frontiers | Frontiers in Virtual Reality

TYPE Original Research
PUBLISHED 24 February 2023
DOI 10.3389/frvir.2023.1108060

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Virtual Reality and Human Behaviour, a section of the journal Frontiers in Virtual Reality

RECEIVED 25 November 2022
ACCEPTED 14 February 2023
PUBLISHED 24 February 2023

CITATION
Cunha F, Campos S, Simões-Silva V, Brugada-Ramentol V, Sá-Moura B, Jalali H, Bozorgzadeh A and Trigueiro MJ (2023), The effect of a virtual reality based intervention on processing speed and working memory in individuals with ADHD—A pilot-study.
Front. Virtual Real. 4:1108060.
doi: 10.3389/frvir.2023.1108060

The effect of a virtual reality based intervention on processing speed and working memory in individuals with ADHD—A pilot-study

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Introduction: This study aimed to evaluate the effectiveness of a virtual reality based intervention in processing speed and working memory in students with ADHD symptomatology.

Methods: A randomized experimental study was conducted, with a sample consisting of 25 adult participants recruited from the Escola Superior de Saúde do Politécnico do Porto. The participants were allocated into two groups: a passive control group and an intervention group that completed 10 sessions using virtual reality-based games from the Enhance VR app. The intervention included 6 games: Whack-a-mole, Shuffled, Assembly, React, Memory Wall, and Maestro. The participants underwent pre- and post-intervention evaluations using the Southwestern Assessment of Processing Speed (SWAPS) and the *Sequence of Letters and Numbers and Spatial Location of the Wechsler Adult Intelligence Scale - 3rd Edition - WAIS-III*. Descriptive statistics were used to characterize the sample and a mixed ANOVA was used to test the effectiveness of the intervention.

Results: There was an improvement in the results of processing speed in the group exposed to the intervention ($p < 0.001$) and the value of the interaction between intervention and time was also significant ($p = 0.004$). There were no statistically significant differences between the participants' working memory in the different variables under study, except for the values of the *Spatial location* test in the experimental group that improved relative to the initial assessment ($p = 0.034$).

Discussion: A virtual reality cognitive training intervention resulted in improvements in the processing speed measures, which were not found in the control group. Although we cannot make the same conclusions regarding working memory, these results suggest that the VR intervention resulted in progress in the experimental group, possibly influenced by the intervention, which should be verified in future studies with longer interventions.

KEYWORDS

attention deficit and hyperactivity disorder, executive functions, processing speed, working memory, virtual reality, cognitive training

1 Introduction

Attention deficit hyperactivity disorder (ADHD) is a neurodevelopmental disorder that manifests in children and adults and is characterized by high levels of inattention, hyperactivity, and impulsivity that often lead to multiple behavioral problems (Association American Psychiatric, 2014; Barkley, 2016). ADHD has a worldwide incidence in approximately 5% in children and 2.5% in adults (Polanczyk et al., 2014). ADHD is increasingly recognized in adulthood as having a negative impact on occupation, activities of daily living, social relationships, psychological and physical wellbeing, and quality of life (Rösler et al., 2010; Birx et al., 2016; Palacios-Cruz et al., 2018; Roselló et al., 2020).

ADHD is a major public health problem associated with a broad range of negative outcomes over the patients' lifetime (Quintero et al., 2018). ADHD symptoms are significantly associated with worse quality of life, lower self-esteem, higher emotional dysregulation, higher manifestation of impulsivity, higher manifestation of psychiatric disorders, higher internet dependence, and worse response inhibition (Chamberlain et al., 2017). Regarding intervention, recent data seem to point to the use of monotherapy with non-pharmacological treatment for the mild disorder and combined treatment for severe disorder (Caye et al., 2019).

The predominant features of ADHD in adults differ from those in children, with fewer symptoms of hyperactivity and impulsivity and more inattention (Hervey et al., 2004; Biederman et al., 2010; Salomone et al., 2020; Roshannia et al., 2021; Plowden et al., 2022). In adults, hyperactivity can be expressed by restlessness, mood swings, involvement in too many activities, racing thoughts, and an inability to relax (Sabhlok et al., 2022). Impulsivity is manifested by interrupted conversations and impulsive behavior, and inattention by disorganization, forgetfulness, and inability to maintain attention while performing activities (Salomone et al., 2020; Plowden et al., 2022; Sabhlok et al., 2022).

For a considerable period, attention problems were considered to be the main neurological deficits underlying ADHD. However, current evidence states that executive function (EF) deficits are the central components of ADHD (Diamond, 2013; Butzbach et al., 2019; Sabhlok et al., 2022). EFs include processes associated with the prefrontal and thalamic-reticular areas of the brain, which are responsible for initiating, directing, and regulating thoughts, emotions, and behaviors to achieve a desired goal (Pennington, 1988; Al-Yagon, 2018; Roselló et al., 2020; Roshannia et al., 2021). Various deficits in EF are described in children and adults, affecting working memory, cognitive flexibility, processing speed, decision-making, problem-solving, verbal fluency, and planning ability (Al-Yagon, 2018; Salomone et al., 2020; Alaghband-Rad et al., 2021; Coelho et al., 2021; Roshannia et al., 2021).

According to the Diamond Model (Diamond, 2013), EFs are composed of three major skills: (1) inhibitory control, which allows the individual to resist automatic impulses or habits; (2) cognitive flexibility, which helps the individual to be creative and flexible to adapt when changes arise and (3) working memory (WM), the function of which is to temporarily store and manipulate information. Some models also include processing speed (PS) as a component of EF, while other models characterize it as a basic skill that affects the acquisition of executive skills (Butzbach et al., 2019; Cook et al., 2019). PS is understood as the speed with which an individual perceives information, processes information and/or initiates a response (Adalio et al., 2018; Sabhlok et al., 2022).

Changes in PS are associated with ADHD (Leib et al., 2021) and, more specifically, inattention (Adalio et al., 2018; Kibby et al., 2019). PS is usually assessed by measuring an individual's reaction time (RT) to simple stimuli. Adults with ADHD show slower RT than adults without a diagnosis. Abnormal neuronal activation in the perceptual and response selection phases has been proposed as a reason for this finding (Cross-Villasana et al., 2015; Kibby et al., 2019; Mohamed et al., 2021). These changes lead to difficulties in focus and have a negative impact on everyday tasks that require reasoning, learning new information and skills, understanding new information, and can lead to mental fatigue. Deficits in PS also impact less stimulating tasks, leading to procrastination and, consequently, disregard and postponement of their completion (Kibby et al., 2019; Weibel et al., 2020). As a result of these deficits, a range of occupational, academic, and social difficulties arise (Salomone et al., 2020; Roshannia et al., 2021; Sabhlok et al., 2022). These deficits in PS explain, at least in part, why ADHD in adults has a considerable impact on schooling and occupational functioning, and on family and peer relationships. Studies show that, compared to the general population, adults with ADHD have lower educational attainment, lower rates of employability, and more unstable family relationships (Stern et al., 2016; Weibel et al., 2020).

WM is a short-term memory that allows the acquisition, storage, and manipulation of new information on a temporary basis (Baddeley, 2012). It has been the subject of investigations in the adult population, with or without an associated clinical condition (Martinussen et al., 2005) and has been identified as one of the most impaired EFs in individuals with ADHD (Diamond, 2013; Areces et al., 2018; Mukherjee et al., 2021), which may negatively influence several areas of life, such as academic achievement, emotional processing and social relationships (Alloway, 2006; Mukherjee et al., 2021). Several authors have argued that WM deficits are more frequent in the predominantly inattentive and the combined subtypes, since there seems to be a relationship between attention deficits and WM functioning (Baddeley and Hitch, 1974; Milla-Cano and Gatica-Ferrero, 2020; Zhao et al., 2020).

The deficits at the level of EF in people with ADHD have been the subject of intervention, and the most adhered treatment appears to be multimodal and based on non-pharmacological interventions that are sometimes complemented with pharmacological treatment (de Crescenzo et al., 2017; Nimmo-Smith et al., 2020; Sandhu et al., 2021; Kastner et al., 2022). The first intervention objective is to reduce functional impairment through psychoeducation, cognitive-behavioral therapy, and adaptive measures, mainly at school and in the workplace, in order to directly improve symptomatology (de Crescenzo et al., 2017; Lopez et al., 2018). The literature states that cognitive training, as the main approach targeting EF, directly and positively influences multiple neuropsychological domains of ADHD (Stern et al., 2016; Savcı et al., 2019; Chen et al., 2022). According to current data on neuroplasticity, cognitive training strengthens key brain networks associated with ADHD and cognitive processes through controlled exposure to information processing tasks (Savcı et al., 2019). This training involves the repeated exercise of one or multiple specific cognitive processes, for a long period of time, where performance gains are expected in the trained task and in behavioral measures. Therefore, it is claimed that it can reduce symptomatology and improve functioning (Stern et al., 2016; Chen et al., 2022).

Among the tools currently available to work with EF in ADHD, the use of intelligent and immersive technologies, such as Virtual Reality (VR) (Rizzo et al., 2004), stands out for its promising results (Shema-Shiratzky et al., 2019; Romero-Ayuso et al., 2021; Goharinejad et al., 2022a). Thus, VR provides a therapeutic alternative, combining motor and cognitive skills as a form of dual-task training while using the properties of gaming to increase adherence and motivation (Shema-Shiratzky et al., 2019; Georgiev et al., 2021).

Few studies and evidence address the effect of cognitive interventions in adults with ADHD. For instance, a screen-based cognitive training intervention using the Cogmed working memory exercises aimed to examine the sustained effects and generalization in an adult population with ADHD. The design used different intensities of training for both the experimental and placebo group. Both groups showed a significant improvement that was maintained after 6 months but did not generalize to executive function improvements (Dentz et al., 2020). Other studies have shown positive effects of working memory training using Cogmed in an adult population with ADHD which resulted in improvements in visuospatial working memory (Gropper et al., 2014; Mawjee et al., 2015) as well as in verbal working memory and on a generalization of effects to other cognitive functions (Mawjee et al., 2015). While these studies show promising results on cognitive training interventions for adults with ADHD, to the best of our knowledge, no studies focused on the PS intervention.

The available literature shows that cognitive training is an effective manner to improve specific cognitive functions. However, screen-based solutions often fail to provide a generalization to global cognitive functioning or daily-life scenarios (Owen et al., 2010). Virtual Reality, on the other hand, due to the embodied experience of the immersive three-dimensional scenarios and naturalistic interaction of the environment (Sanchez-Vives and Slater, 2005), enables the presentation of different tasks for cognitive training, rehabilitation, and assessment (Rizzo et al., 2004; Georgiev et al., 2021) and specifically for the assessment of ADHD (Goharinejad et al., 2022a). Moreover, VR allows for the presentation of realistic scenarios, with control over the distractors and variables (Bashiri et al., 2017). VR has proven useful to assess inattention and impulsivity in a classroom setting (Rizzo et al., 2000) and such tests have shown convergent validity with established gold-standards (Pollak et al., 2009; Díaz-Orueta et al., 2014). Furthermore, VR tasks have been evaluated as more enjoyable than their screen-based counterparts (Bioulac et al., 2012).

VR environments have also shown positive effects as an intervention and are being introduced as a complement to medical treatment for ADHD (Rodrigo-Yanguas et al., 2021; Goharinejad et al., 2022a). However, most intervention studies have been developed with children (Romero-Ayuso et al., 2021) with one particular study showing improvements in cognitive function but also in behavior (Goharinejad et al., 2022a). While most studies focus on improving attention deficits (Lee et al., 2001; Cho et al., 2002a; Cho et al., 2004; Bioulac et al., 2020), some others also report positive results of VR interventions in memory (Tabrizi et al., 2020) planning, time management, and social skills (Bul et al., 2016). Importantly, VR interventions using the well-known VRC-Continued Performance Task (CPT) have shown improvement in attention (Cho et al., 2002b; Bioulac et al., 2020; Hong et al., 2022) working memory (Coleman et al., 2019; Tabrizi et al., 2020), and academic performance (Blume et al., 2019).

In this context and recognizing the paucity of information regarding the effects of cognitive training with VR in adults with ADHD, we conducted a study to assess the effectiveness of a VR intervention on the PS and WM of students with ADHD symptoms from the Escola Superior de Saúde do Politécnico do Porto (ESS|P.Porto). For this purpose, we compared the performance in WM and PS tests in two groups: one underwent 10 sessions of VR cognitive training and a control group. We hypothesized that participants in the VR group would demonstrate better measures than control group both in PS and WM. A positive effect of VR intervention could pave the way for a therapeutic complement to current strategies.

2 Materials and methods

To reach our goal, we designed an experimental, randomized study (Goldberg, 2016; Sheard, 2018) with a passive control group (hereafter, CG) and an experimental group (hereafter, VRG). Investigator blindness was ensured as participants were randomly assigned to the two groups by an independent investigator not involved in the assessment process (Goldberg, 2016). The study took place at the facilities of the Psychosocial Rehabilitation Laboratory (LabRP) of ESS|P.Porto.

2.1 Participants

The access to the population was based on convenience, since students from the ESS|P.Porto were recruited due to easy access and communication. The sampling method was non-probability intentional, and only students with ADHD symptoms were selected (Schiffman and Kanuk, 2000; Aaker et al., 2019).

Inclusion criteria included: 1) Being aged 18 years or over, 2) a score indicative of ADHD as evaluated by the Diagnostic Interview for ADHD in adults (DIVA) (Kooij and Francken, 2007), and 3) have a good command of the Portuguese language. Participants were excluded if they had 1) visual or auditory sensory alterations that compromised performance with the intervention, 2) observable motor problems that prevented the use of the intervention equipment, 3) a presence of some other mental pathology or cognitive impairment proven by a doctor, or 4) were receiving a similar intervention.

2.1.1 Allocation of participants

After the initial assessment, the participants were allocated to either the control (CG) or the experimental group (VRG) *via* the AppSorteos web application using an allocation ratio of 1:1 (AppSorteos, 2022). Only the responsible investigator had access to the list of individuals who made up each of the groups. The assessing investigator was blinded to the allocation, but, due to the nature of the study, it was not possible to ensure the blindness of the

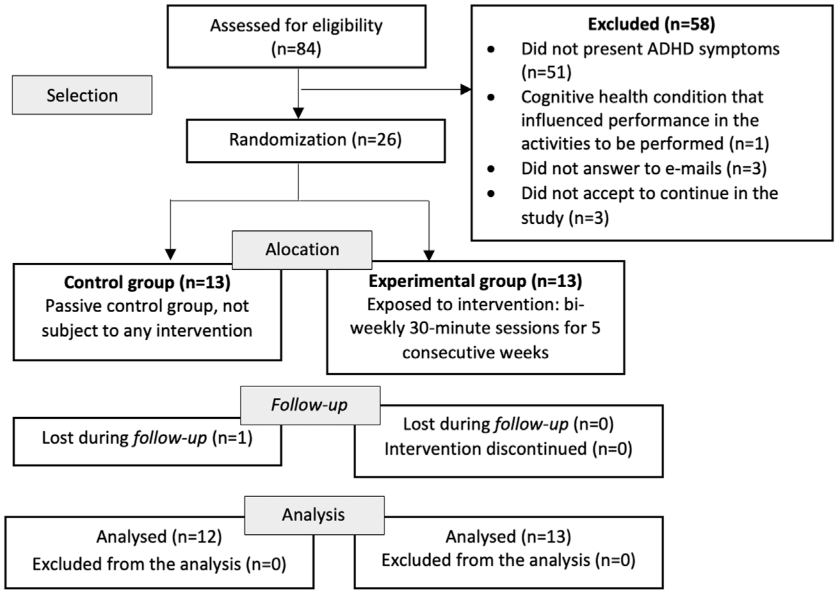


FIGURE 1
Flowchart of the allocation of participants.

investigator responsible for the intervention and the participants. The process of participant randomization is described in the flowchart prepared according to the CONSORT guidelines (Schulz et al., 2010), present in Figure 1.

2.2 Assessment tools

2.2.1 Instruments for selection of participants

To select the participants, ADHD screening tests and an online sociodemographic questionnaire were applied where information such as age, gender, place of residence, year and the course in which they were enrolled were collected, as well as other relevant information for the study, such as the existence of a diagnosis, taking any medication, and whether there had any prior contact with VR devices or games.

The Portuguese version of the Diagnostic Interview for ADHD in adults (DIVA 2.0) (Kooij and Francken, 2007) was used to screen students with ADHD symptoms.

The DIVA 2.0, translated and adapted to the Portuguese population by Grommen (Kooij and Francken, 2007), is a structured interview based on the DSM-IV criteria (American Psychiatric Association, 1994) that allows tracing ADHD symptoms in adulthood and childhood, with a reliability value of = 1. It is divided into three parts: Attention Deficit Criteria (A1); Hyperactivity/Impulsivity Criteria (A2) and Age of Onset and Dysfunction caused by ADHD symptoms (Supplementary Criteria A, B and C). Criterion A1 and A2 are made up of nine questions each, Supplementary Criteria A and B by one question each, and Supplementary Criteria C by two. For the participant to show ADHD symptomatology in criteria A1 and A2, they must have a total of six or more questions completed in each. Depending on the score obtained, there are three types of presentation of ADHD symptoms: Combined (A1 and A2 criteria completion); Predominantly Inattentive (A1 criteria completion); and Predominantly Hyperactivity-Impulsivity (A2 criteria completion). Currently, there is an updated version of the DSM-5 criteria, DIVA-5 (Kooij and Francken, 2010). Due to its similarities with DIVA 2.0 and the fact that, at the time of the study, it was not available in Portuguese, we chose to use version 2.0 (Kooij and Francken, 2007).

2.2.2 PS assessment tool

The Southwestern Assessment of Processing Speed (SWAPS) (Cullum et al., 2021) was used for the assessment of PS. This is an instrument based on the *Coding/Digit Symbol* subtest of the Wechsler Adult Intelligence Scale - Third Edition (WAIS-III) (Wechsler, 2008), which is validated for the adult population. It is easy to apply and validated for all populations because it uses symbols and numbers. It is a test of transcribing numbers into shapes in which seven common shapes are presented on a standard $8.5'' \times 11''$ sheet of paper, each paired with a non-sequential number from one to seven, with the transcription key at the top of the page. All shapes are easily recognizable and distinct from each other. The page is arranged with a nine-row by nine-column configuration under the key. The first six forms in the first row include three demonstration forms completed by the assessor, followed by three practice forms completed by the participant. After these six items are complete and the participant has understood the task, the participant is instructed to continue filling in the number corresponding to each form, from left to right, row by row, as quickly as possible, for 60 s. The participant's total score reflects the total number of correct answers, with a maximum of 75 points. The higher the score, the better their processing speed, and there is no cut-off point (Cullum et al., 2021). Its reliability is high, with an internal consistency of $\alpha = 0.89$, for a sample of 539 participants. For the sample of the present study, the SWAPS shows an internal consistency of $\alpha = 0.619$.

2.2.3 WM assessment tools

The subtests *Sequence of Letters and Numbers* and *Spatial Location* of the Portuguese version of the Wechsler Adult Intelligence Scale - third Edition (Wechsler, 2008) were used to assess WM. The test has a good internal consistency, with reliability values between 0.74 and 0.98, respectively (Tulsky et al., 2003). The WAIS-III is one of the most widely used behavioral tests to assess cognitive function in adults, consisting of 14 subtests grouped into: Verbal IQ, Achievement IQ, Full Scale IQ, Verbal Comprehension Index, Perceptual Organization Index, Working Memory and Processing Speed (Wechsler, 2008).

The *Sequence of Letters and Numbers* subtest involves the oral repetition of a sequence of numbers and letters, in ascending and alphabetical order, respectively. For each item, three tests are allowed, with different sequences of letters and numbers, being scored from 0 to three points, according to the number of correct answers. The maximum score is 21 points (Tulsky et al., 2003; Wechsler, 2008).

The *Spatial Location* subtest consists of the repetition of a sequence performed by the examiner, on a board with 10 cubes numbered from 1 to 10 with the numbers facing the examiner. It is divided into two tasks: (1) direct spatial localization, where the participant must repeat the sequence in the same order and (2) inverse spatial localization, where the participant must repeat the sequence in the opposite order of the examiner. For each item, three trials with different sequences are allowed, being scored from 0 to three points, according to the number of correct answers. The maximum total score of the subtest is 32 points (Tulsky et al., 2003; Wechsler, 2008).

2.2.4 Tools for evaluating satisfaction with the games

To assess satisfaction with the platform, the participants responded to a questionnaire provided by Virtuleap. The questionnaire is composed of nine questions about the experience lived by the participants while using the platform, including ease of use and satisfaction with the equipment, games, and the overall experience. The scoring is done on a scale of −3 (completely disagree) to 3 (completely agree), with two questions about the most and least preferred games.

2.3 Procedures

The study was approved by the Ethics Committee of ESS|P.Porto, with number CE1232. Participants were invited to participate through an email sent to the student contacts of ESS|P.Porto. Interested volunteers were contacted by the research team and were required to sign the informed consent, ensuring data anonymity and confidentiality (World Medical Association, 2013) followed by the completion of the assessment instruments ensuring compliance with the eligibility criteria. The selected participants were assessed by the evaluating research before the intervention, which began immediately after the assessment, which lasted 5 weeks. After its completion, the assessment tests were administered again.

All data concerning the participants were numerically coded in order to maintain confidentiality. Records containing personal data and allowing for their identification were kept separately. In this study, data were collected in digital format for DIVA 2.0, and in paper format for SWAPS and WAIS-III, the latter being transferred to a database and coded to maintain anonymity. Paper and digital data will be stored for 10 years and are the responsibility of the principal investigator (Smith et al., 2015).

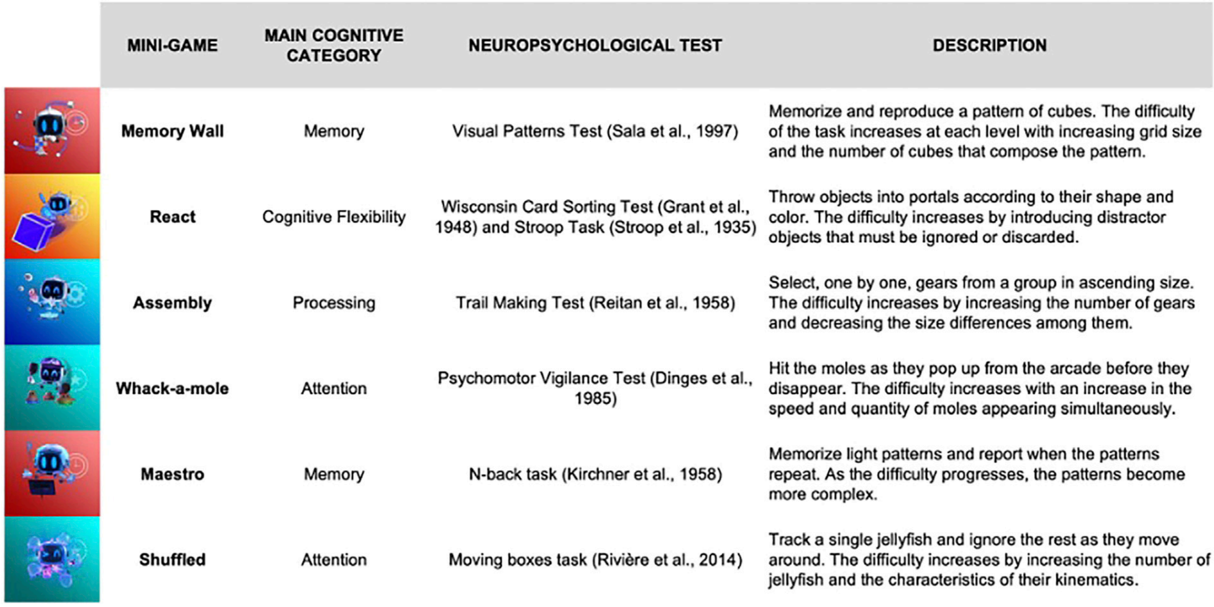
TABLE 1 Sequence of games played in the various sessions.

Session	Games		
1	Whack-a-mole	Memory wall	Assembly
2	Shuffled	Maestro	React
3	Whack-a-mole	Memory wall	Assembly
4	Shuffled	Maestro	React
5	Whack-a-mole	Memory wall	Assembly
6	Shuffled	Maestro	React
7	Whack-a-mole	Memory wall	Assembly
8	Shuffled	Maestro	React
9	Whack-a-mole	Memory wall	Assembly
10	Shuffled	Maestro	React

2.4 Intervention

CG participants did not receive any intervention in order to estimate the absolute effects of the intervention. According to the Declaration of Helsinki (World Medical Association, 2013), not using an intervention is acceptable if it is necessary to determine the effectiveness or safety of an intervention. However, the CG will have access to a post-study intervention if the results obtained are positive and if they wish to do so. The VRG started the intervention after the initial assessment was complete. The intervention protocol consisted of two 30-min sessions per week for five consecutive weeks. The study took place at the LabRP of ESS|P.Porto. The intervention used a subset of 6 games from the Enhance VR library (Brugada-Ramentol et al., 2022). The games were accessed through the Enhance VR platform on a Meta Quest head-mounted display (HMD), qualcomm snapdragon 835 processor, 4Gb RAM, 64 Gb internal memory, resolution per eye in pixels: 1,400 × 1,600, with a refresh rate of 72 Hz and motion controllers. The researcher responsible for the intervention was in the room together with the participants, providing help in handling the equipment, and in accessing the platform.

The games used in the intervention were presented to participants as in Table 1 and included six games, as shown in Figure 2.



MINI-GAME	MAIN COGNITIVE CATEGORY	NEUROPSYCHOLOGICAL TEST	DESCRIPTION
Memory Wall	Memory	Visual Patterns Test (Sala et al., 1997)	Memorize and reproduce a pattern of cubes. The difficulty of the task increases at each level with increasing grid size and the number of cubes that compose the pattern.
React	Cognitive Flexibility	Wisconsin Card Sorting Test (Grant et al., 1948) and Stroop Task (Stroop et al., 1935)	Throw objects into portals according to their shape and color. The difficulty increases by introducing distractor objects that must be ignored or discarded.
Assembly	Processing	Trail Making Test (Reitan et al., 1958)	Select, one by one, gears from a group in ascending size. The difficulty increases by increasing the number of gears and decreasing the size differences among them.
Whack-a-mole	Attention	Psychomotor Vigilance Test (Dinges et al., 1985)	Hit the moles as they pop up from the arcade before they disappear. The difficulty increases with an increase in the speed and quantity of moles appearing simultaneously.
Maestro	Memory	N-back task (Kirchner et al., 1958)	Memorize light patterns and report when the patterns repeat. As the difficulty progresses, the patterns become more complex.
Shuffled	Attention	Moving boxes task (Rivière et al., 2014)	Track a single jellyfish and ignore the rest as they move around. The difficulty increases by increasing the number of jellyfish and the characteristics of their kinematics.

FIGURE 2
Enhance VR games used in intervention.

For attention, the games Whack-a-mole and Shuffled were used, the former training sustained attention and the latter training visual selective attention. For working memory, the games Memory Wall and Maestro were used to train short term visuospatial memory and working memory, respectively. For processing speed, we used Assembly, which trains the processing speed and the capacity to codify, and React, which aims to train task-switching and response inhibition skills (Brugada-Ramentol et al., 2022).

The games were performed by all participants always in the same sequence (Table 1) to keep the study protocol identical for all. The playing position was always standing, in a large and darkened room. Before each game was played for the first time, participants went through a benchmark session that established the baseline that determined the level at which one would start the game.

To promote adherence to the intervention, when the intervention was finished, the researchers provided detailed information about the study and explained the benefits of their participation. A close follow-up was given: The schedule was provided in a timely manner according to the participant's availability and ensuring that the session was rescheduled in case of absences, the session would be rescheduled at a time convenient for both parties. The guarantee of confidentiality was also a way to ensure effective participation. In addition, as the participants often crossed paths in the facilities, it was customary to exchange information, for example, for example, about the score they had achieved or the level they had reached. Having observed that this exchange of information seemed to contribute to the motivation and involvement of the participants in the games, a ranking board was created, where the scores would be marked after the session, by each participant, thus creating a competitive environment (Robiner, 2005; Zweben et al., 2009).

2.5 Data analysis

After data collection, statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) version 28 (IBM, 2021) program, with a significance level (α) of 0.05 being considered for all statistical tests used. Descriptive statistics were used to characterize the sample, using measures of central tendency and dispersion: Mean (x) and standard deviation (σ) for continuous or discrete variables and absolute (n) and relative (%) frequencies for nominal or ordinal data (Maroco, 2018).

The normality of the variables was tested using the Shapiro-Wilk test. To compare the two groups at baseline, t-student tests for independent samples or Mann-Whitney tests were used in the case of non-normally distributed variables (Maroco, 2018). To verify the effect of the intervention on the variables under study, a mixed ANOVA was used, with time (pre- and post-intervention) as an intra-subject factor and its interaction with the intervention. The assumptions for the use of the mixed ANOVA - normal distribution and variances/covariances of the variables were tested using the Shapiro-Wilk and Box's M tests (Beins and McCarthy, 2018; Maroco, 2018). The value of Mauchly's test for sphericity was $p > 0.7$ so Huynh-Feldt's Epsilon analysis was used (Maroco, 2018).

3 Results

Evaluation was completed for 25 participants, 12 in the control group (CG) and 13 in the virtual reality group (VRG). The mean age was around 21 years with no difference between CG and VRG. In the total sample, there was only one male. Previous experience with VR was different in each group, with the CG having the highest percentage of experienced participants (58.33; n = 7) and only

TABLE 2 Sociodemographic characterisation of the sample groups (CG and VRG) regarding age, gender and previous experience with VR.

Groups variables		CG n = 12	VRG n = 13	
		n (%)	*n* (%)	*p-value*
Gender	Female	11 (91.70)	13 (100.00)	0.480[a]
	Male	1 (8.30)	0 (0)	
Previous experience with VR		7 (58.33)	3 (23.17)	0.111[a]
		x ± σ	*x* ± σ	*p-value*
Age (years)		20.17 ± 0.94	21.69 ± 0.75	0.001[b]

($\bar{x}$–*mean*; σ-standard deviation; %-relative frequency; [a]Person's exact test; [b]Independent samples *t*-test).

TABLE 3 Comparison of processing speed values in the two groups.

Variables	CG n = 12	VRG n = 13	
	x ± sd	*x* ± sd	*p-value*
SWAPS pre	43.67 ± 6.99	40.77 ± 6.94	0.309[b]
SWAPS post	44.50 ± 7.68	49.46 ± 6.96	0.104[b]
p-value	0.682[c]	<0.001[c]	
Sequence of letters and numbers pre	10.00 (2.37)	9.23 (1.48)	0.337[b]
Sequence of letters and numbers post	10.58 (1.78)	9.46 (1.39)	0.052[d]
p-value	0.281[c]	0.465[e]	
Spatial Location pre	17.50 (2.57)	15.31 (3.11)	0.069[b]
Spatial Location post	18.58 (3.57)	16.92 (2.39)	0.183[b]
p-value	0.167[c]	0.034[c]	

(*x* –*mean*; sd, standard deviation; [b]Independent samples *t*-test; [c]Paired samples *t*-test; [d]Mann-Whitney test; [e]Wilcoxon Test).

TABLE 4 Group differences across time in processing speed measure.

	CG		VRG					
	Pre	Post	Pre	Post	*p-value*[a]	*p-value*[b]	η_p^{2*}	η_p^{2**}
	x ± σ	*x* ± σ	*x* ± σ	*x* ± σ				
SWAPS	43.67 ± 6.99	44.50 ± 7.68	40.77 ± 6.94	49.46 ± 6.96	0.004[c]	<0.001[c]	0.397	0.309
Sequence of letters and numbers	10.00 ± 2.37	10.58 ± 1.78	9.23 ± 1.48	9.46 ± 1.39	0.631[c]	0.272[c]	0.052	0.010
Spatial Location	17.50 ± 2.58	18.58 ± 3.58	15.31 ± 3.12	16.92 ± 2.40	0.598[c]	0.012[c]	0.242	0.012

($\bar{x}$–*mean*; ; sd, standard deviation; [a]Interaction *p-value*; [b]Within-subjects *p-value*; [c]Repeated measures ANOVA, values with Huynh-feldt correction; *, Within-subjects Partial Eta Squared; **, Interaction Partial Eta Squared).

three participants in the VRG with previous experience with VR systems (Table 2).

Table 3 shows, when comparing between and within groups, no statistically significant differences between the two groups concerning the PS ($p_{initial}$ = 0.309; p_{final} = 0.104) and WM (sequence of letters and numbers $p_{initial}$ = 0.337; p_{final} = 0.052; and spatial location $p_{initial}$ = 0.069; p_{final} = 0.183) values, both at the initial and final assessments. However, when the initial and final evaluations of PS and spatial location in each group are compared, it can be seen that, while the CG shows no significant differences (p_{ps} = 0.682; p_{sl} = 0.167), the VRG shows a statistically significant increase after the intervention (p < 0.001; p_{sl} = 0.034).

No statistically significant differences between groups were found at the initial assessment in PS and WM (Table 4). The analysis of variance shows a within-subjects PS difference is visible in the VRG (time: p < 0.001, power test = 0.961; interaction: p = 0.004, power test = 0.867) but not in the CG. We observed differences between the results obtained in the initial and final evaluation of the subtest (p = 0.012) which were not dependent on the intervention (p = 0.598).

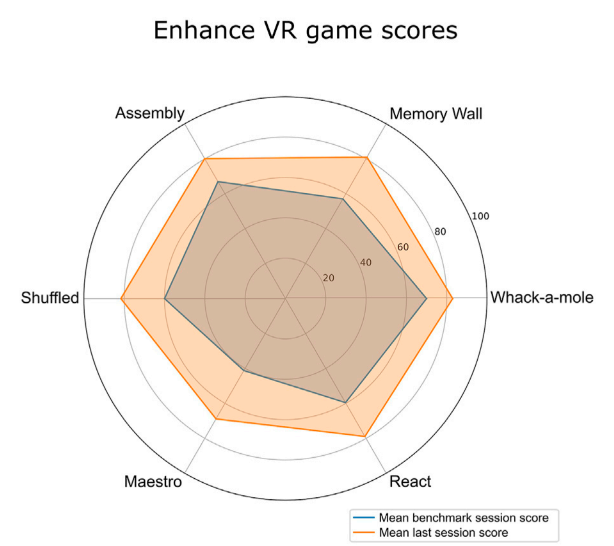


FIGURE 3
Mean benchmark session and last session score for each game. Spider chart depicting the mean of the scores of all participants obtained in the benchmark session (in blue), which assesses the baseline performance in the first session of each game, and the mean score obtained in the last session played of each game (in orange). The graphs show that overall the scores of the participants increased, suggesting better performance in all games. The scores are shown as the Enhance VR score of 0 to 100.

Figure 3 shows the progression of the mean game scores in the benchmark session (in blue) and the last score for each game session (in orange). Overall, we can observe an increase in the scores for every game.

Figure 4 depicts the overall satisfaction of VRG participants with the Enhance VR games that were included in the intervention. The results of the satisfaction questionnaire showed that the participants liked, in general, the experience of the games, with scores mostly at the maximum value (completely agree—Three and agree—2). The questions where there was a greater variation in satisfaction were related to the use of the helmet (Q7) and controls (Q6), with four of the participants reporting difficulty in their use (neutral—0 or slightly agree—1).

4 Discussion

This study aimed to assess the effectiveness of a VR cognitive training intervention on processing speed and working memory in students with ADHD symptoms from the Escola Superior de Saúde do Politécnico do Porto (ESS|P.Porto). Our findings show that the intervention with games that stimulate PS using VR can improve the performance of young adults with ADHD symptoms. However, the results obtained in the WM variable fell short of what was expected. Regarding the WM, there was an improvement in the results of the final assessment compared to the initial in the VRG in the test *Spatial location* unlike what happened in the CG, which seems to indicate an effect, albeit weak, of the intervention when measured with this instrument. On the other hand, when observing the performance of the participants in the games throughout the intervention, there was an increasing trend in the scores obtained in several games, including those related to WM. Thus, it may be suggested that there seems to be a tendency towards a better performance in WM in the individuals exposed to the intervention and that possibly different results could be obtained if the contact time with these games was increased. This longer exposure time, although it may lead to better performance by repeated training, still challenges the player and enables continued learning, since the pattern of the game varies and the levels become more complex, implying that the player will have to adapt to the new demands of the game. Furthermore, of the WM games selected for the intervention, one of them directly addresses WM while the other addresses visuospatial short-term memory (Brugada-Ramentol et al., 2022). However, when considering working memory as a cognitive system that stores and manipulates information for a short period of time to complete a task and knowing that working memory encompasses a visuospatial component (Baddeley, 2012), we can assume that both chosen games address WM as a whole.

We verified an increase in PS performance measures. Although only the Assembly game specifically addressed this executive function, the option to include React, which addresses cognitive flexibility training, may also have contributed to the PS improvement. These two executive functions are considered to be moderately correlated, with this correlation being greater in young people and adults, who constituted the population of this study, than in children (Akshoomoff et al., 2018).

Previous studies have shown that direct training of cognitive skills increases the trained skill (Gibson et al., 2015). In students that completed a cognitive training program using ThinkRx/ReadRx, there was an improvement in several cognitive skills, including PS, when compared to the control group (Gibson et al., 2015). Furthermore, in a sample of individuals aged 18–63 years with ADHD, a 5-week daily training program, consisting of 30–45 min sessions, using an online cognitive training platform (Cogmed) resulted in improved verbal and visuospatial WM in the intervention group, which scored higher on the assessment instruments (Dentz et al., 2020).

However, to the best of our knowledge, this is the first study that uses a VR-based intervention specifically targeting memory and PS for ADHD symptoms in adults. Previous studies have reported a positive effect of a VR intervention on cognitive skills in children with ADHD, specifically in selective and sustained attention (Barati et al., 2021). In a pilot study on a sample of 14 unmedicated children with ADHD, which aimed to improve behavior, cognitive functions, and dual-task functions, the participants had better results in the studied variables following the intervention compared to the pre-intervention assessment (Shema-Shiratzky et al., 2019). These studies were focused on a younger population (children), but they are still relevant for this study, as the deficits in PS and WM, as well as their complications, remain in adulthood (Biederman et al., 2010).

PS and WM have a crucial role in daily functioning in individuals with ADHD. Deficits in PS are, in part, responsible for deficits in other higher-order functions. Specifically, PS accounted for 29% of deficits in memory and 56% of deficits in attention (Butzbach et al., 2019). Therefore, the effectiveness of interventions in these functions has been highlighted by several authors. A systematic review and meta-analysis examining the association of PS deficits in ADHD and clinical

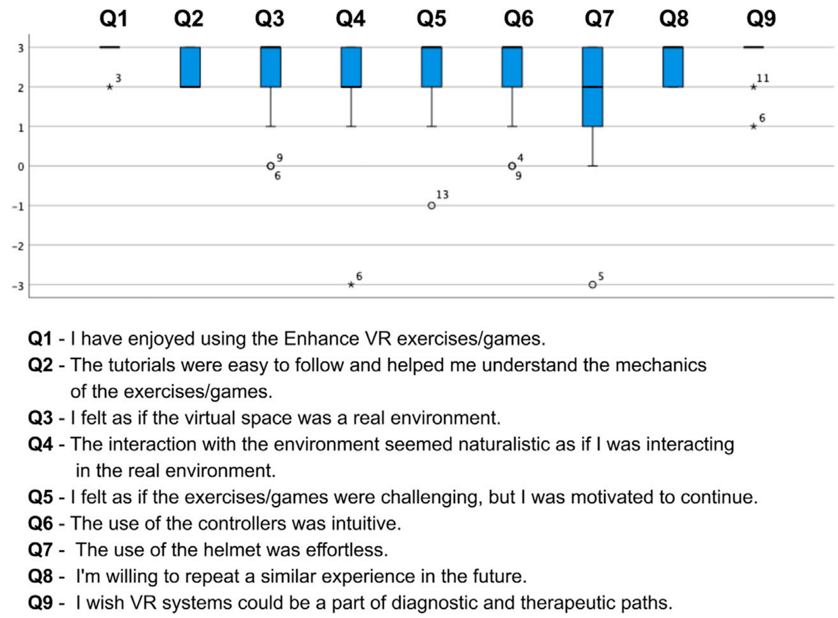


FIGURE 4
Boxplot showing the responses to the satisfaction questionnaires. After the intervention, the participants replied to 9-item satisfaction questionnaires on using and enjoying the Enhance VR games. They responded on a 7-point Likert scale, where -3 means 'completely disagree' with the statement and 3 means 'completely agree' with the statement. The graph shows the distribution of the responses for each statement, the box represents the interquartile range (IQR) and the central line represents the median value. The whiskers indicate all of the values that are not outliers. The circles and asterisks represent the outliers depending on their standard deviation to the mean with the number of subjects.

conditions in children and adolescents concluded that young people with PS deficits report more anxiety, less confidence in their social skills, and deficits in activities of daily living (Cook et al., 2018).

VR is a promising technology in both assessment and improvement of cognitive skills in children with ADHD (Bashiri et al., 2017; Romero-Ayuso et al., 2021; Goharinejad et al., 2022b) and adults (Park et al., 2020). Importantly, both the use of gamification and VR have proven value in increasing individuals' engagement. Thus, the results obtained may also result from motivation factors as the VR games are fun, and engaging, and provide real-time feedback. Our results are consistent with this idea since the participants reported being satisfied with the games and having a positive opinion about their use. The intervention in the present study spanned for 5 weeks, a total of 10 sessions. This training frequency is consistent with previously reported interventions. In a sample of children with ADHD, a 10-session memory intervention resulted in positive results (Tabrizi et al., 2020). A 6-week cognitive intervention consisting of 30-min sessions twice a week remediation program in a virtual classroom found that the intervention reduced cognitive distraction in children with ADHD (Bioulac et al., 2020).

Our study is not without limitations. First, we acknowledge that our sample size is relatively small, it is mainly composed of adult females with no confirmed clinical diagnosis, and it was based on a convenience selection method, which limits the generalization of results. In addition, the SWAPS instrument used to measure PS is still not fully validated for the adult population (Cullum et al., 2021). For this reason, these results, although promising, should be read with caution, namely, due to the small number of participants, which may condition the results obtained in the statistical tests used, and reduces the scope of the results.

Future studies should circumvent the limitations of this study, namely, increasing participant size, selecting individuals with a confirmed clinical diagnosis, extending the intervention time, and assessing for how long the improvements are maintained.

5 Conclusion

This study aimed to assess the effectiveness of a VR intervention on the processing speed and working memory of students with ADHD symptoms. Through this study it was possible to verify that there were improvements in the PS from the first to the second evaluation, but not in the WM.

After the results obtained for the PS considering this sample, it can be hypothesized that VR may be an important and advantageous intervention for this population, with a positive impact on cognitive functioning, which may lead to better daily performance and consequent quality of life. In addition, the characteristics of VR increase adhesion and motivation to the intervention. Although the results obtained for WM did not show statistical significance, it is considered that the improvements observed in the final assessment of the VRG in the test *Spatial location*, as well as the observation of the performance of participants in the games throughout the sessions, may be positive indicators to be considered for the use of this platform in this competence.

Therefore, the need for further studies in this area is highlighted, since new technologies, and more specifically VR, have been increasingly used in health and research, which makes it essential to understand the positive effects that may arise from it in the intervention with people with various health conditions.

Data availability statement

The raw data supporting the conclusion 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 Ethics Committee of ESS|P.Porto, with number CE1232. The patients/participants provided their written informed consent to participate in this study.

Author contributions

FC, SC, MT, and VS-S contributed to the conception and design of the study. FC and SC collected the data and implemented the intervention. MT performed the statistical analysis and created the graphs. FC, SC, and MT, wrote the first version of the manuscript. VS-S, VB-R, and BS-M wrote sections of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Acknowledgments

This article refers to the studies of the Bachelor-project of the two first authors (FC and SC). The authors would like to thank all of the Virtuleap team.

Conflict of interest

AB and HJ are Chief Executive Officer and Chief Technical Officer, respectively, and founders at Virtuleap. VB-R is employed as Lead Neuroscientist and BS-M as Head of Partnerships at Virtuleap.

The remaining 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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