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Stereoscopic objects affect reaching performance in virtual reality environments: influence of age on motor control

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Although the stereoscopic effect in 3D virtual reality (VR) space has been studied, its influence on motor performance, specifically how stereoscopic objects affect behavioral outcomes like reaching, remains unclear. Previous research has primarily focused on perceptual aspects rather than on how stereoscopic visual input impacts motor control at the behavioral level. Thus, we investigated the effects of stereoscopic objects in a VR environment on reaching performance, examining whether the stereoscopic effect of objects is a significant aspect enough to affect performance at the behavioral level. While doing so, we investigated young and older adults separately, as age is a critical factor influencing motor performance. Fourteen young and 23 older participants performed a reaching task in the VR space. The target objects were 2D and 3D, deviating from the initial position by 10 and 20 cm. The movement attributed to feedforward control was analyzed using end-point error and smoothness of movement. Our results revealed that older participants had significantly worse predictive control than young participants in the 3D long task, suggesting that the positions of 3D objects were more difficult to predict than those of 2D objects. Young participants showed a significant difference in smoothness between 2D and 3D objects, which was not observed in older participants. This may reflect the floor effect in older participants. Under the short-distance condition, neither group showed a significant difference, suggesting the ceiling effect by distance. We confirmed that the effect of stereoscopic objects was not drastic but it did hamper the reaching performance.

KEYWORDS

virtual reality (VR), stereoscopic effect, reaching, 3D objects, motor control

1 Introduction

The integration of perception and control is crucial for enhancing the performance of robotic systems in complex and dynamic environments. Immersive virtual reality (VR) enables users to experience a sense of presence (Rose et al., 2018; Kuhne et al., 2023; Alazmi and Alemtairy, 2024; Pallavicini et al., 2019), making it an ideal tool for studying motor function and control, which are critical for designing effective actuators in robotics. VR environments offer practical advantages in a three-dimensional (3D) settings (Knight and

Titov, 2009; Anoffo et al., 2018; Setti and Csapo, 2021) while few studies have been conducted in a non-immersive two-dimensional (2D) environment (Tam et al., 2005). In general, the quality of VR can change user behavior (Lee et al., 2020; Hoffman et al., 2006; Rosa et al., 2016). Creating accurate VR environments helps us understand human motor control and perception.

Reaching has been widely used to evaluate motor function (Roby-Brami et al., 2003; Cirstea et al., 2003; Igarashi et al., 2011; Kim et al., 2020a) because it is a fundamental task in daily life and can include other complex movements. Deployed in VR environments, reaching performance has been evaluated to investigate the effect of different viewing medium (Subramanian and Levin, 2011; Lin et al., 2019) or different displays (Camporesi and Kallmann, 2016). These previous studies successfully indicated that reaching performance could vary depending on visual representation. However, a task for 2D movement does not necessarily need to adopt complex 3D environments. Although planar reaching movements can be easily represented on a monitor using simple cursors (Kim et al., 2019; Brière and Proteau, 2011; Onagawa et al., 2022; de Brouwer and Spering, 2022; Ikegami et al., 2022), the experience provided by VR involving 3D objects is fundamentally different.

The 3D space enables users to perceive more information than the 2D space, leading to different perceptions of visual complexity because of depth information (Li et al., 2020), greater emotional arousal caused by binocular disparity (Tian et al., 2021) and different grip performances that depend on the view angle (Keefe and Watt, 2017), than in 2D environments. Several factors improve the quality of the 3D space and are associated with the mode of 3D information processing by the brain. Although some of these factors contribute to a better appearance, they are not indispensable in enabling people to recognize a VR environment as a 3D space. Thus, as an indispensable factor, we focused on the stereoscopic effects of objects in this study, breaking the 3D environment down into several aspects that compose it. Some previous studies have reported that stereoscopic effects in VR environments are negligible in public speaking (Ling et al., 2012) and in acquiring knowledge about heart disease by watching 2D or stereoscopic heart models (Patel et al., 2021). Nonetheless, the evaluation indicators used were too abstract to investigate the sophisticated role of stereoscopic objects in general immersive VR environments, calling for an investigation based on behaviors in more general and basic tasks to determine whether stereoscopic properties should be considered for creating an immersive VR environment for motor function assessment.

Therefore, in this study, we investigated the effects of stereoscopic objects during a reaching task in a systematical way by observing behavioral performance, examining whether the stereoscopic effect of objects is a significant aspect enough to affect behavioral level. We hypothesized that the stereoscopic effect of reaching objects would influence the reaching performance. As the stereoscopic property is processed for depth perception in the brain (Backus et al., 2001; Guo et al., 2022), cognitive function should be related to the performance, linked to age as a critical factor for the function (Deary et al., 2009). Thus, young and older individuals were recruited separately for the experiment. We adopted 2D and 3D objects as the cursor and target in a reaching task requiring the same reaching trajectory. Moreover, we assessed distance to the target, which is associated

with difficulty of a task (Fitts, 1954), as two conditions (long and short distances) for the experiment. We expect the results to determine rough effects of the factors.

2 Methods

2.1 Participants

Fourteen young (11 male and 3 female; age: 24.14 ± 1.41 (mean \pm standard deviation) years, range, 22–26 years) and 23 older (11 male and 12 female; age: 76.83 ± 5.38 , range, 69–88 years) participants were included in the study. None of the participants had any neurological disorder. All participants were healthy enough to perform the experiment. All participants provided informed consent before participating in the experiment. This study was approved by the Institutional Review Board of Handong Global University and followed the principles of the Declaration of Helsinki.

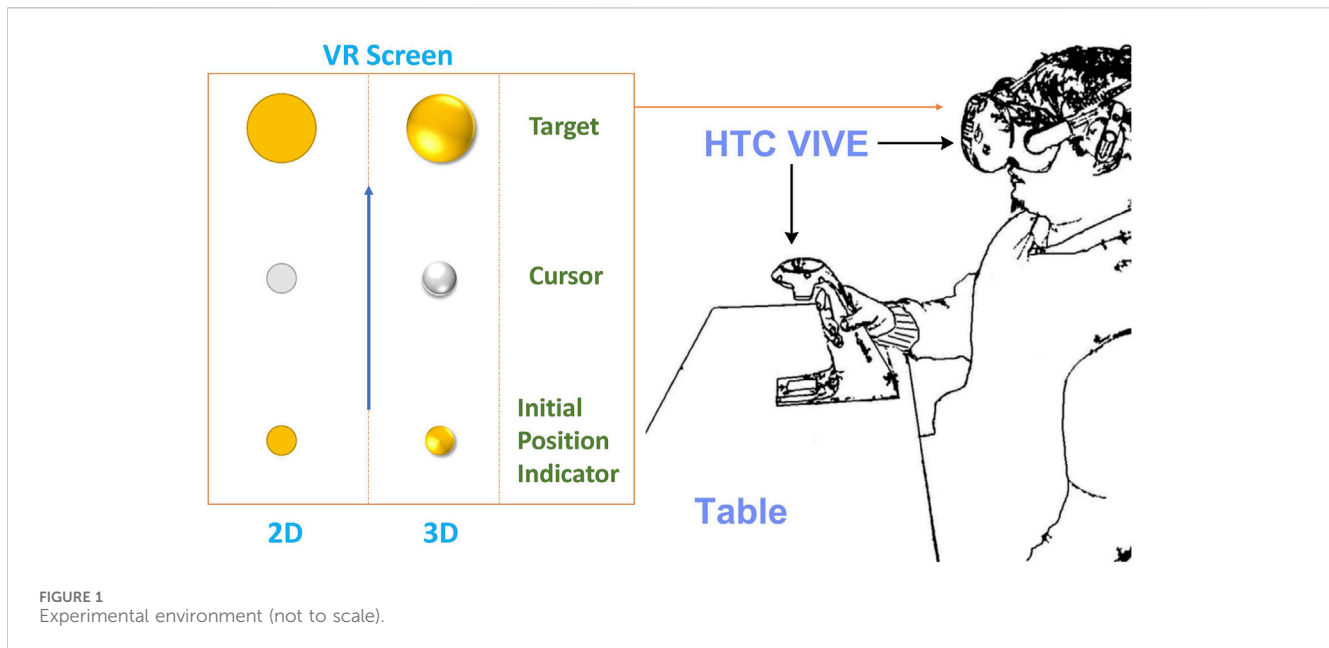
2.2 Experimental environment

Figure 1 shows the experimental environment. During the experiment, the participants sat on a chair and wore a VIVE head-mounted display (HTC Corporation, Taipei, Taiwan) to experience an immersive VR environment. The head-mounted display also featured headphones for enabling the participants to hear sounds in the VR space used during the experiment. The VR environment was developed using Unity, where we optimized quality settings to enhance participants' perception and interaction with the objects. We set the texture quality to full resolution to maximize detail, and applied 4x multi-sampling anti-aliasing to smooth object edges, minimizing visual artifacts like jagged lines. Shadow resolution was set to high, with two shadow cascades and a shadow distance of 40 units to ensure accurate and detailed shadows. For stereoscopic depth, Unity's default settings were applied, with an inter-pupillary distance (IPD) set to 64 mm. The HTC VIVE, however, automatically adjusted IPD for each participant based on individual calibration, and we did not manually measure or adjust this for the experiment. No participants reported discomfort or visual distortion, confirming the suitability of the setup. We used Single Pass rendering to optimize performance, with near and far clipping planes set to 0.3 and 1,000 units, respectively.

The participants gripped the HTC VIVE controller, which was attached to a plastic apparatus as physical restraint for planar movement, to generate purely planar movements on the table. On the VR screen, participants could see a yellow initial position indicator with a radius of 0.5 cm, a yellow target with a radius of 2.5 cm, and a white cursor with a radius of 0.5 cm. View of 2D and 3D objects was induced not by control of the head-mounted display but by the characteristic of the objects. Participants controlled the cursor in the VR space by moving the controller, and the cursor positions were recorded at a sampling rate of 90 Hz.

2.3 Experimental procedure

Before data collection, participants were given approximately 5 min to familiarize themselves with the VR environment. During



this time, they were seated and instructed to move the controller freely in a 2D space on the table to become accustomed to the setup.

At the beginning of the trial, the location of the cursor was matched with that of the initial position indicator. The participants were instructed to move the cursor to reach the target by moving the VIVE controller after hearing a beep. In the final phase of the reaching task, they moved the cursor to decrease the distance between the target and the cursor. Once they stopped moving the cursor, they were instructed to maintain the final position of the cursor until another beep. The objects were slightly transparent; therefore, the participants could recognize the cursor that overlapped with the target. After the second beep (4 s after the first), the participants moved the cursor back to the initial position. This trial was repeated.

The experiment consisted of two conditions: the distance between the target and the cursor was 20 cm (long) or 10 cm (short), and the objects were 2D or 3D. The 2D objects moved as if objects in 3D space would be projected on a plane. In total, the participants performed four types of tasks (2D long, 2D short, 3D long, and 3D short) involving five trials for each task. 2D and 3D conditions have the same physical constraints imposed by the joystick. The two conditions only differed in visual representation.

2.4 Data analysis

For pre-processing, the positional data were filtered using a 5th-order lowpass Butterworth filter with a cut-off frequency of 10 Hz. We then defined the first sub-movement (reaching) as the interval of interest to be analyzed. In this experiment, the participants could reach the target because the cursor and target were visible, and no obstacles existed during the experiment. Therefore, we segmented the reaching trajectory of each trial based on the velocity profile. Based on the idea that the velocity profile forms bell shapes during

arm reaching (Suzuki et al., 1997; Karniel and Inbar, 1997; Matsui et al., 2006), we regarded the moment at which the velocity was zero as an indicator of sub-movement. Thus, the time when the velocity was zero for the first time determined the first sub-movement that reflected reaching by feedforward control. Intervals that could be associated with visual feedback were excluded from the analysis. Trials were manually inspected and rejected only if they met one of two specific conditions: (1) the participant did not reach the target by the second beep, or (2) the participant moved at a nearly constant speed without deceleration, with speed remaining non-zero at the second beep. Trials with either of these conditions lacked evidence of the first sub-movement phase. Approximately 0.9% of the trials were discarded.

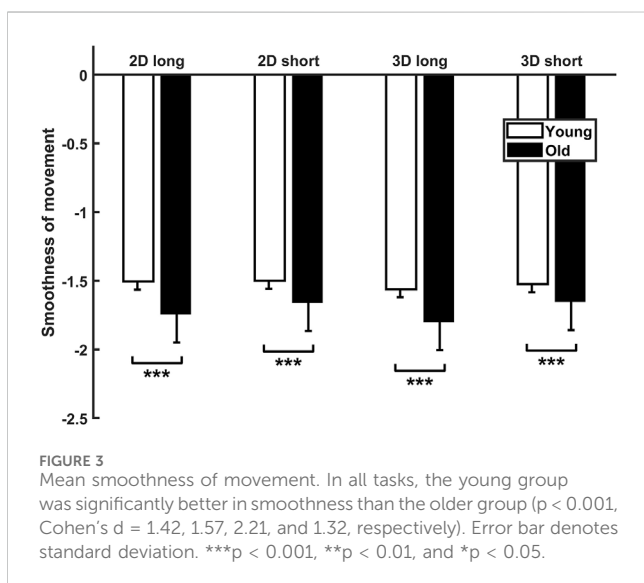
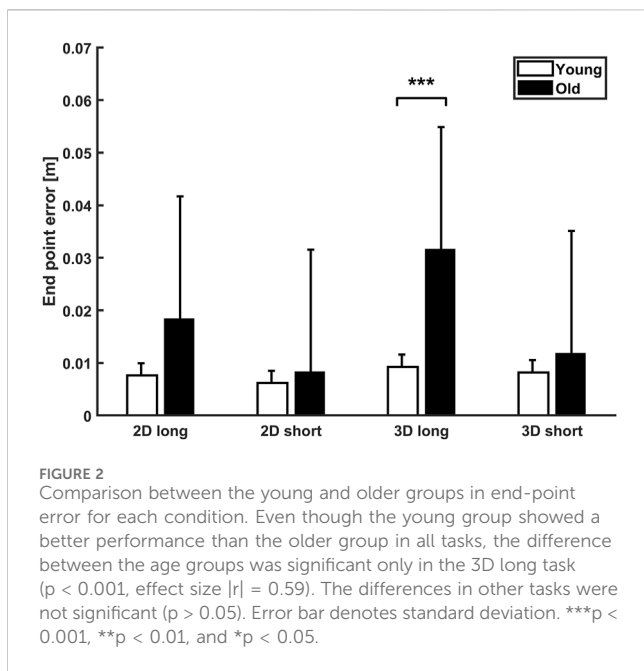
We used the following two parameters to assess reaching performance: end-point error and smoothness of movement. Because we considered a trajectory by feedforward control only, end-point error was directly used to evaluate the performance of the prediction. End-point error was defined as follows:

$$\text{error} = \sqrt{(x_{\text{target}} - x_{\text{cursor}})^2 + (y_{\text{target}} - y_{\text{cursor}})^2}$$

where x and y represent positions on the horizontal and vertical axes, respectively. The spectral arc length was used to evaluate the smoothness of movement (Balasubramanian et al., 2012), which was defined as follows:

$$\text{smoothness} = - \int_0^{\omega_c} \sqrt{\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2} d\omega$$

where ω_c represents the frequency band of movement and $\hat{V}(\omega)$ represents the magnitude spectrum of velocity on the primary axis that was normalized with respect to the DC component. As we used a low-pass filter with a cutoff frequency of 10 Hz, we set the frequency to 10 Hz to calculate smoothness. Smoothness of movement, measured by spectral arc length, was chosen for its



effectiveness in capturing the quality of feedforward control. Other metrics, such as reaction time and trajectory deviation, are typically linked to feedback-driven corrections. In contrast, smoothness reflects the efficiency of control, making it particularly relevant in feedforward tasks like ours, where participants rely on prediction and internal models of motion rather than feedback to guide their actions.

Subsequently, we compared participants in the young and older age groups for each task. Additionally, for each distance, we compared the performances of both age groups with the 2D and 3D objects separately. A two-sample t-test was performed using MATLAB R2022b (MathWorks Inc., Natick, MA, United States) for smoothness, as all groups passed the normality test (Lilliefors test, significance level = 0.01). The error parameter was analyzed using the Wilcoxon rank-sum test.

3 Results

First, we compared end-point errors using feedforward control between the young and older age groups. Figure 2 shows the mean end-point error while comparing the young and older age groups for each condition. For all tasks, the mean end-point error of the young group was less than that of the older group. However, the difference in error was significant ($p < 0.001$, effect size $|r| = 0.59$) only in the 3D long task, where the mean errors for the two groups were 0.009 and 0.032 [m], respectively. The errors in the 2D long task were 0.008 and 0.018 [m], respectively. Tasks that required a long distance were associated with a large difference between the young and older groups.

Figure 3 shows the smoothness of movement. In all tasks, the young group was significantly better in smoothness than the older group ($p < 0.001$). The Cohen's d values for each task were 1.42, 1.57, 2.21, and 1.32, respectively. Consistent with end-point error, long tasks showed a significant difference. The values for smoothness in the young and older groups for the 2D objects were -1.507 and -1.743 , respectively, and those for the 3D objects were -1.563 and -1.799 , respectively. These data suggest that smoothness can be used for more accurate assessment of performance than end-point error.

Because we found that the smoothness parameter was appropriate for evaluating movement performance, we investigated whether stereoscopic objects would make a difference. Figure 4 shows the smoothness of movement in the young and older groups. Although the differences between 2D and 3D objects for the long tasks were larger than those for the short tasks, the difference was significant only for the long task by the young group ($p < 0.05$, Cohen's $d = 0.85$). The mean smoothness in the long task was -1.506 (2D) and -1.563 (3D) for the young group and -1.743 (2D) and -1.799 (3D) for the older group. For both young and older groups, the difference in smoothness between 2D and 3D objects for the short task was almost negligible. No group showed a significant difference in the short task, suggesting the ceiling effect by distance.

4 Discussion

In this study, we investigated whether stereoscopic objects affect reaching performance. Our results revealed that the older group had significantly worse predictive control than the young group in the 3D long task, suggesting that the positions of 3D objects were more difficult to predict than those of 2D objects. The young group showed a significant difference in smoothness between 2D and 3D objects, which was not observed in the older group. Given that older adults are reported to experience a decline in binocular vision and stereopsis, which are crucial for depth perception (Norman et al., 2009), the results for the older group may reflect a floor effect. Under the short-distance condition, neither group showed a significant difference, suggesting the ceiling effect by distance. We confirmed that the effect of stereoscopic objects was not drastic but it did hamper the reaching performance.

In a different situation, it was reported that an immersive stereoscopic picture impeded people from learning vocabulary and that learning with 2D images was more effective (Kaplan-

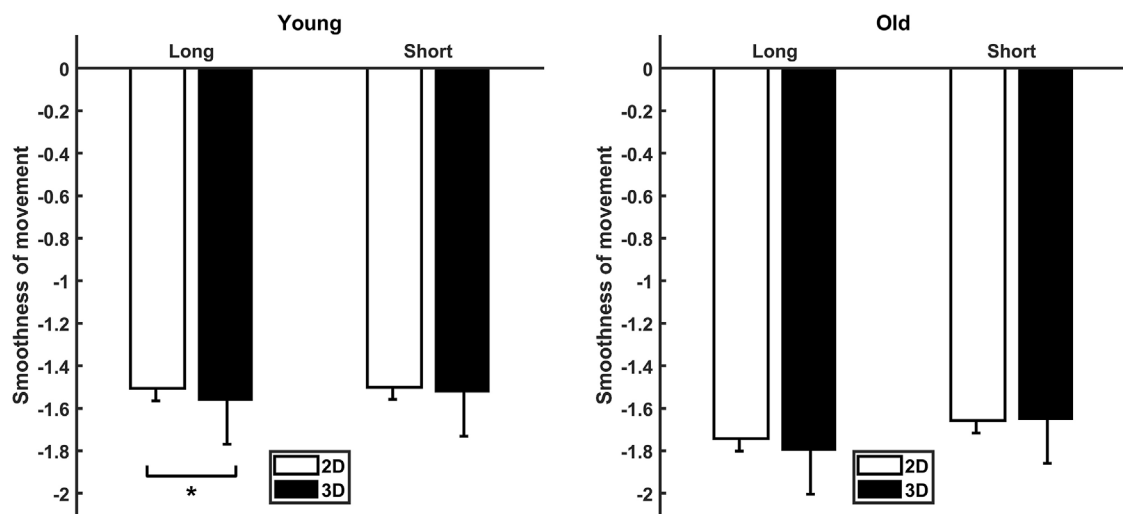


FIGURE 4

Comparison between 2D and 3D objects in smoothness. The left plot shows smoothness in the young group and the right plot shows smoothness in the older group. The short tasks showed a limited difference, while the long tasks contributed to larger differences. However, the difference was significant only for the young group ($p < 0.05$, Cohen's $d = 0.85$). Error bar denotes standard deviation. *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

Rakowski et al., 2022). The authors conjectured that the immersive nature of stereoscopic pictures was a distractor or drained some of the cognitive resources required for learning. Similarly, the perception of stereoscopic objects may necessitate additional information processing in the brain, which is not necessary when a 2D object is perceived. Considering this, prior experience with 2D or 3D devices could potentially influence participants' performance. Although we did not collect information on participants' prior exposure to these devices, it would be worthwhile for future studies to investigate whether such exposure affects performance. Several factors contribute to the perception of an object as stereoscopic. For example, shading is important for perceiving the shape of 3D objects (Ramachandran, 1988; Todd et al., 1997; Todd et al., 2023; Liu and Todd, 2004; Todd, 2004; Todd et al., 2014; Norman et al., 2004). The brain also uses binary disparity (Gonzalez and Perez, 1998; Murphy et al., 2016; Mitchison and Westheimer, 1984), motion parallax (Kim et al., 2016; Yoonessi and Baker, 2011), and textures (Ichiyama et al., 2007; Thomas G. et al., 2002; O'Brien and Johnston, 2000) for depth perception, which are most likely involved in the perception of stereoscopic objects. In addition, the interaction effect among disparity, motion parallax, and shading was observed in a previous study (Schiller et al., 2011), indicating that the behavior of these factors is complicated, which makes it difficult to investigate their effects. Reaching performance can also be affected by irrelevant factors due to the added cognitive load of using virtual reality. It has been reported that simply adopting tasks where real movements are represented on a monitor, translated into a cursor on the screen, can induce a perceived delay that does not actually exist, even in non-immersive VR settings (Kim et al., 2020b, Kim et al., 2021). Considering this, the factors contributing to the floor effect in the older group observed in the present study remain elusive.

We considered movement over the interval using feedforward control in the analysis. Thus, the significant differences between the 2D and 3D objects indicate that stereoscopic information is involved in movement planning. When a reaching task performed in a 3D VR

environment requires depth perception for successful performance, an extended Fitts' law model that adds terms related to depth information to the traditional Fitts' law model better predicts movements (Clark et al., 2020), which is associated with the relation between difficulty and target depth. The stereoscopic effect in this study may have served as an additional requirement in depth movement. Because a better performance was shown with 2D objects, visuomotor transformation during movement planning should not include the stereoscopic effect for better performance. Moreover, the difference in the stereoscopic effect may be attributed to visuomotor adaptation. The participants in the present study controlled the cursor on the screen using the controller. For visuomotor transformation, the brain must find an appropriate calibration model that matches the actual arm position to the cursor position in the VR space. In a previous study, a differently mapped cursor induced by visuomotor adaptation influenced depth perception (Volcic et al., 2013). Alterations in internal calibration caused by this classical visuomotor adaptation task may be intrinsically similar to the differences triggered by adding the stereoscopic effect. In addition, brain activities related to learning for visuomotor adaptation have been observed (Paz et al., 2003), supporting a neural basis. Another previous study reported that the brain may perform calibration suitable for binocular vision when monocular vision is input, leading to an underestimation of the distance in a reaching task (Servos, 2000). These incorrect internal calibration models may have been influenced by the stereoscopic effect.

What factors contributed to the age-related differences? Let's revisit our aim and task. We aimed to observe behavior changes influenced by stereoscopic effects through a ballistic reaching task, which involves multiple cognitive processes. First, depth perception itself requires additional cortical processing, particularly in the visual cortex (Backus et al., 2001; Thomas O. M. et al., 2002; Smith and Parker, 2021). This processing becomes more demanding for older adults due to general declines in neural efficiency and adaptability. Furthermore, changes in binocular

vision, such as near exophoria and reduced convergence ability, are common with aging (Leat et al., 2013), and studies have shown that binocular vision processing is altered in older adults (Yan et al., 2021). Such disturbances can significantly impact tracking performance, as seen in manual tracking tasks where performance is poorer under monocular vision compared to binocular (Kim et al., 2023). Aging is also associated with a decline in depth perception from binocular disparity (Norman et al., 2000; 2006). Collectively, these changes in visual processing, particularly in stereoscopic depth perception, contribute to the observed age-related differences in reaching performance. Beyond depth processing, aging also affects motor behavior through changes in sensory integration and control strategies. A critical factor is the increased reliance on visual feedback for motor tasks. Older adults tend to rely more on visual feedback (Seidler et al., 2010), which compensates for a decline in proprioceptive control (Boisgontier et al., 2012; Olszewska et al., 2016). Proprioceptive control is essential for effective feedforward control (Wolpert et al., 1995), enabling quick online corrections during reaching (Kasuga et al., 2022). Delayed responses in adjusting movements when the target position shifts suddenly (Sarlegna, 2006) suggest reduced use of proprioceptive input, which forces older adults to rely more on visual feedback for making corrections in reaching tasks. Given that our task emphasized feedforward control, similar to typical reaching actions in everyday life, these likely contributed to the observed differences in performance. Our findings on age-related differences in reaching performance align with previous research that observed a floor effect in tracking tasks, where older adults' performance showed reduced sensitivity to depth-related visual information, likely due to age-induced constraints (Kim et al., 2024). Taken together, these findings indicate that changes in stereoscopic depth perception, combined with shifts in sensory integration and motor control strategies, could impact reaching performance in older adults. Our results suggest that the use of stereoscopic effects in VR-based tasks and interventions should be approached with caution, especially considering the age-related changes in visual and motor processing.

In this study, we confirmed the stereoscopic effect of objects in VR environments. However, we did not set sophisticated parameters to adjust the stereoscopic effect, as we initially aimed to determine a rough effect. We discovered the floor effect by age and the ceiling effect by distance. Additionally, movements through feedback control during ongoing reaching should be investigated in future studies. In this case, the effect of motion parallax could have affected the internal calibration. Naturally, users may subconsciously strive to estimate the distance between the objects and the virtual camera used for the first-person view implemented in the VR space. Thus, this distance should also be investigated in the future, including whether the perceived distance is identical to the actual distance between the target and the camera. Moreover, while we focused on two specific distances (10 cm and 20 cm) as proxies for task difficulty, future studies should investigate whether the stereoscopic effect generalizes across a broader range of distances. Furthermore, while we focused on young and older participants to capture distinct age-related differences, future studies could include middle-aged participants to explore potential regressive changes in movement planning or identify an inflection point in motor control across the lifespan. Additionally, future research should account for participants' prior VR experience and systematically control IPD, as

these factors may influence how participants interact with virtual environments. Including a group of experienced VR users could further provide valuable insights into performance differences across age groups. In conclusion, we confirmed that the effect of stereoscopic objects is not negligible in VR reaching tasks.

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 humans were approved by the Institutional Review Board of Handong Global University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HK: Conceptualization, Formal Analysis, Methodology, Software, Validation, Visualization, Writing—original draft, Writing—review and editing. YK: Conceptualization, Formal Analysis, Methodology, Validation, Writing—review and editing. JL: Conceptualization, Methodology, Resources, Visualization, Writing—review and editing. JK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing—review and editing.

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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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