of the N170 by backward masked fearful faces. *Brain Cogn.* 73, 20–27. doi: 10.1016/j.bandc.2010.01.007

Cecere, R., Bertini, C., Maier, M. E., and Làdavas, E. (2014). Unseen fearful faces influence face encoding: evidence from ERPs in hemianopic patients. *J. Cogn. Neurosci.* 26, 2564–2577. doi: 10.1162/jocn_a_00671

Celeghin, A., de Gelder, B., and Tamietto, M. (2015). From affective blindsight to emotional consciousness. *Conscious. Cogn.* 36, 414–425. doi: 10.1016/j.concog.2015.05.007

Chang, C.-C., and Lin, C.-J. (2011). LIBSVM: a library for support vector machines. *ACM Trans. Intell. Syst. Technol. (TIST)* 2, 1–27. doi: 10.1145/1961189.1961199

De Gelder, B., Morris, J. S., and Dolan, R. J. (2005). Unconscious fear influences emotional awareness of faces and voices. *Proc. Natl. Acad. Sci.* 102, 18682–18687. doi: 10.1073/pnas.0509179102

Del Zotto, M., Deiber, M. P., Legrand, L. B., De Gelder, B., and Pegna, A. J. (2013). Emotional expressions modulate low α and β oscillations in a cortically blind patient. *Int. J. Psychophysiol.* 90, 358–362. doi: 10.1016/j.ijpsycho.2013.10.007

Del Zotto, M., and Pegna, A. J. (2015). Processing of masked and unmasked emotional faces under different attentional conditions: an electrophysiological investigation. *Front. Psychol.* 6:1691. doi: 10.3389/fpsyg.2015.01691

Delorme, A., and Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21. doi: 10.1016/j.jneumeth.2003.10.009

Eimer, M., and Kiss, M. (2007). Attentional capture by task-irrelevant fearful faces is revealed by the N2pc component. *Biol. Psychol.* 74, 108–112. doi: 10.1016/j.biopsycho.2006.06.008

Fields, E. C., and Kuperberg, G. R. (2020). Having your cake and eating it too: flexibility and power with mass univariate statistics for ERP data. *Psychophysiology 57*:e13468. doi: 10.1111/psyp.13468

Gaspelin, N., and Luck, S. J. (2018). Combined electrophysiological and behavioural evidence for the suppression of salient distractors. *J. Cogn. Neurosci.* 30, 1265–1280. doi: 10.1162/jocn_a_01279

Giattino, C. M., Alam, Z. M., and Woldorff, M. G. (2018). Neural processes underlying the orienting of attention without awareness. *Cortex* 102, 14–25. doi: 10.1016/j.cortex.2017.07.010

Gray, K. L., Adams, W. J., Hedger, N., Newton, K. E., and Garner, M. (2013). Faces and awareness: low-level, not emotional factors determine perceptual dominance. *Emotion* 13, 537–544. doi: 10.1037/a0031403

Grootswagers, T., Wardle, S. G., and Carlson, T. A. (2017). Decoding dynamic brain patterns from evoked responses: a tutorial on multivariate pattern analysis applied to time series neuroimaging data. *J. Cogn. Neurosci.* 29, 677–697. doi: 10.1162/jocn_a_01068

Groppe, D. M., Urbach, T. P., and Kutas, M. (2011). Mass univariate analysis of event-related brain potentials/fields I: a critical tutorial review. *Psychophysiology* 48, 1711–1725. doi: 10.1111/j.1469-8986.2011.01273.x

Hedger, N., Garner, M., and Adams, W. J. (2019). Do emotional faces capture attention, and does this depend on awareness? Evidence from the visual probe paradigm. *J. Exp. Psychol. Hum. Percept. Perform.* 45, 790–802. doi: 10.1037/xhp0000640

Kayser, J., and Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: I. evaluation with auditory oddball tasks. *Clin. Neurophysiol.* 117, 348–368. doi: 10.1016/j.clinph.2005.08.034

Koster, E. H., Verschuere, B., Burssens, B., Custers, R., and Crombez, G. (2007). Attention for emotional faces under restricted awareness revisited: do emotional faces automatically attract attention? *Emotion* 7, 285–295. doi: 10.1037/1528-3542.7.2.285

Langner, O., Dotsch, R., Bijlstra, G., Wigboldus, D. H., Hawk, S. T., and Van Knippenberg, A. D. (2010). Presentation and validation of the Radboud faces database. *Cognit. Emot.* 24, 1377–1388. doi: 10.1080/02699930903485076

Lavie, N. (2005). Distracted and confused?: selective attention under load. *Trends Cogn. Sci.* 9, 75–82. doi: 10.1016/j.tics.2004.12.004

Lavie, N., Hirst, A., De Fockert, J. W., and Viding, E. (2004). Load theory of selective attention and cognitive control. *J. Exp. Psychol. Gen.* 133, 339–354. doi: 10.1037/0096-3445.133.3.339

Lien, M. C., Taylor, R., and Ruthruff, E. (2013). Capture by fear revisited: an electrophysiological investigation. *J. Cogn. Psychol.* 25, 873–888. doi: 10.1080/20445911.2013.833933

Liu, Y., Wang, P., and Wang, G. (2020). The priority of goal-relevant information and evolutionarily threatening information in early attention processing: evidence from behavioural and ERP study. *Sci. Rep.* 10, 1–9. doi: 10.1038/s41598-020-65062-5

Lopez-Calderon, J., and Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Front. Hum. Neurosci.* 8:213. doi: 10.3389/fnhum.2014.00213

Luck, S. J., Gaspelin, N., Folk, C. L., Remington, R. W., and Theeuwes, J. (2021). Progress toward resolving the attentional capture debate. *Vis. Cogn.* 29, 1–21. doi: 10.1080/13506285.2020.1848949

Luria, R., Balaban, H., Awh, E., and Vogel, E. K. (2016). The contralateral delay activity as a neural measure of visual working memory. *Neurosci. Biobehav. Rev.* 62, 100–108. doi: 10.1016/j.neubiorev.2016.01.003

Ma, W. J., Husain, M., and Bays, P. M. (2014). Changing concepts of working memory. *Nat. Neurosci.* 17, 347–356. doi: 10.1038/nn.3655

Milders, M., Sahraie, A., and Logan, S. (2008). Minimum presentation time for masked facial expression discrimination. *Cognit. Emot.* 22, 63–82. doi: 10.1080/02699930701273849

Oosterhof, N. N., Connolly, A. C., and Haxby, J. V. (2016). CoSMoMVPA: multi-modal multivariate pattern analysis of neuroimaging data in Matlab/GNU octave. *Front. Neuroinform.* 10:27. doi: 10.3389/fninf.2016.00027

Papaioannou, O., and Luck, S. J. (2020). Effects of eccentricity on the attention-related N2pc component of the event-related potential waveform. *Psychophysiology* 57:e13532. doi: 10.1111/psyp.13532

Pegna, A. J., Darque, A., Berrut, C., and Khateb, A. (2011). Early ERP modulation for task-irrelevant subliminal faces. *Front. Psychol.* 2:88. doi: 10.3389/fpsyg.2011.00088

Pegna, A. J., Landis, T., and Khateb, A. (2008). Electrophysiological evidence for early non-conscious processing of fearful facial expressions. *Int. J. Psychophysiol.* 70, 127–136. doi: 10.1016/j.ijpsycho.2008.08.007

Peirce, J. W., Gray, J. R., Simpson, S., MacAskill, M. R., Höchenberger, R., Sogo, H., et al. (2019). PsychoPy2: experiments in behaviour made easy. *Behav. Res. Methods* 51, 195–203. doi: 10.3758/s13428-018-01193-y

Pessoa, L., Japee, S., and Ungerleider, L. G. (2005). Visual awareness and the detection of fearful faces. *Emotion* 5, 243–247. doi: 10.1037/1528-3542.5.2.243

Pourtois, G., Grandjean, D., Sander, D., and Vuilleumier, P. (2004). Electrophysiological correlates of rapid spatial orienting towards fearful faces. *Cereb. Cortex* 14, 619–633. doi: 10.1093/cercor/bhh023

Qiu, Z., Becker, S. I., and Pegna, A. J. (2022a). Spatial attention shifting to emotional faces is contingent on awareness and task relevancy. *Cortex* 151, 30–48. doi: 10.1016/j.cortex.2022.02.009

Qiu, Z., Becker, S. I., and Pegna, A. J. (2022b). Spatial attention shifting to fearful faces depends on visual awareness in attentional blink: an ERP study. *Neuropsychologia* 172:108283. doi: 10.1016/j.neuropsychologia.2022.108283

Qiu, Z., Lei, X., Becker, S. I., and Pegna, A. J. (2022c). Neural activities during the processing of unattended and unseen emotional faces: a voxel-wise meta-analysis. *Brain Imaging Behav.* 16, 2426–2443. doi: 10.1007/s11682-022-00697-8

Qiu, Z., Li, X., and Pegna, A. J. (2022d). Decoding neural patterns for the processing of fearful faces under different visual awareness conditions: a multivariate pattern analysis. *BioRxiv*. [Preprint] doi: 10.1101/2022.12.19.520904

Qiu, Z., Zhang, J., and Pegna, A. J. (2023). Neural processing of lateralised task-irrelevant fearful faces under different awareness conditions. *Conscious. Cogn.* 107:103449. doi: 10.1016/j.concog.2022.103449

Schindler, S., and Bublatzky, F. (2020). Attention and emotion: an integrative review of emotional face processing as a function of attention. *Cortex* 130, 362–386. doi: 10.1016/j.cortex.2020.06.010

Schupp, H. T., Öhman, A., Junghöfer, M., Weike, A. I., Stockburger, J., and Hamm, A. O. (2004). The facilitated processing of threatening faces: an ERP analysis. *Emotion* 4, 189–200. doi: 10.1037/1528-3542.4.2.189

Smith, S. M., and Nichols, T. E. (2009). Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. *NeuroImage* 44, 83–98. doi: 10.1016/j.neuroimage.2008.03.061

Smith, F. W., and Rossit, S. (2018). Identifying and detecting facial expressions of emotion in peripheral vision. *PLoS One* 13:e0197160. doi: 10.1371/journal.pone.0197160

Tamietto, M., and De Gelder, B. (2010). Neural bases of the non-conscious perception of emotional signals. *Nat. Rev. Neurosci.* 11, 697–709. doi: 10.1038/nrn2889

Tipura, E., and Pegna, A. J. (2022). Subliminal emotional faces do not capture attention under high attentional load in a randomized trial presentation. *Vis. Cogn.* 30, 280–288. doi: 10.1080/13506285.2022.2060397

Torrence, R. D., and Troup, L. J. (2018). Event-related potentials of attentional bias toward faces in the dot-probe task: a systematic review. *Psychophysiology* 55:e13051. doi: 10.1111/psyp.13051

Torrence, R. D., Wylie, E., and Carlson, J. M. (2017). The time-course for the capture and hold of visuospatial attention by fearful and happy faces. *J. Nonverbal Behav.* 41, 139–153. doi: 10.1007/s10919-016-0247-7

van Rooijen, R., Ploeger, A., and Kret, M. E. (2017). The dot-probe task to measure emotional attention: a suitable measure in comparative studies? *Psychon. Bull. Rev.* 24, 1686–1717. doi: 10.3758/s13423-016-1224-1

Vuilleumier, P. (2005). How brains beware: neural mechanisms of emotional attention. *Trends Cogn. Sci.* 9, 585–594. doi: 10.1016/j.tics.2005.10.011

Wirth, B. E., and Wentura, D. (2018). Attentional bias to threat in the general population is contingent on target competition, not on attentional control settings. *Q. J. Exp. Psychol.* 71, 975–988. doi: 10.1080/17470218.2017.1307864

Xu, Y., and Chun, M. M. (2009). Selecting and perceiving multiple visual objects. *Trends Cogn. Sci.* 13, 167–174. doi: 10.1016/j.tics.2009.01.008

Zhou, X., Du, B., Wei, Z., and He, W. (2020). Attention capture of non-target emotional faces: an evidence from reward learning. *Front. Psychol.* 10:3004. doi: 10.3389/fpsyg.2019.03004

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INs and OUTs of faces in consciousness: a study of the temporal evolution of consciousness of faces during binocular rivalry

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Contents of consciousness change over time. However, the study of dynamics in consciousness has been largely neglected. Aru and Bachmann have recently brought to the attention of scientists dealing with consciousness the relevance of making inquiries about its temporal evolution. Importantly, they also pointed out several experimental questions as guidelines for researchers interested in studying the temporal evolution of consciousness, including the phases of formation and dissolution of content. They also suggested that these two phases could be characterized by asymmetric inertia. The main objective of the present investigation was to approximate the dynamics of these two phases in the context of conscious face perception. To this aim, we tested the time course of content transitions during a binocular rivalry task using face stimuli and asked participants to map their subjective experience of transitions from one content to the other through a joystick. We then computed metrics of joystick velocity linked to content transitions as proxies of the formation and dissolution phases. We found a general phase effect such that the formation phase was slower than the dissolution phase. Furthermore, we observed an effect specific to happy facial expressions, such that their contents were slower to form and dissolve than that of neutral expressions. We further propose to include a third phase of stabilization of conscious content between formation and dissolution.

KEYWORDS

binocular rivalry, consciousness time course, facial expression, happy expressions, joystick

Introduction

Contents of consciousness change over time. These transitions from one content to another content characterize our whole mental life, from perceptions in the different sensory modalities (e.g., as it happens during the succession of words in consciousness during reading) to thoughts (e.g., when thinking back to the points of a to-do list of the day), and are definitely shaped by attentional and memory processes. Despite this intuition granted on our subjective experience of transitioning from one conscious content to another content, scientific research has largely neglected the study of how these changes occur and evolve over time.

In the present investigation, we sought to examine transitions of consciousness contents that could be reliably monitored in a laboratory setting by focusing on the transitions of contents of visual stimuli presented in binocular rivalry (BR; Wheatstone, 1843).

Aru and Bachmann (2017) have recently brought to the attention of scientists dealing with consciousness the relevance of making inquiries about its temporal evolution. While this opinion piece has not received much citation, it is one of Frontiers' most viewed articles,[1] thus suggesting significant interest by the scientific community regarding this topic. The kind of investigation suggested by these authors is all the more relevant when considering a micro-genetic tradition, according to which the *formation* of conscious content is not instantaneous but, indeed, time-consuming. From a phenomenological perspective, the content enriches over time by acquiring a more significant number of qualities, becoming clearer, more stable, and more detailed. Similarly, Aru and Bachmann (2017) proposed that investigating the phase of *dissolution* from consciousness, what they define as the "anti-genesis" of consciousness, is equally crucial. Importantly, they also point out several experimental questions as guidelines for researchers interested in studying the temporal evolution of consciousness, including the phases of formation and dissolution of a content. For example, whether the formation and dissolution phases' inertia is symmetric (or not) is unknown. It is also unknown if the inertia of the two phases varies as a function of stimuli parameters (such as contrast) in a way that their time course can be manipulated by the experimenters. **Figure 1** shows the dynamics of "conscious experience evolving over time" (Aru and Bachmann, 2017; **Figure 1**, p. 2) for two different conscious contents, A and B, differing in terms of formation and dissolution time-courses.

To summarize, Aru and Bachmann stressed the benefit of investigating both the formation and dissolution phases and considered the possibility that these two phases do not have the same duration and that stimuli of different natures may be characterized by differences in the duration of the two phases.

In the present work, we present a method to investigate the dynamics of conscious experience of faces characterized by an emotional expression or gender. Here, the "dissolution" and "formation" phases are not meant to imply that something happens prior to the perceptual change, but rather they indicate the visual perceptual changes (as experienced by the subjects) themselves.

We implemented a variant of a binocular rivalry (BR) paradigm. Under ecological circumstances, slightly discordant visual inputs to the two eyes result in a stable stereo experience. When the dissimilarity exceeds a certain threshold, periods of perceptual dominance of one stimulus over the other stochastically alternate, such that one monocular image is dominantly consciously experienced while the other is suppressed and invisible (Alais and Blake, 2005; Brascamp et al., 2015). This is the condition called BR; phenomenologically, the visual *quale* of one stimulus comes in and goes out over time. According to the theories of consciousness, the shift from unconscious to conscious perception arises as a process of formation; as such, the *formation phase* consists in updating the current version of the phenomenal content (Bachmann, 2000; Aru and Bachmann, 2017), i.e., conscious content arises and replaces the previous content. To note, BR conscious content is also often the result of the integration of processing from multiple systems (e.g., visual and proprioceptive), as we showed in one previous study using BR with facial expressions (Quettier et al., 2021). As such, during the formation phase, processing from multiple channels/brain regions is integrated to generate that particular conscious content and no other content. This might suggest that the processing of stimuli that varies on the number of involved channels/brain regions could lead to differences in the inertia of the formation and/or dissolution phases. Changes in visual experience during formation and/or dissolution phases can occur in different ways, such as through traveling wave-like transitions or local dis/appearing, as described by Yang et al. (1992) and Lee et al. (2005).

When using a simple two-choice response (A or B content) to monitor participants' experience of alternations in BR, the researcher can only analyze data about the onset of consciousness (formation phase; Aru and Bachmann, 2017) and data about the stabilization/maintenance of the conscious content (Quettier et al., 2021). On the other hand, some studies have employed a three-choice response procedure (including a response for the experience of something unclear, i.e., "mixed" percept"; Knapen et al., 2011; Davidson et al., 2018). However, this procedure too, although providing a higher resolution of participants' subjective experience during the BR, cannot characterize the phases of formation and dissolution in a fine-grained way. Skerswetat and Bex (2023) provided a detailed historical overview of methods in reporting subjective experience in BR.

Here we asked participants to map their subjective experience of transitions in BR using a joystick. The rationale behind this methodological choice is that the time course of joystick responses can be considered a good proxy for the dynamics of "conscious experience evolving over time" as proposed by Aru and Bachmann (Naber et al., 2011). Despite criticisms of the use of a joystick as a reporting tool (Fahle et al., 2011), we assumed that delay in the participants' report with respect to the subjective expeience would be consistent across conditions and thus would not have a significant impact on our results.

To analyze the time-series data of BR obtained using the joystick, we defined a few dependent variables to estimate the inertia of the formation and dissolution phases and the periods of stabilization of contents:

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[1] https://loop-impact.frontiersin.org/impact/article/238706#totalviews/views

1. kinematic speed parameters able to capture the BR transitions as measured by the joystick movements, i.e., *speed* ($|V|$) that could be considered as a proxy of the time-course of the formation (Speed_{IN}; $|V|$ *-in*) and dissolution ($\text{Speed}_{\text{OUT}}$; $|V|$ *-out*) phases of conscious contents (see Methods for details);
2. a measure of the proportion of total time of dominance in awareness of one percept over the other during the same rival competition, excluding the periods of transitions and the initial competition, i.e., *cumulative time* (*CT*). In other words, CT is a metric that allows an estimate of the periods of stable resolution following the initial competition (see Alpers and Gerdes, 2007) for similar measures);
3. a measure of the proportion of total time of dominance in awareness of one percept over the other during the same rival competition, including the time needed for the initial disambiguation and the periods of transitions, i.e., *mean of predominance* (*MP*). In other words, *MP* is a metric that estimates the periods of relative preference of one percept over the other.

We have shared all the necessary information, including scripts and a step-by-step description of the procedure to compute the metrics presented above here: https://osf.io/2pzmg/.

We have implemented two BR conditions, a "facial expression rivalry" and a "gender rivalry". In the first condition, the stimuli placed in rivalry were two different facial expressions of the same individual (neutral vs. happy); in the second condition, the rivalrous stimuli were the faces of individuals of different gender (female vs. male) but with the same expression.

The main objective of this work was to approximate the temporal evolution of consciousness for faces characterized by specific attributes (emotional expression and gender).

We had no precise predictions regarding the speed of the formation and dissolution phases for the different categories of stimuli, although, as regards the "facial expression rivalry", several studies using the standard two/three-choice response approach have shown that happy expressions dominate in awareness and are associated with longer stabilization times (i.e., cumulative time) (Alpers and Gerdes, 2007; Bannerman et al., 2008; Yoon et al., 2009; Quettier et al., 2021). As briefly discussed in a previous paragraph, these response methods do not allow monitoring the entire temporal evolution of content in awareness. Nonetheless, higher dominance rates for faces with happy vs. neutral expressions may suggest a longer formation and/or dissolution phase duration for the former than the latter.

Materials and methods

Participants. Based on multiple findings in BR, happy stimuli rivaling versus neutral stimuli lead to large effect sizes (Alpers and Gerdes, 2007; Yoon et al., 2009; Hernández-Lorca et al., 2019; Quettier et al., 2021). For medium effect size (i.e $d = 0.5$), a sample size of 34 participants is required to reach an 80% power level. Power has been estimated using the pwr package (Champely et al., 2017). Forty healthy participants were recruited among students at the University of Padua (average age in years = 22.35, SD = 2.6, 20 males, 3 left-handed). All of them were volunteers and gave written informed consent in accordance with the Declaration of Helsinki. All experimental procedures were previously approved by the local research ethics committee (Comitato Etico della Ricerca Psicologica Area 17, University of Padua) and performed in accordance with its guidelines. Participants self-reported to have a normal or corrected-to-normal vision. Because we administered stimuli with emotional content, participants completed the Toronto Alexithymia Scale (TAS-20) and the Interpersonal Reactivity Index (IRI) questionnaires at the end of the experiment to obtain indices, however crude, that could reassure us about a normotypical affective competence. Alexithymia is defined as a difficulty in experiencing emotions, and Empathy is defined as the ability to share and understand others' emotions and affective states (Nemiah et al., 1976; Zaki and Ochsner, 2012). Scores on both questionnaires were not in the cut off range (TAS-20: $M = 46.05$, SD = 12.12 (Parker et al., 2003); IRI: $M = 100.2$, SD = 10.45 (Maddaluno et al., 2022)).

Material and apparatus. Visual stimuli were displayed using Opensesame v 3.0 on a Bestview S5 (luminosity: 50; contrast: 50) 60 Hz monitor mounted on a stereoscope mounted on a chin-rest. Visual stimuli covered 6.5 ± 0.5 degrees of visual angle and 10 cm in height and width. Original pictures (AM10NES, AM10HAS, AF01NES, AF01HAS) of facial expressions have been selected from the Karolinska Directed Emotional Faces set (KDEF).[2] A white 12-pixel fixation point and 40-pixel black and white squares frame were applied to the images to facilitate binocular fusion using GIMP (version 2.8.10).[3] Monocular images contrast and luminance features were controlled (Skerswetat et al., 2018) by matching histograms by using Fiji (ImageJ 1.52c)[4] and faces where misaligned in opposite direction with respect to the fixation point by 4 pixels.

Procedure. Participants were seated on a comfortable chair in a silent, temperature-controlled room. Before starting the experiment, the visual apparatus was set, and participants were trained. During the training, participants reported the rivalry experience by using both joystick and speech to ensure they undertood the task instructions. During the experiment, participants were asked to focus on a fixation point placed in the middle of the visual field. The experiment consisted of one session of four blocks, with two blocks for "emotion rivalry" (happy vs. neutral facial expression rivalry, **Figure 1** left) and two blocks for "gender rivalry" (male vs. female face gender rivalry, **Figure 1** right). The order of these emotional expressions or gender rivalry conditions was counterbalanced between subjects. In each block, combinations of rivalry stimuli (i.e., 4 pairs; see **Figure 2**) were randomly presented three times, for a total of 12 trials in each block (for a total of 48 trials in the experiment). See **Figure 2**, which shows all the possible combinations of rivalry stimuli shown in the experiment.

Each stimulus was presented for 15 s, preceded by a 2-s fixation point, followed by a black screen lasting 3 s, we avoided long BR exposure to minimize mixed perception (Klink et al., 2010). Participants were informed that, on each trial, they could see one of two faces and that the appearance might change from one to the other during the trial. Participants were asked to report their visual experience in real-time by means of a joystick over the left-right

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[2] https://www.kdef.se/

[3] https://www.gimp.org

[4] https://fiji.sc

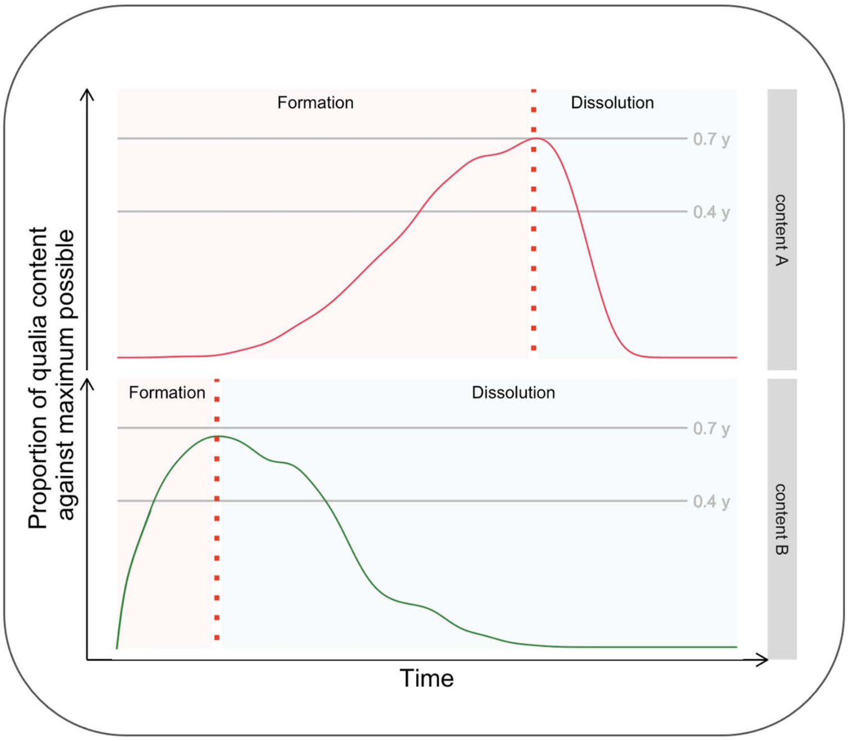

FIGURE 1
Hypothetical time course of the formation and dissolution of two different contents, A and B.

axis range. The trial started with a central position of the joystick, with the leftmost and rightmost positions corresponding to the stimulus "clearly" seen according to the coding instruction. Coding instructions were presented before the beginning of the block; the order of the "left" and "right" joystick positions corresponding to the coding of the "happy or male" and "neutral or female" faces was counterbalanced across blocks. Joystick responses were recorded at 100 Hz sampling frequency. At the end of each block, a short break was recommended to the participants to avoid any kind of visual tiredness. At the end of the last block, valence and arousal of each stimulus were measured respectively on a -3/ + 3 and 1/7 Likert scales using custom keyboard keys. Valence and arousal evaluation may be an important control to ensure that participants assigned aan emotional meaning to happy faces when compared to neutral faces (Hodges and Fox, 1965; Carter et al., 2007).

Data reduction

Preprocessing. Joystick positions were a continuous signal ranging from -1 (i.e. leftmost position) to 1 (i.e., rightmost position), or vice-versa according to the counterbalance. All trials were aligned, multiplying by -1 those of which the range was from 1 to −1.

Postprocessing. We computed three measures from the data time series: (1) the mean of predominance (MP) as a measure of perceptual dominance. MP is a measure of the dominance between the two stimuli in rivalry (happy vs. neutral expressions OR male vs. female). MPs were computed by averaging the joystick signals for each trial and each participant; (2) cumulative time (CT), as a measure of the BR stabilization (i.e., the sum of PSPs epochs). Cumulative time (CT) was computed as the sum of periods of stable perception (i.e. when the joystick position was 1/-1, that is, velocity was equal to zero) for each percept separately for each rivalry condition (happy and neutral for the emotion rivalry, and male and female for gender rivalry). (3) Speed_{IN} and $\text{Speed}_{\text{OUT}}$ as measures of the BR transitions. The speed of the joystick was estimated by averaging the absolute velocity separately for each episode of the formation ($\text{Speed}_{\text{IN},}$ **Figure 3A** green lines) and the dissolution ($\text{Speed}_{\text{OUT},}$ **Figure 3A** red lines) for each percept within each rivalry condition (happy and neutral for the emotion rivalry, and male and female for gender rivalry; see **Figure 2**).

Data analysis

Differences in stimuli rating for valence and arousal and differences in rivalry conditions (emotion rivalry and gender rivalry) for MPs were assessed in separate analyses of variance (ANOVAs) and *post hoc* comparisons (paired t.test) since we had no specific *a priori* predictions. All *post hoc* comparisons were corrected for multiple comparisons (Bonferroni), to ensure that the cumulative Type I error was below.05. We used R (R Core Team, 2012) and lme4 (Bates et al., 2014) to perform a linear mixed effects analysis of the relationship between rivalry conditions (emotion or gender) and consciousness phases (Speed_{IN} and $\text{Speed}_{\text{OUT}}$) for cumulative time (CT). For all models, as random effects, we had intercepts for subjects. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. Model selection is based on the

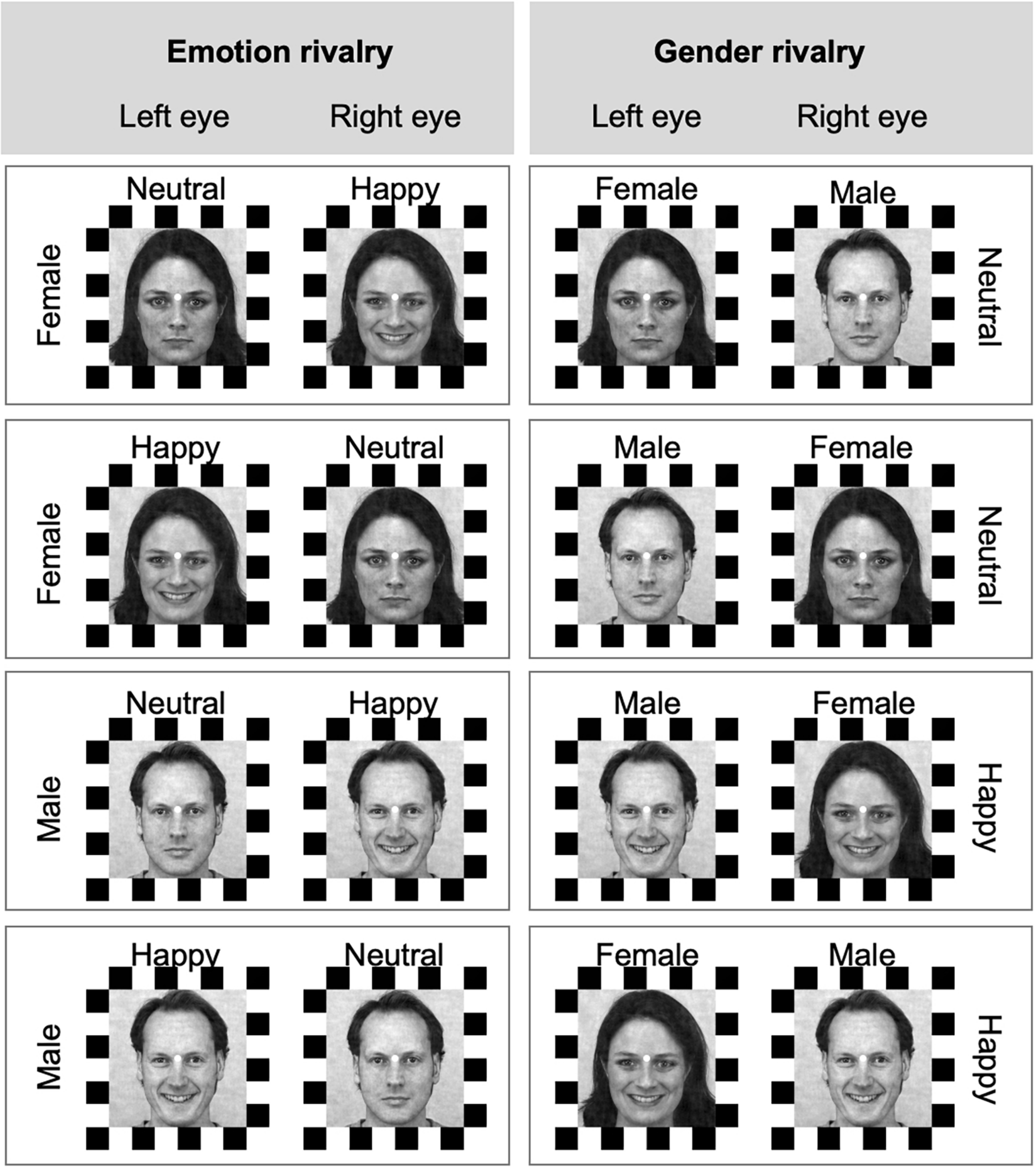

FIGURE 2
Rival conditions for expression and gender rivalries. Each row represents a pair of stimuli presented in rivalry. The four possible combinations of stimulus and eye of presentation are presented in each column. In the expression rivalry **(left column)**, the same identity is presented during a trial, and the expressions are in competition. In the gender rivalry **(right column)**, the same expression is presented during a trial, and the identities are in competition. Face stimuli from the Karolinska Directed Emotional Faces can be freely used for non-commercial research purposes. We included information about the KDEF images' ID in the main text.

likelihood of different models' comparison (see Open science framework repository).[5] For CT models, as fixed effects, we entered rivalry (i.e., emotion rivalry or gender rivalry) into the model. *P*-values were obtained by ANOVA of the full models for emotion blocks: *CT∼ rivalry + (1| subject)* and null model for gender *CT∼ 1 + (1| subject)*. For Speed_{IN} and $\text{Speed}_{\text{OUT}}$ models, as fixed effects, we entered rivalry and phases (with interaction term) into the model. P-values were obtained by ANOVA of the full models for emotion blocks: *speed∼ rivalry* phase + (1| subject)* and model 2 for gender block: *speed∼ phase + (1| subject)*.

Results

Ratings

Evaluation of valence and arousal were performed on gender and facial expression stimuli. Valence ratings differed according

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[5] https://osf.io/2pzmg/

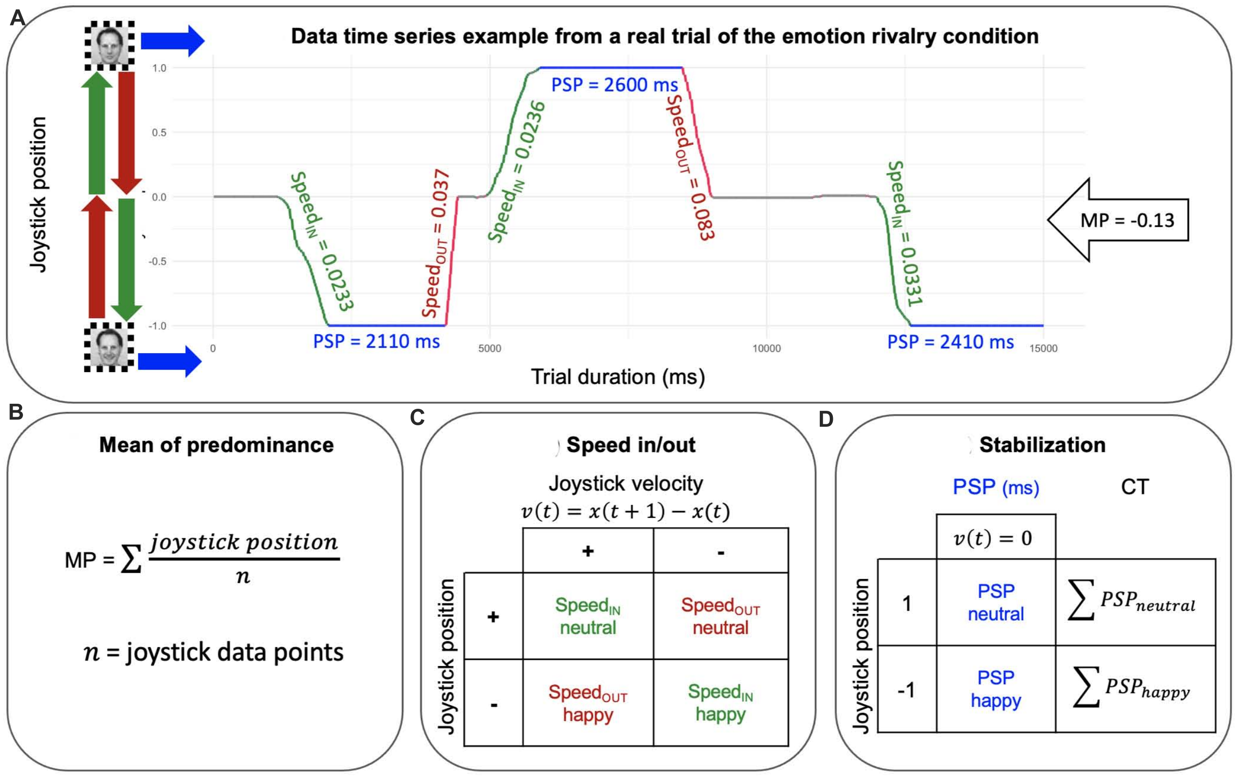

FIGURE 3
(A) Joystick time series from a real trial, which is one of 12 unique trials collected from one participant and serves as an example to illustrate how the measures are applied to the data. The green segments represent SpeedIN, which is the period of joystick movement as it transitions into a new perceptual state. The red segments represent SpeedOUT, which is the period of joystick movement as it exits from the dominant content. The blue segments represent periods of stable perception (PSP), during which a single perceptual state is dominant and the joystick is stationary. Joystick position and time are projected on the x and y axes, respectively. **(B)** Mean of predominance is the mean of all joystick position data points. **(C)** Speed movements were extracted from trials by averaging the absolute velocity separately for the formation (SpeedIN) and the dissolution (SpeedOUT) epochs and for each percept within each rivalry condition (happy and neutral for the emotion rivalry, and male and female for gender rivalry). **(D)** Cumulative time (CT) was computed as the sum of PSPs (i.e. when the joystick position was 1/-1, that is velocity was equal to zero) for each percept separately for each rivalry condition (happy and neutral for the emotion rivalry, and male and female for gender rivalry).

to *a priori* expectations, $F(1, 38) = 323.92$, $p < 0.001$, $d = 5.84$. Neutral facial expressions were rated under zero ($M = -2.11$; SD = 0.86; range = −3 to 3), which is more negative than happy ($M = 1.51$; SD = 1.29; range = −3 to 3). Arousal ratings also differed according to *a priori* expectations, $F(1, 39) = 80.45$, $p < 0.001$, $d = 2.91$. The ratings were lower for neutral expressions ($M = 2.49$; SD = 1.66; range = 1 to 7) than for happy expressions ($M = 4.64$, SD = 1.36; range = 1 to 7). See **Figure 4**. Some participants reported spontaneously that the female's happy facial expression did not appear genuine. No correlations were significant with MP or Speed measures.

Mean of predominance (MP)

A significant effect was observed for MP as a function of the rivalry condition ($F(1,38) = 100.03$ $p < 0.001$); interestingly, all participants in the emotion rivalry showed an advantage for the happy expression (vs. neutral expressions). MP for the emotion rivalry in favor of happy faces ($M = -0.38$; SD = 0.19 s) was significantly different from zero, $t(39) = -12.76$, $p < 0.001$. MP for the gender rivalry ($M = -0.028$; SD = 0.17 s) was not significantly different from zero, $t(39) = 0.967$, $p = 0.339$ (see **Figure 5**).

Cumulative time (CT)

In emotion rivalry, a significant effect was observed for CT as a function of the type of emotion (CT_{HAPPY} vs. $CT_{NEUTRAL}$) ($F(1{,}635.54) = 407.072$, $p < 0.001$, $d = 1.6$): CT_{HAPPY} were longer than $CT_{NEUTRAL}$ $t(35) = 11.362$ $p < 0.0001$, $d = 1.92$). As the better model for gender rivalry is the null model, no effects are considered (see **Figure 6**).

Speed$_{IN}$ and Speed$_{OUT}$. In emotion rivalry, a significant effect was observed for the transition ($Speed_{IN}$ vs $Speed_{OUT}$) ($F(1{,}7017.0) = 144.761$ $p < 0.001$, $d = 0.29$): $Speed_{OUT}$ were faster than $Speed_{IN}$ ($z = 12.03$, $p < 0.0001$, $d = 0.14$). A significant effect was observed for the rivalry (happy vs neutral) ($F(1{,}7021) = 63.288$ $p < 0.001$, $d = 0.19$): *neutral* were faster than *happy* ($z = -7.955$ $p < 0.0001$, $d = -0.09$). A significant interaction was found between percepts in rivalry and the transition ($F(1{,}7017.9) = 4.628$ $p = 0.031$, $\eta 2 = 0.0006$): $Speed_{IN}$ for happy faces were slower than $Speed_{IN}$ for neutral faces ($z = -4.267$ $p < 0.001$, $d = -0.05$) and $Speed_{OUT}$ for happy faces were slower than $Speed_{OUT}$ for

FIGURE 4
Evaluation of stimuli arousal and valence. Valence and arousal of each stimulus were measured respectively on a -3/+3 and 1/7 scales. Each participant is represented by one circle and one triangle; dark color intensity means that more than one participant gave the same evaluation.

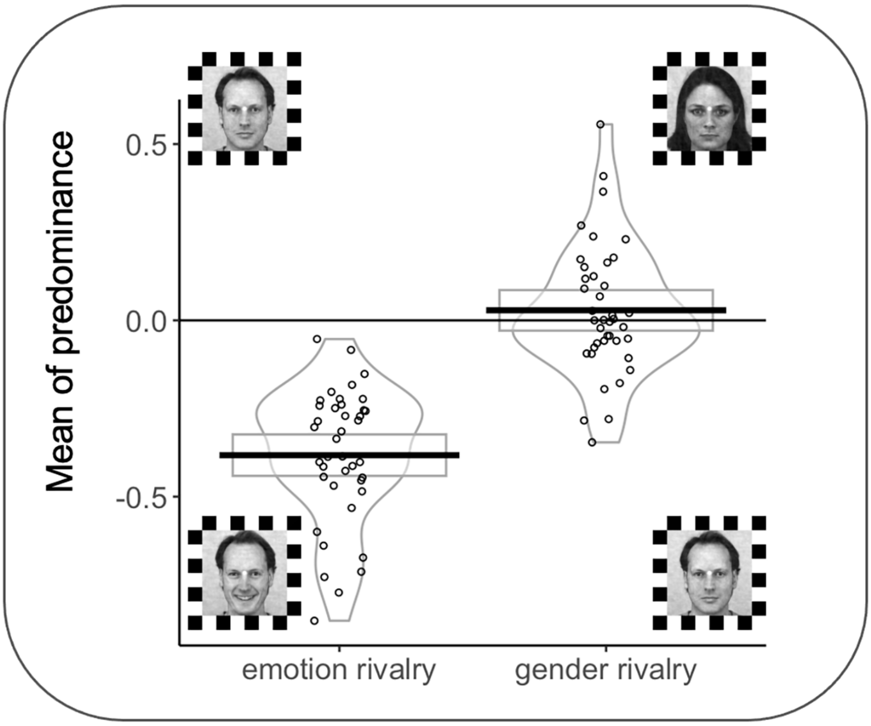

FIGURE 5
Rectangles, beans, and points represent confidence intervals, smoothed densities, and raw data, respectively. MP = 0 indicates no preference between the two percepts in rivalry during the trial. MPs were computed by averaging the joystick signals for each trial and each participant. Face stimuli from the Karolinska Directed Emotional Faces can be freely used for non-commercial research purposes. We included information about the KDEF images' ID in the main text.

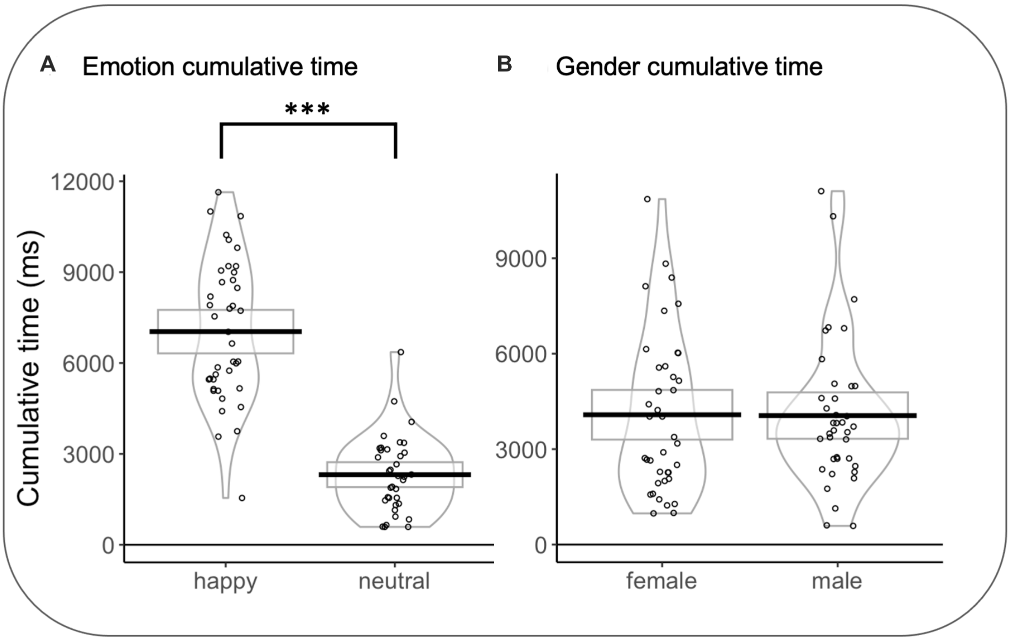

FIGURE 6

(A) Cumulative time in the emotion rivalry condition. **(B)** Cumulative time in gender rivalry condition. Rectangles, beans, and points represent confidence intervals, smoothed densities, and participants' mean data, respectively. $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

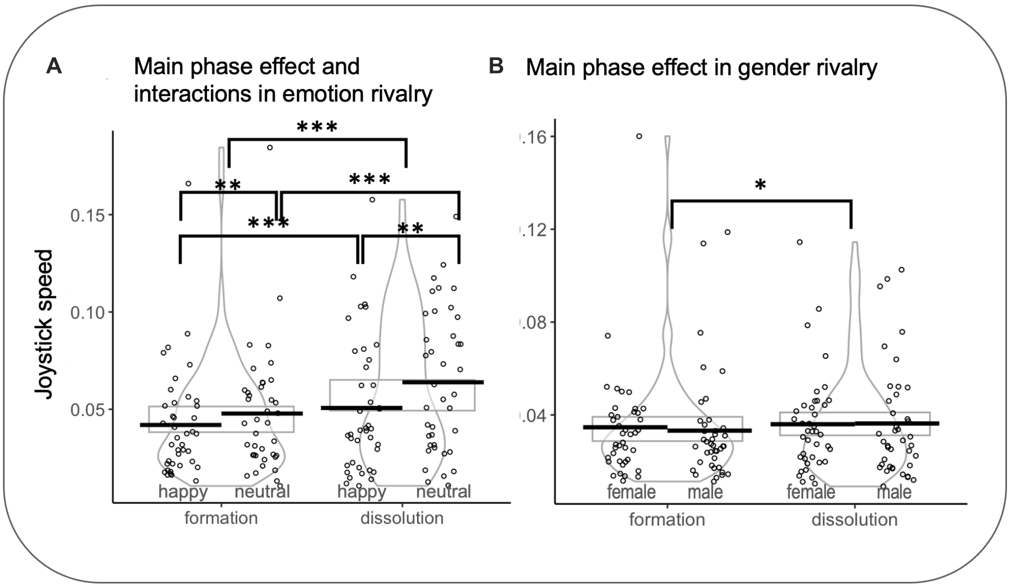

FIGURE 7

(A) Main effect of phase and interactions for joystick speed in emotion rivalry. **(B)** Main effect of phase for joystick speed in gender rivalry. Rectangles, beans, and points represent confidence intervals, smoothed densities within formation and dissolution, and participants' mean data, respectively. $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

neutral faces ($z = -6.961$ $p < 0.001$, $d = -0.08$). Speed_{IN} for happy faces were slower than $\text{Speed}_{\text{OUT}}$ for happy faces ($z = 8.06$ $p < 0.001$, $d = 0.1$) and Speed_{IN} for neutral faces were faster than $\text{Speed}_{\text{OUT}}$ for neutral faces ($z = 8.969$ $p < 0.001$, $d = 0.11$).

In gender rivalry, a significant effect was observed for the transition (Speed_{IN} vs $\text{Speed}_{\text{OUT}}$) ($F(1,7094.3) = 22.175$ $p < 0.001$, $d = 0.11$): $\text{Speed}_{\text{OUT}}$ were faster than Speed_{IN} ($z = 1.28$ $p = 0.039$, $d = 0.06$) (see **Figure 7**). It is important to note that, in some cases, such as in rivalry using faces, the two competing images may merge into a stable perception, eliminating binocular rivalry transitions (Klink et al., 2017). In these cases, it would be impossible to compute speed metrics.

Questionnaires

In exploratory analyses, we tested if MP and Speed were correlated (Pearson, two-sided correlations) with the TAS-20 and the IRI. No correlations were significant with the IRI scores or TAS-20.

Discussion

The dynamics of consciousness (from formation to dissolution) is rarely examined in consciousness research, and even when it is considered, the studies have mostly focused on the phase of formation of the conscious content. In contrast and complementary to consciousness genesis, a few researchers have drawn attention to the anti-genesis of consciousness, that is the phase in which the content fades out from consciousness (Pun et al., 2012; Aru and Bachmann, 2017). Aru and Bachmann (2017) have, for example, proposed the possibility that asymmetrical inertia could characterize the two phases of formation and dissolution of the conscious content.

One limitation in investigating the entire dynamics of consciousness is that not all paradigms allow such investigation.

The present work's main objective was to gain information that could allow approximating the temporal evolution of consciousness hypothesized by Aru and Bachmann, in the specific context of face perception. Here, we used a binocular rivalry task to examine the time course of consciousness. In the first condition, the stimuli placed in rivalry were two different facial expressions of the same individual (neutral vs. happy); in the second condition, the rivalrous stimuli were the faces of individuals of different gender (female vs. male) but with the same expression.

We asked participants to map their conscious experience using a joystick. The movements of the joystick were then processed in such a way as to obtain some *ad hoc* variables that would provide a proxy of the formation and dissolution phases of the conscious content. In particular, the movements were analyzed in terms of the speed of the transitions in binocular rivalry in such a way as to have distinct measures for the formation phase (Speed_{IN}, i.e. the joystick velocity for the formation of the dominant percept) and for the dissolution phase ($\text{Speed}_{\text{OUT}}$, i.e. the joystick velocity for the dissolution of the dominant percept). Furthermore, we computed some traditional metrics commonly examined in binocular rivalry studies, namely mean of predominance (i.e. the average of the joystick signals) and cumulative time (i.e. the sum of the periods of stable perception). Importantly, both mean of predominance and cumulative time measures replicated the effect found with regard to happy expression in BR in which happy percept dominates over neutral percept (Alpers and Gerdes, 2007; Yoon et al., 2009).

The results supported Aru and Bachmann's (2017) hypothesis regarding the possible different inertia between the formation and the dissolution of conscious content. Indeed, a general phase effect was found in both rivalrous conditions (i.e., emotion and gender). The formation phase was slower than the dissolution phase, indicating an asymmetric inertia of formation and dissolution of the conscious content with a slower inertia for the formation phase than the dissolution phase. Furthermore, although in the case of the gender rivalry condition, only a general effect of the phase was observed, with contents' formation being slower than dissolution, the results of the emotion rivalry condition highlighted additional dynamics of the temporal evolution of consciousness. One potential explanation[6] for the finding is that the decision to judge a stimulus as no longer ambiguous may be easier, as it only requires the detection of a single dissimilar feature that violates the exclusive state. In contrast, for the formation of an exclusive percept, many features and their configural processing need to align across time, which may require additional attentional resources and the engagement of different perceptual and cognitive processes.

But, in this emotion condition, in addition to the general effect of the phase reported above, differences in the time course were also observed as a function of the specific facial expression, such that faces with happy expressions were associated with lower velocity indexes than neutral faces, suggesting that both their formation and dissolution as contents of consciousness were slower than for faces with a neutral expression.

To note, the attribution of the meaning to emotional facial expressions requires the combination of multiple sources of processing by visual, limbic, and sensorimotor areas (Carr et al., 2003; Fox et al., 2009; Trautmann et al., 2009; Haxby and Giobbini, 2011; Furl et al., 2013; Johnston et al., 2013; Harris et al., 2014). From this point of view, the number of involved channels/brain regions could lead to differences in the inertia of the formation and dissolution phases.

In light of our general research objective, we propose to annex a third phase between the formation and the dissolution phases in addition to the original phases proposed by Aru and Bachmann. In fact, following the content's formation and before it fades from consciousness, the content is stabilized in consciousness for a while (i.e., stabilization phase).

In January 2023, Skerswetat and Bex published an article describing a new method called InFoRM (Indicate-Follow-Replay-Me) to study perceptual multistability, specifically in the context of binocular rivalry for Gabor patches with different orientations. As highlighted in the Introduction, the current methods used to assess multistability have limitations. InFoRM is a more advanced method than the one proposed by us for researchers interested in capturing all potential perceptual states and it offers a continuous high-temporal resolution. In this sense, we invite readers interested in implementing a method with these characteristics to refer to the work of Skerswetat and Bex (2023). InFoRM has the specific goal of mapping in detail not only the experience of "exclusive" percepts but also the different possible experiences of mixed percepts (piecemeal/superimposition; see **Figure 1** on p. 4 of Skerswetat and Bex, 2023), while we were interested in mapping the subjective experience of accessing and exiting from "exclusive" face percepts with particular characteristics (connoted by a specific emotional expression or gender). Of note, faces in binocular rivalry are much less prone to piecemeal rivalry (where piecemeal rivalry is measurable in terms of low coherence index; seem e.g., (Alais and Parker, 2006) than other, low-level, stimuli (e.g., Gabor patches), likely due to the different size of receptive fields of the high-level vs. early visual areas

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[6] We thank the reviewer for this interesting possible explanation.

(Blake et al., 1992). Thus stimuli such as Gabor (used in the experiment by Skerswetat and Bex, 2023) tend to be associated with a lot of mixed/piecemeal rivalry; on the other hand, high-level stimuli (such as faces) are characterized by a high coherence index (i.e., stronger alternations from one face to another, and very little piecemeal rivalry and superimposition). For example, in one of their studies, Alais and Parker (2006) reported a coherence index for faces (face 1 vs. face 2 in rivalry) equal to 80%, therefore very high. Moreover, in our study, we implemented further precautions to favor a high coherence index: (a) the participants were accurately instructed to map the experience of precise contents—rather than single features possibly diagnostic of emotion or gender—using the leftmost/rightmost joystick positions; (b) the face stimuli, both in the condition of emotion rivalry and gender rivalry, were slightly misaligned with respect to the fixation point to favor the rivalry between faces rather than between individual features (i.e., mixed percepts); (c) the face stimuli were relatively small in size (6.5° of visual angle).

The present study has some limitations which should be mentioned.

Inverted faces are often used as a control condition in cognitive neuroscience and psychology experiments involving face perception. The main reason for using inverted faces as a control condition is to test whether the observed effects are specific to the processing of upright faces or whether they are simply a result of low-level visual features (such as luminance and contrast). We have not included a control condition with inverted faces, so one possibility is that the observed pattern of results may depend at least partially on low-level features or both low and high- level features (Yang et al., 2007). Although we believe this is unlikely since we have carefully calibrated the contrast and luminance of rivalrous faces (see Method section) and counterbalanced stimuli colors, positions and coding, future research should consider adding such control condition with inverted faces.

Secondly, another potential limitation concerns the absence of a replay condition. In the replay block, a physical replay of the binocular rivalry is encoded by the participants to compare their responses between the two visual experiences (replay vs. binocular rivalry). This control allows controlling for participants' accuracy and compliance with coding instructions. This replay method has been implemented by Skerswetat and Bex (2023) and we recommend its use. In the present study, due to time constraints, we chose to counterbalance the joystick coding instructions to control possible difference in joystick movements due to supination and pronosupination movements.

Finally, we want to propose some feasible directions. Firstly, future studies could include neural measures that can reassure about the validity of the method we proposed here by examining the relationship between the joystick velocity metrics and the trend of neural indices associated with (faces') consciousness (Doesburg et al., 2005, 2009; Kim and Blake, 2005; Wilcke et al., 2009; Dehaene and Changeux, 2011; Blake et al., 2014; Frässle et al., 2014; Gelbard-Sagiv et al., 2018; Cha and Blake, 2019; Hernández-Lorca et al., 2019). Secondly, one possible direction for future research is to examine the possible effects of small eye movements on rivalry, which is still debated in this field since the days of the controversy between Hering and von Helmholtz. The description of these eye movements may advance our understanding of the mechanisms underlying unstable perception and provide further insight into the neural processes involved.

Thirdly, future investigations could explore the issue of whether the three different phases of the consciousness temporal evolution are related to each other, such that the inertia or duration of one phase could predict the inertia or duration of another phase.

To conclude, the similarity between the temporal evolution of consciousness hypothesized by Aru and Bachmann and the time course detected through the joystick in this study is remarkable, which is why we believe - with cautious optimism - that this approach can allow researchers to map with a good approximation the dynamics of the subjective experience of faces' contents in consciousness.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary material**.

Ethics statement

The studies involving human participants were reviewed and approved by Ethical Board of Psychology – University of Padova. The patients/participants provided their written informed consent to participate in this study.

Author contributions

TQ developed the study concept, programmed the experiment and prepared the stimuli, and performed the data analysis. ND gathered the data. PS, TQ, and NT interpreted the data. TQ and PS drafted the manuscript. NT provided critical revision. All authors contributed to the study design, approved the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2023.1145653/full#supplementary-material

References

Alais, D., and Blake, R. (2005). *Binocular Rivalry*. Cambridge, MA: MIT Press.

Alais, D., and Parker, A. (2006). Independent binocular rivalry processes for motion and form. *Neuron* 52, 911–920. doi: 10.1016/j.neuron.2006.10.027

Alpers, G., and Gerdes, A. (2007). Here is looking at you: Emotional faces predominate in binocular rivalry. *Emotion* 7, 495–506. doi: 10.1037/1528-3542.7.3.495

Aru, J., and Bachmann, T. (2017). In and out of consciousness: How does conscious processing (D)evolve over time? *Front. Psychol.* 8:128. doi: 10.3389/fpsyg.2017.00128

Bachmann, T. (2000). *Microgenetic Approach to the Conscious Mind*. Amsterdam: John Benjamins Publishing Company. doi: 10.1075/aicr.25

Bannerman, R., Milders, M., De Gelder, B., and Sahraie, A. (2008). Influence of emotional facial expressions on binocular rivalry. *Ophthalmic Physiol. Opt.* 28, 317–326. doi: 10.1111/j.1475-1313.2008.00568.x

Bates, D., Mächler, M., Bolker, B., and Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv*. Available online at: http://arxiv.org/abs/1406.5823 (accessed June 23, 2014).

Blake, R., Brascamp, J., and Heeger, D. (2014). Can binocular rivalry reveal neural correlates of consciousness? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 369:20130211. doi: 10.1098/rstb.2013.0211

Blake, R., O'Shea, R., and Mueller, T. (1992). Spatial zones of binocular rivalry in central and peripheral vision. *Vis. Neurosci.* 8, 469–478. doi: 10.1017/s0952523800004971

Brascamp, J., Klink, P., and Levelt, W. (2015). The 'laws' of binocular rivalry: 50 years of Levelt's propositions. *Vis. Res.* 109(Pt A), 20–37. doi: 10.1016/j.visres.2015.02.019

Carr, L., Iacoboni, M., Dubeau, M., Mazziotta, J., and Lenzi, G. (2003). Neural mechanisms of empathy in humans: A relay from neural systems for imitation to limbic areas. *Proc. Natl. Acad. Sci. U. S. A.* 100, 5497–5502. doi: 10.1073/pnas.0935845100

Carter, O., Hasler, F., Pettigrew, J., Wallis, G., Liu, G., and Vollenweider, F. (2007). Psilocybin links binocular rivalry switch rate to attention and subjective arousal levels in humans. *Psychopharmacology* 195, 415–424. doi: 10.1007/s00213-007-0930-9

Cha, O., and Blake, R. (2019). Evidence for neural rhythms embedded within binocular rivalry. *Proc. Natl. Acad. Sci. U. S. A.* 116, 14811–14812. doi: 10.1073/pnas.1905174116

Champely, S., Ekstrom, C., Dalgaard, P., Gill, J., Weibelzahl, S., Anandkumar, A., et al. (2017). *Pwr: Basic Functions for Power Analysis*. Available online at: https://nyuscholars.nyu.edu/en/publications/pwr-basic-functions-for-power-analysis (accessed March 17, 2020).

Davidson, M., Alais, D., van Boxtel, J., and Tsuchiya, N. (2018). Attention periodically samples competing stimuli during binocular rivalry. *Elife* 7:e40868. doi: 10.7554/eLife.40868

Dehaene, S., and Changeux, J. (2011). Experimental and theoretical approaches to conscious processing. *Neuron* 70, 200–227. doi: 10.1016/j.neuron.2011.03.018

Doesburg, S., Green, J., McDonald, J., and Ward, L. (2009). Rhythms of consciousness: Binocular rivalry reveals large-scale oscillatory network dynamics mediating visual perception. *PLoS One* 4:e6142. doi: 10.1371/journal.pone.0006142

Doesburg, S., Kitajo, K., and Ward, L. (2005). Increased gamma-band synchrony precedes switching of conscious perceptual objects in binocular rivalry. *Neuroreport* 16, 1139–1142. doi: 10.1097/00001756-200508010-00001

Fahle, M., Stemmler, T., and Spang, K. (2011). How much of the "Unconscious" is just pre - threshold? *Front. Hum. Neurosci.* 5:120. doi: 10.3389/fnhum.2011.00120

Fox, C., Iaria, G., and Barton, J. (2009). Defining the face processing network: Optimization of the functional localizer in fMRI. *Hum. Brain Mapp.* 30, 1637–1651. doi: 10.1002/hbm.20630

Frässle, S., Sommer, J., Jansen, A., Naber, M., and Einhäuser, W. (2014). Binocular rivalry: Frontal activity relates to introspection and action but not to perception. *J. Neurosci.* 34, 1738–1747. doi: 10.1523/JNEUROSCI.4403-13.2014

Furl, N., Henson, R., Friston, K., and Calder, A. (2013). Top-down control of visual responses to fear by the amygdala. *J. Neurosci.* 33, 17435–17443. doi: 10.1523/JNEUROSCI.2992-13.2013

Gelbard-Sagiv, H., Mudrik, L., Hill, M., Koch, C., and Fried, I. (2018). Human single neuron activity precedes emergence of conscious perception. *Nat. Commun.* 9:2057. doi: 10.1038/s41467-018-03749-0

Harris, R., Young, A., and Andrews, T. (2014). Dynamic stimuli demonstrate a categorical representation of facial expression in the amygdala. *Neuropsychologia* 56, 47–52. doi: 10.1016/j.neuropsychologia.2014.01.005

Haxby, J., and Giobbini, M. I. (2011). "Distributed neural systems for face perception," in *Oxford Handbook of Face Perception*, eds G. Rhodes, A. Calder, M. Johnson, and J. Haxby (Oxford: Oxford University Press), 93–110.

Hernández-Lorca, M., Sandberg, K., Kessel, D., Fernández-Folgueiras, U., Overgaard, M., and Carretié, L. (2019). Binocular rivalry and emotion: Implications for neural correlates of consciousness and emotional biases in conscious perception. *Cortex* 120, 539–555. doi: 10.1016/j.cortex.2019.08.003

Hodges, W. F., and Fox, R. (1965). Effect of arousal and intelligence on binocular rivalry rate. *Percept. Motor Skills* 20, 71–75.

Johnston, P., Mayes, A., Hughes, M., and Young, A. (2013). Brain networks subserving the evaluation of static and dynamic facial expressions. *Cortex* 49, 2462–2472. doi: 10.1016/j.cortex.2013.01.002

Kim, C., and Blake, R. (2005). Psychophysical magic: Rendering the visible 'invisible'. *Trends Cogn. Sci.* 9, 381–388. doi: 10.1016/j.tics.2005.06.012

Klink, P., Boucherie, D., Denys, D., Roelfsema, P., and Self, M. (2017). Interocularly merged face percepts eliminate binocular rivalry. *Sci. Rep.* 7:7585. doi: 10.1038/s41598-017-08023-9

Klink, P., Brascamp, J., Blake, R., and van Wezel, R. (2010). Experience-driven plasticity in binocular vision. *Curr. Biol.* 20, 1464–1469. doi: 10.1016/j.cub.2010.06.057

Knapen, T., Brascamp, J., Pearson, J., van Ee, R., and Blake, R. (2011). The role of frontal and parietal brain areas in bistable perception. *J. Neurosci.* 31, 10293–10301. doi: 10.1523/JNEUROSCI.1727-11.2011

Lee, S., Blake, R., and Heeger, D. (2005). Traveling waves of activity in primary visual cortex during binocular rivalry. *Nat. Neurosci.* 8, 22–23. doi: 10.1038/nn1365

Maddaluno, O., Aiello, E., Roncoroni, C., Prunas, A., and Bolognini, N. (2022). The reading the mind in the eyes test, iowa gambling task and interpersonal reactivity index: Normative data in an italian population sample. *Arch. Clin. Neuropsychol.* 37, 929–938. doi: 10.1093/arclin/acab100

Naber, M., Frässle, S., and Einhäuser, W. (2011). Perceptual rivalry: Reflexes reveal the gradual nature of visual awareness. *PLoS One* 6:e20910. doi: 10.1371/journal.pone.0020910

Nemiah, J. C., Freyberger, H., and Sifneos, P. E. (1976). "Alexithymia: A view of the psychosomatic process," in *Modern Trends in Psychosomatic Medicine*, Vol. 3, ed. O. W. Hill (London: Butterworths), 430–439.

Parker, J., Taylor, G., and Bagby, R. (2003). The 20-Item Toronto Alexithymia Scale. III. Reliability and factorial validity in a community population. *J. Psychosom. Res.* 55, 269–275. doi: 10.1016/s0022-3999(02)00578-0

Pun, C., Emrich, S., Wilson, K., Stergiopoulos, E., and Ferber, S. (2012). In and out of consciousness: Sustained electrophysiological activity reflects individual differences in perceptual awareness. *Psychon. Bull. Rev.* 19, 429–435. doi: 10.3758/s13423-012-0220-3

Quettier, T., Gambarota, F., Tsuchiya, N., and Sessa, P. (2021). Blocking facial mimicry during binocular rivalry modulates visual awareness of faces with a neutral expression. *Sci. Rep.* 11:9972. doi: 10.1038/s41598-021-89355-5

R Core Team (2012). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/

Skerswetat, J., and Bex, P. (2023). InFoRM (Indicate-Follow-Replay-Me): A novel method to measure perceptual multistability dynamics using continuous data tracking and validated estimates of visual introspection. *Conscious Cogn.* 107:103437. doi: 10.1016/j.concog.2022.103437

Skerswetat, J., Formankiewicz, M., and Waugh, S. (2018). More superimposition for contrast-modulated than luminance-modulated stimuli during binocular rivalry. *Vis. Res.* 142, 40–51. doi: 10.1016/j.visres.2017.10.002

Trautmann, S., Fehr, T., and Herrmann, M. (2009). Emotions in motion: Dynamic compared to static facial expressions of disgust and happiness reveal more widespread emotion-specific activations. *Brain Res.* 1284, 100–115. doi: 10.1016/j.brainres.2009.05.075

Wheatstone, C. (1843). Contributions to the physiology of vision.—part the first. On some remarkable and hitherto unobserved phenomena of binocular vision. *Abstracts Papers Print. Philos. Transact. R. Soc. Lond.* 4, 76–77.

Wilcke, J., O'Shea, R., and Watts, R. (2009). Frontoparietal activity and its structural connectivity in binocular rivalry. *Brain Res.* 1305, 96–107. doi: 10.1016/j.brainres.2009.09.080

Yang, E., Zald, D., and Blake, R. (2007). Fearful expressions gain preferential access to awareness during continuous flash suppression. *Emotion* 7, 882–886. doi: 10.1037/1528-3542.7.4.882

Yang, Y., Rose, D., and Blake, R. (1992). On the variety of percepts associated with dichoptic viewing of dissimilar monocular stimuli. *Perception* 21, 47–62. doi: 10.1068/p210047

Yoon, K., Hong, S., Joormann, J., and Kang, P. (2009). Perception of facial expressions of emotion during binocular rivalry. *Emotion* 9, 172–182. doi: 10.1037/a0014714

Zaki, J., and Ochsner, K. (2012). The neuroscience of empathy: Progress, pitfalls and promise. *Nat. Neurosci.* 15, 675–680. doi: 10.1038/nn.3085