Toward Making Virtual Reality (VR) More Inclusive for Older Adults: Investigating Aging Effects on Object Selection and Manipulation in VR

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ABSTRACT

Recent studies show the promise of VR in improving physical, cognitive, and emotional health of older adults. However, prior work on optimizing object selection and manipulation performance in VR was mostly conducted among younger adults. It remains unclear how older adults would perform such tasks compared to younger adults and the challenges they might face. To fill in this gap, we conducted two studies with both older and younger adults to understand their performances and user experiences of object selection and manipulation in VR respectively. Based on the results, we delineated interaction difficulties that older adults exhibited in VR and identified multiple factors, such as headset-related neck fatigue, extra head movements from out-of-view interactions, and slow spatial perceptions, that significantly decreased the motor performance of older adults. We further proposed design recommendations for improving the accessibility of direct interaction experiences in VR for older adults.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**; *Interaction paradigms*; *Virtual reality.*

KEYWORDS

Virtual/Augmented Reality, Older Adults, Empirical study that tells us about people, Lab Study

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1 INTRODUCTION

VR provides immersive 3D environments and rich interaction techniques (e.g., hand gestures [40]) for users to experience different environments and interact with virtual objects. Prior research shows that VR could be beneficial for older adults. For instance, it could potentially aid older adults in preserving or enhancing their physical and cognitive capabilities, encompassing aspects such as postural stability [49, 71], reaction speed [11], and overall physical well-being [12, 18]. It could also promote their social and emotional well-being. For example, VR could allow older adults to collaborate with remote family members, reminisce with their peers [4, 5], and communicate with their grandchildren [1, 68].

Despite the potential benefits of VR, its interaction techniques have rarely been designed or studied with older adults [20]. As people age, the changes in their perceptual, motor, and cognitive abilities can significantly impact their performance and experience when operating interactive devices. This consideration becomes particularly relevant when examining the aging effects on basic interaction tasks, such as object selection and manipulation [10, 32], on 2D and 3D interfaces. Previous research has demonstrated that older adults may exhibit higher error rates and longer completion times in these tasks compared to younger adults when using mouse clicks and touch inputs [31, 42]. Furthermore, the performance of

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users in object selection tasks can vary depending on the type of input device employed, whether it be direct or indirect [61, 63]. Drawing inspiration from research exploring the impact of aging on 2D interfaces, we hypothesized that older adults may exhibit dissimilar performance outcomes and user experience compared to their younger counterparts when utilizing interaction techniques in VR. This hypothesis is based on the fact that VR interactions necessitate additional physical movements beyond those required by 2D interfaces [20]. Thus, comprehensively understanding the impact of aging on VR input interaction could potentially help designers and researchers to develop more inclusive VR input interaction techniques for older adults.

In order to gain an in-depth understanding of the user experience of older adults and the effect of aging on direct interactions (e.g., use handheld controllers to reach and contact virtual 3D objects directly) in VR between older and younger adults, we aimed to answer the following research questions (RQs):

- RQ1: How do spatial factors (e.g., target layout, distance from users, and interaction surfaces) affect the interaction performance and user experience of older adults when interacting with VR?
- RQ2: How do their performance and user experience differ from younger adults?

Selection and manipulation have been identified as the most general and fundamental interactions in 2D and 3D interfaces [32]. The present study focused on evaluating these two types of interactions in VR to address the above research concerns. For RQ1, we conducted two comparative user studies in VR (Fig. 1 and Fig. 6) to measure interaction performance such as completion speed, accuracy, and comfort level in object selection and manipulation tasks within spatially distinct VR sub-spaces [10] (e.g., ISO circle in 3D spaces [14, 67]). The findings of these two studies revealed that various interrelated factors, including the spatial arrangement of 3D targets, their dimensions, the proximity between targets and users, as well as the utilization of users' dominant hands for interactions, significantly influence the interaction experiences of older adults in VR. To better answer RQ2, we conducted quantitative data analysis supplemented by qualitative feedback to understand the difference in performance between younger and older participants. The differences in their user experiences and performance in object selection and manipulation tasks demonstrate that older adults tend to be more susceptible to distances that require more physical movements to interact and neck fatigue afterward. Furthermore, compared to younger participants, significantly more task completion time, more adjustment attempts, and decreased accuracy were observed in older participants, which strongly indicates that age-related changes such as vision and cognitive degradation may impose negative influences on the interaction performance of older adults [54, 59]. Lastly, we deliberated on design recommendations for creating aging-friendly interactions in VR, and highlighted potential improvements for future applications and interaction designs with older adults. In summary, the current research has made the following contributions:

- We took a first step to undertake two within-subject user studies to investigate the performance of older adults in both object selection and manipulation tasks in VR, while also comparing their performance and user experience to younger adults. We further highlighted the challenges that older adults may encounter during VR interactions.
- We formulated design recommendations based on our findings through optimizing target layouts and interaction strategy to make VR interaction more accessible and inclusive.

2 RELATED WORK

Our work is mainly inspired by previous research on age-specific interaction difficulties encountered by older adults and evaluations of target selection and manipulation techniques in VR.

2.1 VR and Older Adults

VR has been widely demonstrated to have benefits in promoting older adults' health and physical function. For example, reducing fall rates during treadmill training, enhancing dynamic balance, and improving gait- and balance-related performance, as well as functional balance, mobility, and reaction time [11, 41, 49, 71]. Furthermore, VR has also been found to positively impact older adults' cognitive abilities, with studies showing greater improvements in cognition and executive functions through VR-based cognitive stimulation compared to traditional methods and significant enhancements in memory tests following VR memory training [22, 44]. With respect to the benefits of using VR in social contexts, researchers have examined its potential to facilitate social connections among older adults. This has been accomplished through the development of remote communication and shared activities with friends in VR [4, 6]. The utilization of VR activities between elderly family members and younger generations has also been investigated to promote positive emotions and relationships [68].

Although many VR apps and 3D immersive scenes, like the ones mentioned above, could be beneficial for older adults' daily lives, they tend to adopt default interaction methods, such as hand controllers and in-air gestures, which are not specifically designed or adjusted for ease of use and access by older adults, especially for ones limited by degradation of physical and cognitive abilities [54]. Ljaz et al. conducted a scoping review of previously presented VR applications for older adults and identified a series of challenges and usability issues regarding older adults using VR [29]. Zhao et al. further revealed a range of issues, such as physical discomfort and usability inconveniences reported for older residents needed to be considered when deploying VR systems in aged care settings [79]. The symptoms of motion sickness as one of the most common side effects were found to be more remarkable among older adults compared to younger ones [25]. Negative feedback about the use of head-mounted displays (HMDs) is also highly reported in VR scenarios for older adults. Participants in a handful of studies mainly complained about the weight of HMDs as it affects their overall viewing, head movements, and interaction experiences [27, 50, 51]. Although Baker et al., for instance, reflected on usability issues that pose notable impacts on the aged-care residents' abilities to enjoy interactive VR technology [7], there are limited discussions for understanding and evaluations of difficulties and challenges that arise from interaction activities and use preferences with older adults in VR. The findings of their study also strongly suggest the need for research into interaction challenges that older adults may encounter in VR-related activities for guiding future accessibility designs [7, 51].

2.2 Interaction Barriers of Digital Technology

While VR tools and applications have been tested and utilized broadly for older adults, it is common that those people are excluded from the development and design process, and the digital divide between younger and older people is largely ignored. For example, aging effects play a critical role in diminishing the experiences of digital products [33, 54, 59]. Physical and cognitive declines often pose barriers and hindrances to the usage of digital systems. Around 28% of old adult interviewees in Pew's social study have reported suffering from disabilities, health degradation, or hindrance leading to significantly less use of digital products than those without aged inconvenience [2].

From the perspective of interaction barriers in digital products, previous research works about the effects of aging on interaction tasks have demonstrated that older adults mostly exhibit higher error or missing rates and much longer task completion times in contrast with younger people in target selection tasks such as button clicks, pointing drags, and mouse movements [31, 42, 43]. Sultana et al. further studied the effects of aging on small target selection with touch input to highlight that separated considerations are needed for investigating interaction performance and accessibility among different digital devices for older adults [59]. Gao et al. also demonstrated difficulties and reduced performance for older users through the interaction tasks of rotation and zooming objects on touchscreens [23]. For aspects of interaction barriers more related to motor skills among older people, Liang et al. investigated the age-related issues for usages of hand gesture interface [35]. However, it still remains unclear that interaction difficulties and age-related motor performance of object selection and manipulation tasks within a simulated immersive world. For instance, to what extent of accuracy under different spatial layouts may older adults perform in those interaction tasks using VR controllers. Motivated by the literature and the gaps mentioned above, the present work took a step further to extend the exploration of aging effects on interaction tasks of 2D screen-based digital products to 3D immersive worlds with VR technology [8, 30].

2.3 Evaluation of Object Selection and Manipulation Tasks in VR

VR technology creates a novel interaction paradigm that immerses users in 3D environments and delivers a sense of presence. To improve immersive experiences with engaging and efficient interactions, many surveys on the design of selection and manipulation techniques in VR are put forward [9, 64, 65]. The spatial and immersive features of VR also inspired new forms of 3D user interfaces (e.g., on-body interactions with mid-air gestures [76], gaze-supported [55, 75], and eye-free target [72]), multi-target acquisition [70], interaction designs for occluded target selection [34, 77] and distant object manipulations [46], and social interactions [56, 60].

Understanding the impact of a newly proposed technique on user experience is essential. Hence, many thorough evaluations have been conducted to gain a comprehensive understanding of its practical usability and accessibility [13, 32]. Bergström et al. reviewed 20 years of studies on VR object selection and manipulation tasks with the purposes of building standards and a checklist for researchers planning object selecting and manipulation studies [10]. Research on object selection in VR investigated and recommended independent and dependent variables for the assessment of human performance (e.g., miss errors, learning time, selection areas, feedback types, and use preferences) [3, 37, 74]. Previous research also explored experiment designs of how to measure human performances in VR-based interaction tasks with quantitative and qualitative analysis [40, 78]. For instance, Yu et al. suggested rendering more visual hints in selection tasks for indications of targets and highlighting pointing directions [73]; Lou et al. shed light on empirical experiments designs of hand controller interaction evaluations with considerations of arm posture influences [36]; Poupyrev et al. built comparative studies to discuss and understand relative strength and weakness among object manipulation properties in immersive VR [47]. However, there is a dearth of research on interaction evaluations and performance analysis of VR applications that are tailored to specific target users, particularly older adults.

As previously discussed, elderly individuals experiencing age-related declines in motor functionality and degradation of cognitive conditions are limited to fully participating in technology-centered activities [53, 59]. Fan et al. studied recent papers in a list of HCI venues and found that less than one percent of VR-related papers were conducted with older adults [20]. Recent studies also demonstrated that simulated immersive scenarios may not be equally accessible for elderly people due to general interaction design issues [23, 79], but no further user studies were performed to rigorously evaluate the accessibility caused by age-related changes among older adults for experiencing VR applications. Moreover, the digital divide that significantly influences on usage differences between younger and older adults may prevent older adults from acquiring similar levels of benefits through immersive VR scenes in their everyday lives [16, 53].

To bridge this research gap, the present study conducted a two-phase comparative and exploratory investigation aimed at examining the motor space performance and interaction experience of older adults. We sought to provide insights on design improvements for object selection and manipulation tasks to inspire and guide future interactive applications within VR for older individuals.

3 USER STUDY 1: OBJECT SELECTION

In this study, we aimed to evaluate the performance and accessibility of different spatial factors (i.e., position) in VR space. Specifically, we evaluated and compared the object selection performance between older and younger adults. Our research received ethical approval from our institution.

3.1 Participants

We recruited 18 older adults (10 female and 8 male, aged 60–85) and 18 younger adults (9 female and 9 male, aged 20–30), all of whom self-reported as right-handed, with no motor impairments, and as having normal or corrected-to-normal vision. Participants self-reported their familiarity levels with VR, and all of them had no or limited knowledge of VR (older adult mean = 1, younger adult mean = 3, on a 5-point Likert scale).

3.2 Apparatus

The VR environments in the present study were designed in Unity Engine and displayed via an Oculus Quest 2 headset with a per-eye resolution of 1832 × 1920, a refresh rate up to 120 Hz and tracking precision less than 0.1mm [28]. All the participants were instructed to utilize touch controllers on both hands to perform selection tasks.

3.3 Experiment Overview

Fig. 1 shows the study overview, including visualization of independent variables (IVs) and participants. We adopted a $3 \times 5 \times 5 \times 3 \times 3$ within-subject design with three repetitions and the following four IVs based on the guidelines of interaction evaluations in VR [10]:

- *Horizontal Offset (-60°, -30°, 0°, 30°, 60°)*: The *horizontal offset* from the participant's perspective. We selected *30°* as the level since it represents a range of positions and at the same time minimizes the number of trials.
- *Vertical Offset (-60°, -30°, 0°, 30°, 60°)*: The *vertical offset* from the participant's perspective
- *Distance (0.45 m, 0.6 m, and 0.75 m)*: The *distance* from the center point to the target. The chosen distance was based on the average arm length, representing the condition of easily reaching targets with the following postures: half-bent arm, stretched arm, and slightly leaning forward.
- *Size (1°, 2°, 3°)*: The *size* of targets in visual angles

To ensure the distance was consistent in each position, we placed the targets according to the updated sitting position of each participant in VR under Cartesian coordinates (Fig. 1a). Each trial employed a single target, and participants were instructed to move on to the next trial by touching the "re-home" object (Fig. 1b), which was located near the belly of participants. This contributed to the consistency of each trial's starting point. We recorded both task performance and participants' subjective feedback:

- *Spatial Deviation (i.e., Error)*: The *Spatial Deviation* is defined as the distance between the position that the participant clicked at and the target position. The deviation is marked as $0.0m$ if the participant selects the target successfully.
- *Completion Time*: The time from the start of the trials till the participants trigger the confirmed selection.
- *Subjective Rating*: We measured the workload of the task using the NASA-TLX questionnaire and an additional question that assessed the comfort level of each position on a 7-point Likert scale.

3.4 Procedure

The study lasted approximately 150 minutes for older participants and 120 minutes for younger participants. Before formal trials, participants filled in a questionnaire to collect their demographic information. They were introduced to the experiment setup and signed a consent form. Next, they were invited to wear a headset and were given around 5 minutes to familiarize themselves with VR where they could look around the simulated experimental environment. Once they entered the experimental environment, we introduced an additional calibration phase to ensure the targets were generated precisely in their facing directions. To do so, we asked participants to make a click at the center point in front of their necks, as Fig. 1a shown. The whole study was separated into three sessions by the three distance conditions as mentioned in Sec. 3.3. The order of these sessions was counterbalanced by Latin Square, and the order of each trial inside each session was randomized. Participants were asked to fill in another questionnaire after completing each session, where their subjective feedback on workload using the NASA-TLX questionnaire and an additional question that reported their comfort level for each position. Participants had enough rest time to relax at the end of each session. We also conducted a semi-structured interview on their experience at the end of the study.

3.5 Data Analysis

In total, 24,300 data points were collected (36 participants×3 distance× 5 horizontal offset×5 vertical offset×3 size×3 repetition) from the experiment. We first removed 445 trials (199 trials for older participants and 246 trials for younger participants) of outliers, in which the completion time was above three standard deviations from the mean in each distance condition. Upon eliminating the outliers, the Shapiro-Wilk normality test was executed, revealing that the data did not follow a normal distribution. Consequently, the Aligned Rank Transform was employed to pre-process the data [19, 69]. Subsequently, repeated-measures ANOVA (RM-ANOVA) and ART-based pairwise comparisons were conducted to assess the performance and user experiences across age groups. In the subsequent sections, the analytic emphasis is placed on the main effects and two-way interaction effects associated with distance, horizontal and vertical positions, and age differences. This focus aligns with the primary objective of investigating the experiential differences between age groups when interacting in varying spatial positions.

3.6 Results

In this section, we show the difference in performance between older and younger participants and how different factors affect their performance. To better understand the result, we support statistical results with participants' qualitative feedback, which is annotated with additional contextual information in the form of (participant ID, age, gender).

Performance Comparison with Younger Adults. RM-ANOVA indicated that *Age* and *Vertical Offsets* as interrelated factors significantly affect the *Spatial Deviation* ($F_{4,23371} = 982, p < .001$). Interaction effects between *Age* and *Horizontal Offsets* were also identified ($F_{4,23371} = 945.7, p < .001$). Besides, significant interaction effects were found between *Age* and *Distance* ($F_{2,23371} = 1603.4, p < .001$), and between *Age* and *Size* ($F_{2,23371} = 531.3, p < .001$).

Spatial Deviation (i.e., Error). RM-ANOVA results showed that all variables significantly affected the *Spatial Deviation* of the acquisitions for older participants (*Distance*: $F_{2,11709} = 69.3, p < .001$;*Horizontal Offset*: $F_{4,11709} = 35.9, p < .001$; *Vertical Offset*: $F_{4,11709} = 64.4, p < .001$; *Size*: $F_{2,11709} = 9.2, p < .001$). Post-hoc test confirmed that *Spatial Deviation* increased as *Horizontal and Vertical Offsets* augmented as shown in Figure 2. And the *Spatial Deviation* at the *Distance* of $0.75\ M$ was significantly larger than those at

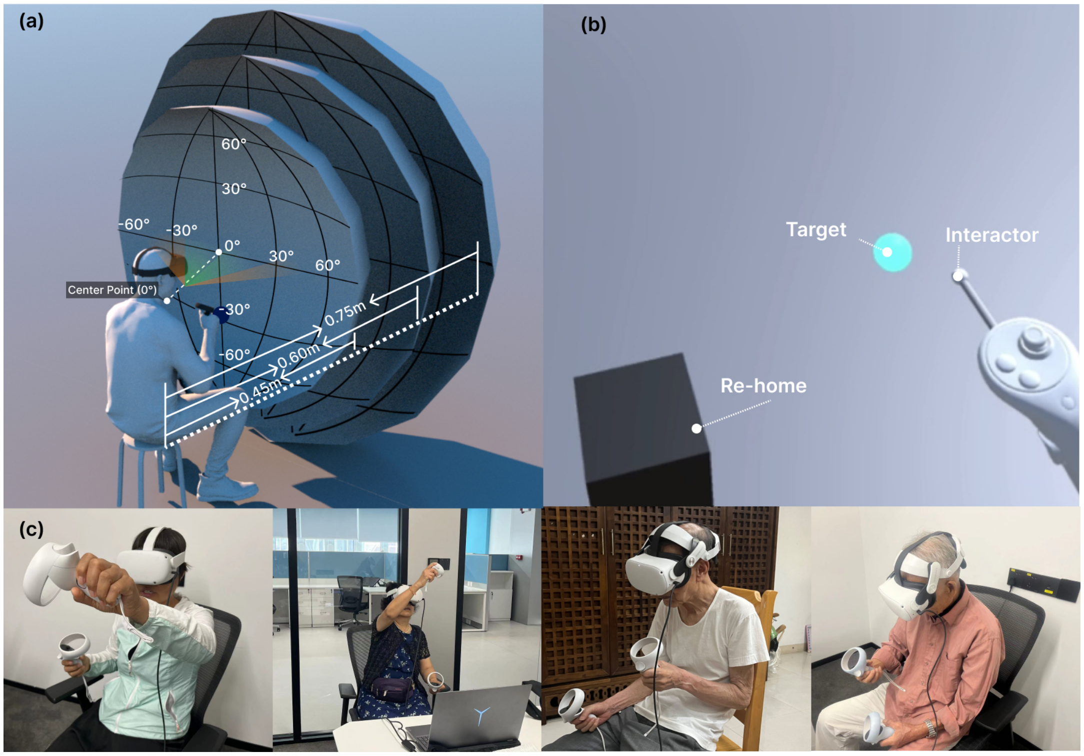


Figure 1: Overview of study 1: (a) Experiment settings. The three virtual hemispheres represent the three distance levels of the target position. The horizontal and vertical spatial offsets were labeled. The targets were generated at the intersections of the lines marked on the hemispheres. The target is generated based on the center point. (b) Screenshots for the VR task scenes. The sphere was the target for this trial. The black cube represents the Re-home button. Participants were asked to touch and select the target by the interactor of the controller. (c) Some older adult participants completing tasks in Study 1

0.45 *M* and 0.6 *M* (p < 0.0001). This is in line with the participants' subjective feedback, where older adult participants felt that targets were hard to select when their locations were largely varied in the vertical direction. Also, though no discomfort was reported when the amplitude of horizontal variations was large(i.e., on the most left or right), two of the older participants still reported that *"it was hard to select the targets precisely, especially it appeared on the left side (i.e., non-dominant side)."* (O4, 65, F). RM-ANOVA results showed that all variables significantly affected the *Spatial Deviation* of the acquisition task for younger participants as well (*Distant*: $F_{2,11662} = 15.6, p < .001$;*Horizontal Offset*: $F_{4,11662} = 221.4, p < .001$; *Vertical Offset*: $F_{4,11662} = 182.2, p < .001$; *Size*: $F_{2,11662} = 35.8, p < .001$). Similar to the older participants, the *Spatial Deviation* for younger participants increased as *Horizontal and Vertical Offsets* increased.

Completion Time. RM-ANOVA results showed that all variables significantly affected the duration of the acquisition tasks for older participants (*Distance*: $F_{2,11709} = 290.5, p < .001$; *Horizontal Offset*: $F_{4,11709} = 271.8, p < .001$; *Vertical Offset*: $F_{4,11709} = 151.3, p < .001$; *Size*: $F_{2,11709} = 189.6, p < .001$). Post-hoc test confirmed that *Completion Time* increased as *Horizontal Offset* and *Vertical Offsets* enlarged as shown in Figure 4. This might be due to the continuing deliberations of selection tasks in spatial variations of vertical and horizontal directions, which causes extra time for them to react and reach. Specifically, One older participator emphasized that he felt less confident in selecting the targets located at the upper position as he explained, *"it was difficult to pinpoint them precisely"* (O5, 64, M), while it was less comfortable but more precise to select targets at the lower position. He elaborated: *"I could observe the targets closely by bending down"* (O12, 70, M). It was also interesting to observe that older participants stayed around for a few seconds near the target before clicking the button to confirm selections, while younger participants showed less hesitance. Besides, older participants attempted to click many times on buttons when using the left hand to confirm selections, while less number of clicks were observed when controlling with the right hand. Comparably, the *Completion Time* increased as the *Object Size* shrank and *Distance* increased. RM-ANOVA results showed that all variables significantly affected the *Spatial Deviation* of the acquisition task for younger participants as well (*Distant*: $F_{2,11662} = 749.9, p < .001$;*Horizontal Offset*: $F_{4,11662} = 739.6, p < .001$; *Vertical Offset*: $F_{4,11662} = 404.1, p < .001$; *Size*: $F_{2,11662} = 201.4, p < .001$).

Correlation. We found a positive correlation between the *Spatial Deviation* and the *Comfort Rating* in the *Vertical Offset* when the *Distance* is equal to 0.75m, as shown in the Fig. 5, supported by a Point-Biserial test (correlation = 0.92, p = 0.02).

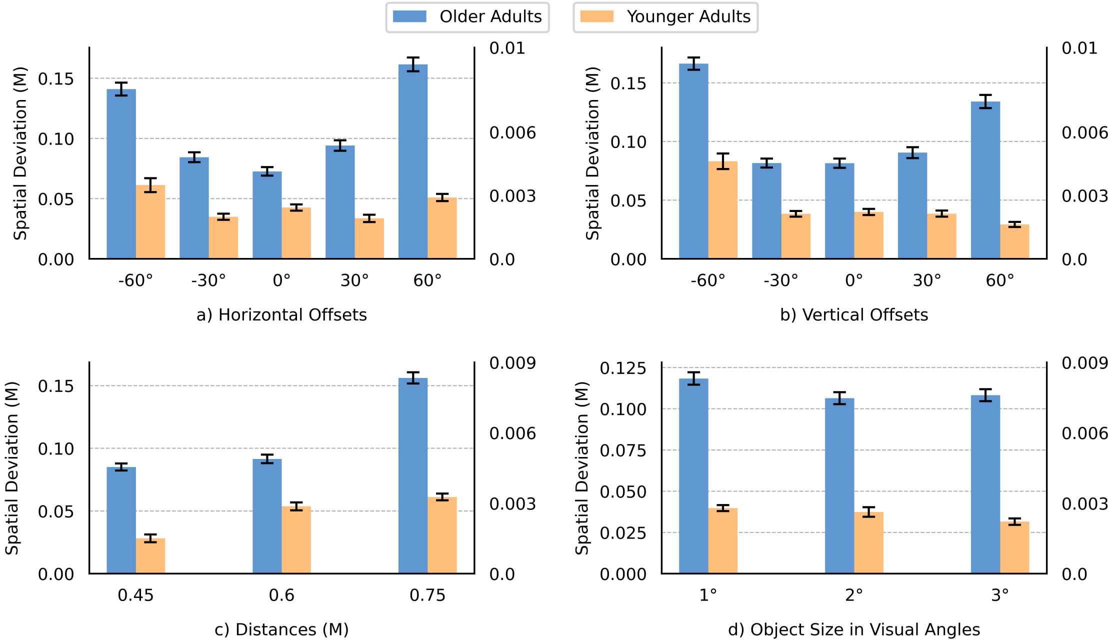


Figure 2: The summary of spatial deviation for each independent variable for older (left y-axis) and younger (right y-axis) participants. (a) The effect of horizontal offsets and age on the spatial deviation. (b) The effect of vertical offsets and age on the spatial deviation. (c) The effect of distance of targets and age on the spatial deviation. (d) The effect of object size and age on the spatial deviation. The error bar shows the standard error.

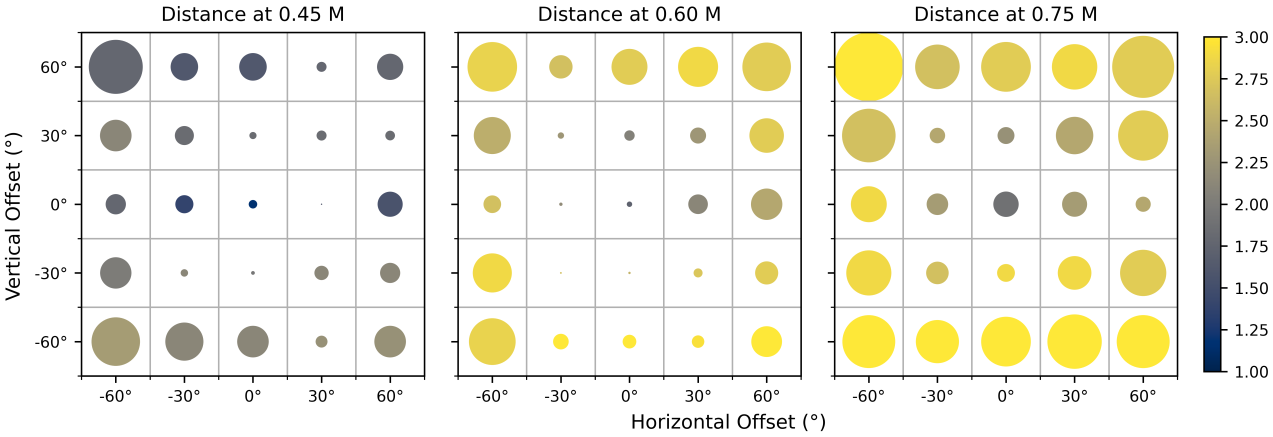


Figure 3: Summary of the spatial deviation and comfort level of older adults. The circle size represents the error deviation in meters of each position (i.e., a combination of a horizontal offset and a vertical offset in degrees in study 1). The color represents the comfort level of each position. The higher score represents the lower comfort level.

***Comfort Level* Analysis.** RM-ANOVA results showed that all the following IVs significantly affected the comfort level of the acquisitions for older participants (*Distance*: $F_{2,1258} = 277.8440, p < .001$; *Horizontal Offset*: $F_{4,1258} = 5.0899, p < .001$; *Vertical Offset*: $F_{4,1258} = 83.1242, p < .001$). Specifically, four older participants commented that arm fatigue was introduced when the target was located at an upper position, while neck discomfort was reported when the target was in a lower position. They mentioned amplified discomfort when selecting targets that were outside the field of view (FOV). One of them felt *"more head movement when searching and incurred sickness as well"* (O4, 65, F). RM-ANOVA result also showed *Distance* and *Vertical Offset* have significantly affected the comfort level of the acquisition for younger participants (*Distance*: $F_{2,1258} = 191.8, p < .001$; *Vertical Offset*: $F_{4,1258} = 41.2, p < .001$).

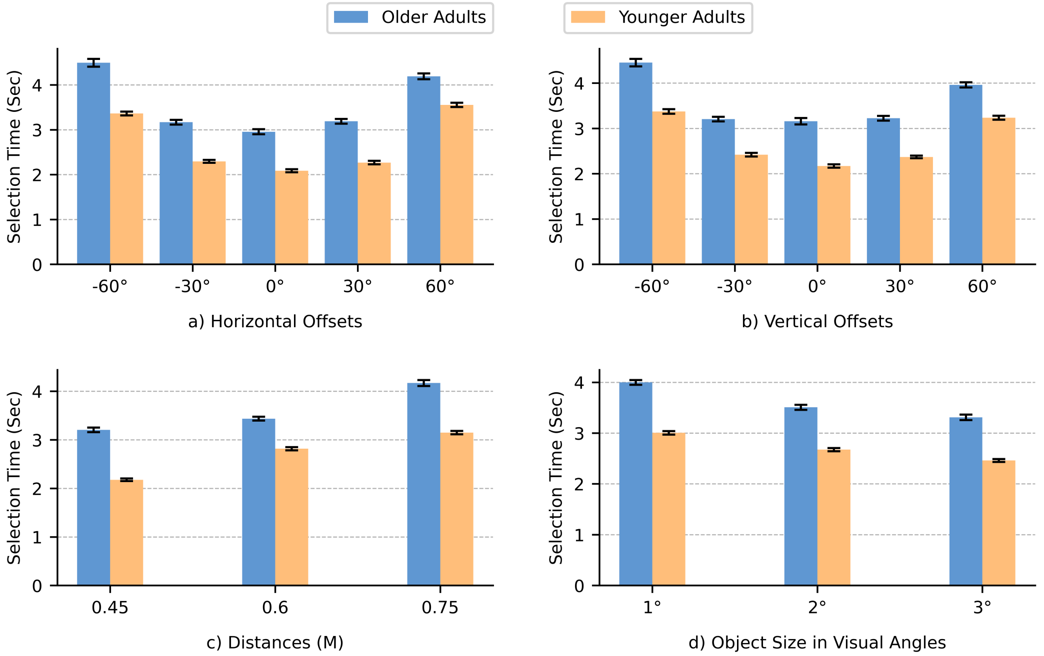


Figure 4: (a) The effect of horizontal offsets and age on the selection task completion time. (b) The effect of vertical offsets and age on the selection task completion time. (c) The effect of target distances and age on the selection task completion time. (d) The effect of object size and age on the selection task completion time. Error bars show the standard error.

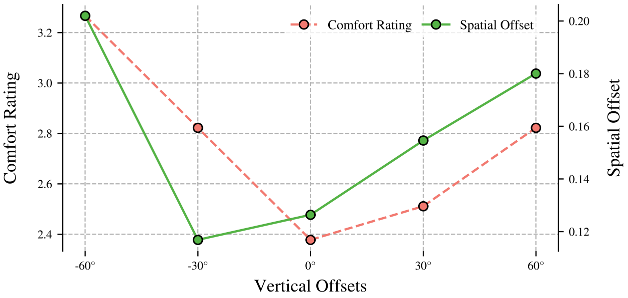


Figure 5: Summary of the correlation between spatial offset and comfort level across vertical offsets at a distance of $0.75m$. The lower score of comfort rating represents the more comfortable for older adults to reach.

3.7 Summary and Discussion

Based on the statistical test results and qualitative feedback above, we further summarized the key findings and discussed on their novelty and implications.

3.7.1 Older Adults' Target Selection Performance in VR.

We derived the following five key findings related to older adults' target selection performance and experiences in VR.

Target layout (vertical and horizontal offsets) significantly impacts selection performance. In general, the study found that targets located exactly in front of the participants were the most accurate, least time-consuming, and most comfortable to select. An almost symmetric trend was observed for horizontal offsets. Conversely, targets situated at lower positions demonstrated significantly worse performance than those located at upper positions. This discrepancy may be attributed to the discomfort experienced by participants when selecting targets at lower positions, which significantly affected their accuracy. The study's findings are consistent with Lou et al.'s research, which similarly observed that arm fatigue resulted in low accuracy when selecting targets at upper positions [36]. However, in contrast to their findings, the present study identified that participants were significantly uncomfortable when selecting targets at lower positions in VR, leading to worse performance. Possible reasons for this discomfort include the headset's weight, in which the weight of the headset applied additional force in the vertical direction, thereby incurring additional effort to perform head movements upside-down [7, 29].

The distance between the target and the user has significantly affected the selection performance. Particularly when the target was located beyond the arm-reach distance and required participants to lean forward to reach it, the performance was significantly worse than in the other two conditions. The study identified two potential reasons for this diminished performance. Firstly, the more distant target necessitated greater physical demand than the others, involving additional body movements (e.g., arm stretching, leaning forward). Secondly, participants made increased search efforts in more distant conditions. Furthermore, the distance between participants and targets influenced the perception of object size, as the portion of targets on the screen decreased with increasing distance due to perspective projection [39].

While older adult participants held two controllers in two hands, they preferred using their dominant hand only to perform selection tasks. In contrast to Lou's findings, which suggest that participants tend to select targets using the same side of the hand (i.e., selecting left targets using the left hand and right targets using the right hand) [36], our study discovered that older participants faced difficulties when using controllers with their non-dominant hand. Specifically, these participants attempted to press undesired multiple times on buttons while trying to select targets using the left controller, and they preferred to use the right controller to select objects even around the left part of their bodies, indicating a challenge in mastering the use of non-dominant hand controllers for target selection tasks.

The error deviation and comfort level positively correlated along vertical position in the farthest distance condition. This finding suggests that comfort level has a significant impact on the accuracy of target selection. In line with participants' feedback, the lower position imposes extra physical movements, resulting in a lower comfort rating. However, we did not observe a strong correlation between the error deviation and comfort rating for the closer distances. This lack of correlation may be attributed to factors besides the aforementioned ones, such as the obstructions caused by the participants' bodies and the chairs they were seated in.

3.7.2 Performance Comparison with Younger Adult.

We derived the following four insights while comparing the performance of older adult participants with younger adult participants.

Older participants tended to feel more physical strain caused on the neck. Our study identified that the most frequently reported feedback from older adults was neck fatigue, which younger participants rarely mentioned. Based on their qualitative feedback, older adults perceived excessive physical efforts on their necks while searching for targets, particularly those outside their field of view. This issue may be attributed to age-related health degradation, which results in decreased neck flexibility [48]. Consequently, our observations revealed that two participants experienced difficulty locating out-of-view targets, although they had been informed of the spatial layouts of targets, further highlighting the impact of age-related changes on spatial searching performance.

Older participants were more susceptible to distance. We further observed that the performance of older participants was more easily affected by distance changes compared to younger participants. The time cost and error deviation notably increased with distance for older participants, particularly in the 0.75 *m* distance condition. This susceptibility might be attributed to the physical degradation of older adults, which limits their flexibility while moving their upper body [7, 29]. Specifically, we noticed a phenomenon of "unable to reach" among a few older participants, which was restricted by their body condition and concerns, although they reported healthy states during experiments. Two participants tried to point to the targets instead of adjusting their posture (e.g., leaning) to really reach them. One of them commented that *"I felt unsafe to do so due to spinal injuries ten years ago, though I have fully recovered from it"* (O8, 85, M). This issue did not occur among younger participants. However, two younger participants with longer arm spans (185 *cm*) who commented that *"I felt uncomfortable to reach the targets in the closest distance, cause I need to twist my arm uncomfortably"* (Y5, 24, M). These phenomenons suggest a clear distinction between age groups in terms of distance-related performance in target selection tasks.

Both older and younger participants were frustrated about acquiring targets closely around their bodies. During this stage of experiments, both statistical results and qualitative feedback indicated that it was difficult and frustrating for older and younger participants to select targets around their bodies. Despite controlling the experimental environment, participants still encountered unavoidable obstacles caused by the chair in which they were seated and their bodies, particularly for targets situated at lower positions, which they report *"Sometimes I felt something blocking my hand when I was reaching the target, such as the chair or my body, but I can not realize it since I completely immerse in the virtual environment" (Y10, 23, F).* Participants expressed frustration about not noticing these physical obstacles in the real world until making contact with them, as they were not displayed in virtual environments. Consequently, participants had to adjust their body movements to acquire the targets, such as moving their thighs or bending down to avoid touching the chair when the targets appeared near or under it.

Older participants took more time to complete the target acquisition tasks. In accordance with Fitt's law, we observed that selection time increased with enlarged distance and decreased target size for both younger and older participants [21, 57]. Furthermore, we noted that older participants were more susceptible to all IVs and took significantly more time than younger participants, consistent with the findings of Sultana and Moffatt's work [42, 59]. Two distinct rationales can be consolidated to elucidate this particular observation. First, age-related changes may require extra physical effort for older participants when selecting targets that are farther, smaller, and non-egocentric. Second, older participants' tendency to linger around targets before confirming their selection may have led to significantly longer time for location perceptions.

4 USER STUDY 2: OBJECT MANIPULATION

The objective of this study was to examine The performance and difference of single-handed and bi-manual object manipulation with older and younger adults under different spatial factors (i.e., position, interaction surface).

4.1 Participants

We recruited 16 older (9 female and 7 male, aged 60–85, 4 of them had taken part in the first part of the study, and 2 of them had quit during the study and were removed for further analysis) and 14 younger adults (6 female and 8 male, aged 20–30, 6 of them had taken part in the first part of the study), all of whom self-reported as right-handed, with no motor impairments, and as having normal or corrected-to-normal vision. Participants self-reported their familiarity levels with VR, and all of them had no or limited knowledge of VR (older adult mean = 1, younger adult mean = 3, on a 5-point Likert scale).

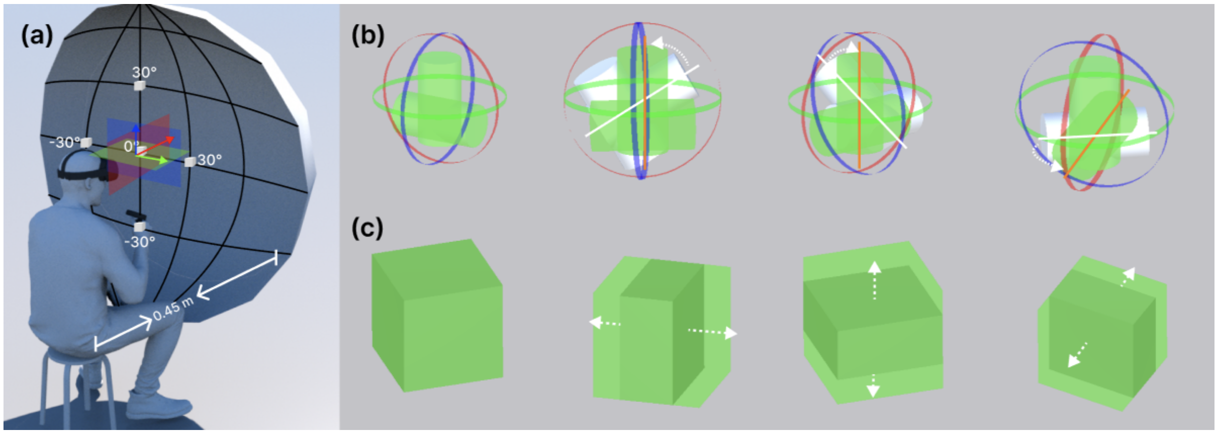


Figure 6: Overview of study 2: (a) Experiment settings. The cube indicated the position that the objects generated (i.e., top, left, central, right, bottom) at the distance of $0.45m$ from participants. (b) Rotation task. The green semi-transparent shape represents the target rotation angle. The four sub-graphs represent the completion state, the rotation around the horizontal surface, the vertical surface and the depth surface respectively. (c) Scaling task. The green semi-transparent shape represents the target scale size. The four sub-graphs represent the completion states: the scaling at the horizontal surface, the scaling at the vertical surface, and the scaling at the depth surface respectively.

4.2 Experiment Overview

We utilized equipment and apparatus identical to those in Study 1. We employed two types of within-subject object manipulation tasks in this study, including object rotation and scaling. For the rotation task, we incorporated three varying factors:

- *Interaction Surface (horizontal, vertical, and depth surface)*: The surface on which the manipulation happened, as shown in figure 6(a).
- *Position (left, right, central, top, bottom)*: The *position* where the object is located. The central was located at the front of the participants, and all the other *position* have a 30° spatial deviation from the central point.
- *Inclination (30°, 60° , 90°)*: The *inclination* angle that the object deviated from its target rotation.

Trials for the scaling task consisted of two repetitions and three varying factors:

- *Interaction Surface (horizontal, vertical and depth surface)*: Follow the same designs as the rotation task.
- *Position (left, right, central, top, bottom)*: Follow the same designs as the rotation task.
- *Scale Size (*×1.5, ×0.5*)*: The relative object size that the participants were asked to adjust towards. The designed target size of the object was its original size ×1.5 or ×0.5 as shown in figure 6.

Based on the result from study 1, the deviation angle at 60° both horizontally and vertically incurs significantly lower accuracy and reduced comfort level. Hence, we chose the 30° as the maximum deviation angle. The target distance from participants was set at 0.45 *m*. To maintain distance consistency in each varied position of the object, similar refinements that have been applied to Study 1 were utilized, corresponding to the designated Cartesian Coordinates. The object was inclined or scaled towards the designed rotation and size, with a semi-transparent shadow indicating the manipulation targets.

Upon self-perceived task completion, participants could forward to the subsequent task by clicking the "re-home" cube. Task performance, manipulation strategy, and participants' subjective feedback were documented:

- *Spatial Deviation (i.e., Error)*: The angular deviation for the rotation task between the last adjustment and the intended object rotation. The size deviation for scaling tasks between the last adjustment and the intended object size.
- *Completion Time*: The time from the start of the trials till the time that participants lastly adjust the object.
- *Attempt*: The number of times that participants have adjusted the object.
- *Adjustments per Attempt*: The amount of transformation adjustments for each attempt.
- *Subjective Rating*: We measured the workload of the task using the NASA-TLX questionnaire and an additional question that assessed the comfort level of each position on a 7-point Likert scale.

The manipulation operations required by all the trials were set to one degree of freedom (DOF) to minimize the effect of additional complexity and spatial ability of individuals [17].

4.3 Procedure

Each participant completed 150 trials of object manipulation, consisting of 90 target rotation tasks and 60 target scaling tasks. At the beginning of the study, participants were briefed on its objectives and given time to become familiar with immersive environments. Prior to the start of the experiment, participants received instructions and were afforded ample time to practice each interaction technique. A calibration process similar to Study 1 was also introduced. Upon the end of each session, participants received sufficient break time and completed a post-test questionnaire. Semi-structured interviews were conducted following the completion of all trials to gain deeper insights into their experiences. The entire study required approximately 90 minutes for older participants and 50 minutes for younger participants to finish.

4.4 Data Analysis

In total, 4,200 data points were collected (28 participants × 5 position × 3 interaction surface × 3 rotation inclination × 2 repetition + 28 participant × 5 position × 3 interaction surface × 2 scale size × 2 repetition) from the experiments. We first removed 157 trials (138 trials from the rotation tasks and 19 trials from the scaling tasks) of outliers, in which the completion time was above three standard deviations from the mean in each condition. Upon eliminating the outliers, we perform a normality test and repeated-measures ANOVA as Study 1. The analytic emphasis is placed on the main effects and two-way interaction effects associated with target layout, interaction surface, and age difference.

4.5 Results

In the following section, we demonstrated the difference in performance between older and younger participants for the rotation and scaling tasks and how different factors affect their performance. We incorporated qualitative feedback from participants with the statistical results.

4.5.1 Performance Measures - Rotation.

Angular Offset. For older participants, RM-ANOVA results showed that the *Rotate Surface* has a significant effect on the *Angular Offset* for the rotation task ($F_{2,1067} = 312.2, p < .001$), with the vertical surface having significant lower accuracy than the other two surfaces. Besides, an effect of the *Position* on *Angular Offset* has been identified ($F_{4,1067} = 61.1, p < .001$), with the right and top having a significantly lower accuracy than the others as figure 7 shows. Similarly, for younger participants, RM-ANOVA results showed that the *Rotate Surface* has a significant effect on the *Angular Offset* for the rotation task ($F_{2,1198} = 214.4, p < .001$), and an effect of the *Position* on *Angular Offset* has also been identified ($F_{4,1198} = 170.4, p < .001$).

Completion Time. For older participants, RM-ANOVA results showed that the *Rotate Surface* of the target has a significant effect on the *Completion Time* for the rotation task ($F_{2,1067} = 15.8, p < .001$), with the horizontal surface costing significantly less time than the other two surfaces. Also, an effect of *Position* on *Completion Time* has also been identified ($F_{4,1067} = 5.2, p < .001$), in which the target locating at central costs less time. Similarly, for younger participants, RM-ANOVA results showed that the *Rotate Surface* has a significant effect on the *Angular Offset* for the rotation task ($F_{2,1198} = 57, p < .001$), and an effect of the *Position* on *Angular Offset* has also been identified ($F_{4,1198} = 11.7, p < .001$).

4.5.2 Strategy Measures - Rotation.

Attempt No. For older participants, RM-ANOVA results showed that *Rotate Surface* have effect on the *Attempt Times* for the rotation task ($F_{2,1067} = 41.2, p < .01$). For younger participants, RM-ANOVA results showed that the *Rotate Surface* have significant effect on the *Angular Offset* for the rotation task ($F_{2,1198} = 65.4, p < .001$), and an effect of the *Position* on *Angular Offset* has also been identified ($F_{4,1198} = 5.6, p < .001$), as shown in figure 8.

Adjustment Amount per Attempt. For older participants, RM-ANOVA results showed that the *Position* of target has a significant effect on the *Adjustment Amount per Attempt* for the rotation task ($F_{4,1067} = 13.9, p < .001$). Besides, a significant effect of *Rotation Surface* has been identified ($F_{2,1067} = 175.3, p < .001$), with the horizontal surface exhibiting the highest amount of adjustment per attempt. For younger participants, a effect of *Rotation Surface* has been identified ($F_{2,1198} = 246.2, p < .001$).

4.5.3 Subjective Measures - Rotation.

Comfort Level. RM-ANOVA results showed that the *Position* of target has a significant effect on the *Comfort Level* for the rotation task ($F_{4,182} = 100.5, p < .01$), four older and two younger participants remarked that rotating targets on top was demanding, where they needed to keep their arms lifting when rotating it. Also, a significant effect of *Interaction Surfaces* has been identified ($F_{2,182} = 1252, p < .01$).

4.5.4 Performance Measures - Scale.

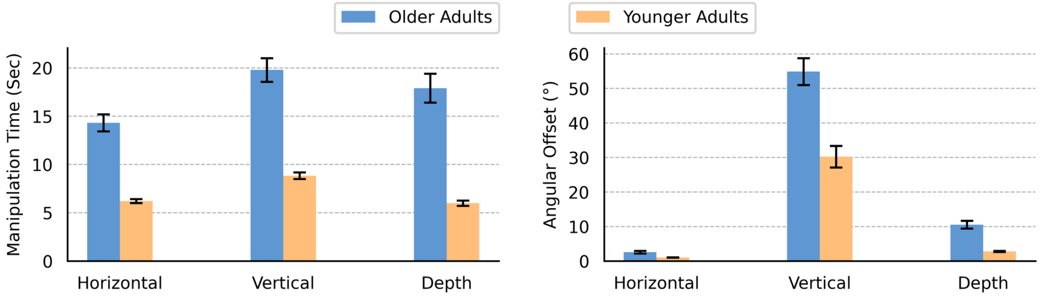
Scale Offset. For older participants, RM-ANOVA results showed that the *Positions* have an effect on the *Scale Offset* for the scaling task ($F_{4,785} = 4.7, p < .001$). Besides, a significant effect of *Scale Surface* on *Scale Offset* has been identified ($F_{2,786} = 4.7, p = .009$), with the vertical surface showing a lower offset compare to the other two surfaces, as shown in figure 7. Similarly, for younger participants, RM-ANOVA results showed that the *Scale Surface* have significant effect on the *Scale Offset* for the rotation task ($F_{2,792} = 28.2, p < .001$), and an effect of the *Position* on *Scale Offset* has also been identified ($F_{4,792} = 2.8, p = .03$).

Completion Time. RM-ANOVA results showed that the *scaling surface* of the target has a significant effect on the *Scale Offset* for the scaling task ($F_{2,786} = 18.8, p < .001$). For younger participants, RM-ANOVA results showed that the *Scale Surface* has a significant effect on the *Scale Offset* for the rotation task ($F_{2,792} = 21.6, p < .001$), and an effect of the *Position* on *Scale Offset* has also been identified ($F_{4,792} = 2.5, p = .04$).

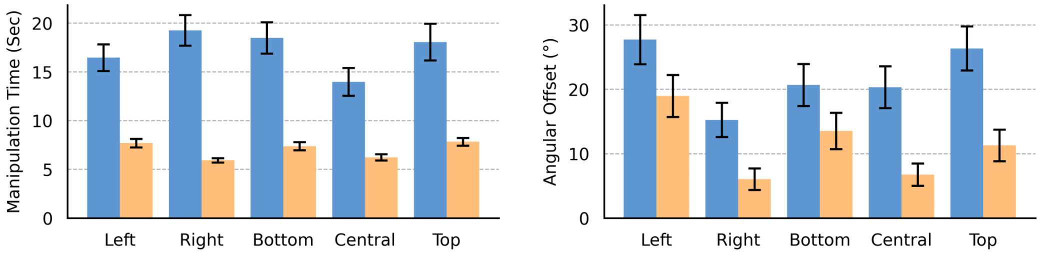
4.5.5 Strategy Measures - Scale.

Attempt no. RM-ANOVA results showed the *Scale Surfaces* have a significant effect on the *Attempt Times* for the scaling task ($F_{2,785} = 27, p < .001$), as shown in figure 8. Eight older participants and three younger participants reported it was difficult to see hand movement on the depth surface. Indeed, we found that older participants tend to make more intermittent and discontinuous movements from the original moving track on the depth surface than on the other two surfaces, resulting in more attempts on this surface.

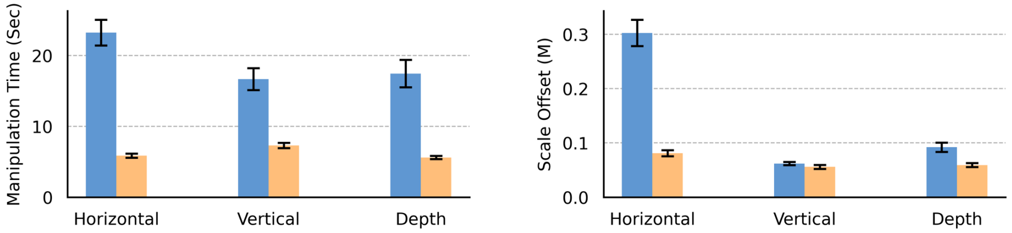
Adjustment Amount per Attempt. RM-ANOVA results showed that the *Scaling Surface* have a significant effect on the *Adjustment Amount per Attempt* for the scaling task ($F_{2,785} = 115.9, p < .001$). Also, an effect of *Position* on *Adjustment Amount per Attempt* have been identified ($F_{4,785} = 5.6, p < .001$). For younger participants, a significant effect of *Scale Surface* on *Adjustment Amount per Attempt* has been found ($F_{2,792} = 26, p < .001$).



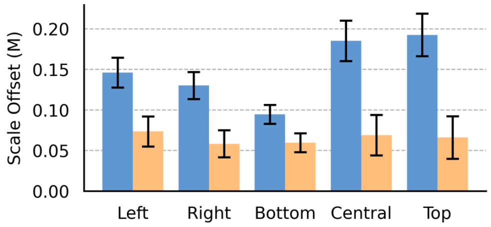
a) Rotation Tasks on Interaction Surfaces



b) Rotation Tasks on Spatial Positions



c) Scaling Tasks on Interaction Surfaces



d) Scaling Tasks on Spatial Positions

Figure 7: The summary of performance for each independent variable for older and younger participants. a) Rotation task on interaction surfaces: (left) The manipulation time for the rotation task on each surface, and (right) the angular offset (i.e., error) for the rotation task on each surface. b) Rotation task on Spatial Positions: (left) the manipulation time for rotation task on each position, and (right) the angular offset for rotation task on each position. c) Scaling task on interaction surfaces: (left) the manipulation time for the scaling task on each surface, and (right) the Scale Offset (i.e., error) for the scaling task on each surface. d) Scaling task on Spatial Positions: the scale offset for the scaling task on each position. Error bars show standard errors.

4.5.6 Subjective Measures - Scale.

Comfort Level. RM-ANOVA results showed that the *Position of the target* has a significant effect on the *Comfort Level* for the scaling task ($F_{4,182} = 60.2, p < .01$). In addition, a significant effect of *Scaling Surface* has been identified ($F_{2,182} = 177.7, p < .01$). Similar to the rotation task, participants expressed weariness from managing the target at the top.

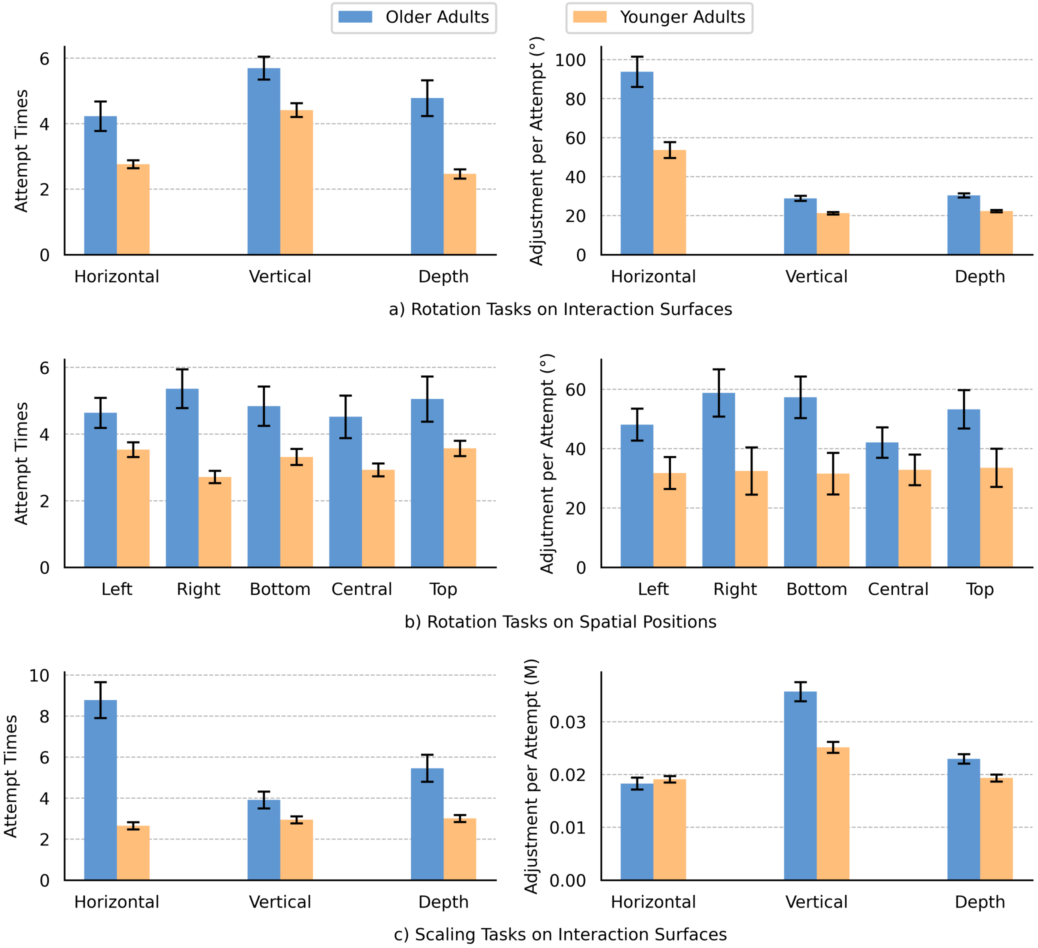


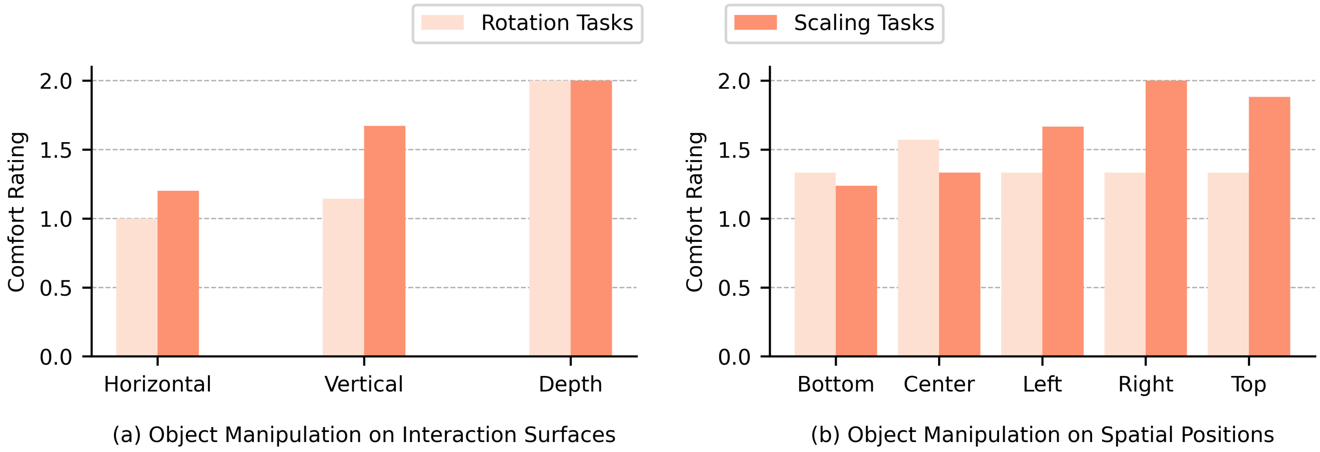
Figure 8: The summary of the number of attempts and adjustment per attempt for older and younger participants in rotation tasks. (a) Rotation tasks on interaction surfaces: (left) the number of rotation attempts on each interaction surface, and (right) The amount of adjustment per attempt on each interaction surface. (b) Rotation tasks on spatial positions: (left) the number of rotation attempts on each Position, and (right) the amount of adjusting rotation per attempt on each position. (c) Scaling tasks on interaction surfaces: (left) the number of scale attempts on each interaction surface, and (right) the amount of adjusting scale per attempt on each interaction surface. Error bars show the standard errors.

4.6 Summary and Discussion

In general, consistent with Study 1, older adults exhibit significantly worse performance in completing both rotation and scaling tasks. This may be attributed to the decline in motor control ability from age-related changes, such as tremors and reduced muscle strength [24]. In addition to motor control deterioration, older adults face vision decay challenges, which can further affect their poorer performance in rotation and scaling tasks. Age-related changes in eyes, such as decreased visual acuity, contrast sensitivity, and depth perception, can make it difficult for older individuals to perceive and interpret visual information accurately [45].

With regard to rotation surface, both younger and older participants demonstrated similar performance trends, with the vertical surface requiring significantly more time and yielding lower accuracy than the other two axes. This may be due to participants' inability to observe their hand movements clearly and difficulty in perceiving the correct movement gestures when completing the rolling task (i.e., rotating around the vertical surface), ultimately resulting in movements that are not on the correct track. Furthermore, targets are difficult to observe for older participants when the rotation happens on the depth surface, where they mentioned that due to perspective difficulties, it was particularly difficult to see targets that had been rotated 90° in the depth surface. This may be due to the visual display perspective, in which the target appears to be in the correct rotation when viewed from the front but is not in the correct rotation when observed directly, necessitating head movement to find a perspective from which the target can be easily observed.

Differences in rotation patterns between younger and older participants were also observed. Firstly, older participants made



(a) Object Manipulation on Interaction Surfaces (b) Object Manipulation on Spatial Positions

Figure 9: The summary of comfort level and object manipulation task across spatial settings for older participants: (a) on interaction surfaces and (b) on spatial positions.

more adjustments per attempt than younger participants. We observed that older participants made more adjustments while performing the rotation task (e.g., they tend to continue to rotate in the same direction when they overshoot, rather than rotating back.). This may suggest that rotating targets in the reverse direction is harder than continuing in the same direction. Secondly, distinct strategies for both rotation and scaling tasks were identified. Older participants tended to make more but smaller adjustments than younger adults. Although older participants generally made significantly more attempts than younger participants, we noted that three younger participants made multiple small adjustments for the scaling tasks after largely approaching the target scale (i.e., moving the controller slowly and constantly clicking the button to refine the object size), whereas other participants made substantial adjustments each attempt to approach the target scale step by step. In contrast, older adults made fine adjustments when the targets approached the correct transformation, but the magnitude of transformations per attempt was considerably larger.

Additionally, it was worth noting that older participants were more affected by the height of the target when performing rotation tasks. Older participants tend to experience increased difficulty and discomfort while performing hand movements with an elevated arm, as evidenced by their feedback, which is also in line with the findings from Study 1. The arm fatigue experienced by older adults during tasks with elevated targets could result from several age-related physiological changes. These may include a decline in muscle strength and endurance, as well as a reduction in joint flexibility and range of motion. As a result, older individuals may find it more challenging to maintain the necessary posture and control required to perform rotation tasks at various heights [52].

The scaling task exhibited higher accuracy for the vertical surface compared to the depth and horizontal surface. Similar to the rotation task, scaling on the vertical surface occurred on the primary perspective surface of the participants, suggesting that the interaction occurring on this surface would yield better performance compared to other surfaces. However, despite also occurring on the primary perspective surface, scaling on the horizontal surface demonstrated the lowest accuracy. This discrepancy might be attributed to arm fatigue experienced by participants when extending their arms horizontally in a manner akin to chest expansion exercises. In contrast to the other two axes, which predominantly involve joint rotation, this movement imposes greater demands on the muscles and joints.

Our study found that older participants experienced challenges when engaging in bi-manual interactions, particularly when using both hands simultaneously to scale a target from the central position. We observed that older participants have shown difficulty in controlling two hands simultaneously. Instead of employing a coordinated, two-handed approach, older adults often adopted a strategy where they held one hand stationary while manipulating the target with the other hand. This behavior could be a result of age-related declines in motor control and coordination, which can impact their ability to execute complex, synchronized movements using both hands in rotation tasks at various heights [15, 52]. Furthermore, we observed that scaling from the central position resulted in a higher scale offset, which could explain the difficulties in hand-eye coordination. For example, when participants were asked to scale an object on a horizontal or vertical surface, they had to observe their hands from two sides. These findings suggest that older adults may require alternative strategies to effectively perform bi-manual interactions, particularly when scaling targets from the central position.

5 DESIGN RECOMMENDATION

To understand the user experience of older adults and the effects of aging on the interaction in VR between older and younger adults, we have conducted two empirical user studies to answer two RQs in the Section 3 and 4. Based on the above findings and discussions, we distilled five types of design recommendation (DR) for relevant interaction techniques and user interfaces in VR in order to provide a better user experience for the elderly.

DR 1: Position targets within in the spatial range of -30° and 30° respects to users' facing directions, if possible, to make target selection more accessible to older adults. Our research and empirical data emphasize that the amplitude of horizontal and vertical layouts negatively affects the performance and comfort level of completing target acquisition and manipulation tasks, which demonstrated that interactions tend to become more error-prone and time-consuming as the amplitude of spatial variations increase both vertically and horizontally. Especially, when the target position is far away from the center (e.g. 60° or -60° in Fig. 2 and 4), exacerbating the discomfort when searching and reaching. Hence, it is beneficial to design VR scenarios within the proposed range that minimizes head and eye movement, reducing stress on the user's neck muscles and reducing the potential for discomfort. However, trading off the design of interaction region becomes crucial to avoid information overwhelmed [26]. Given the potential for introducing additional usability issues, such as increased cognitive load and visual fatigue [79], as well as reduced selection accuracy when selecting cluster and occluded targets, it is advisable to exercise caution when placing a large number of interaction elements in this region [77].

DR2: Customizing target distance for different arm spans to adapt to users with different arm spans. Our findings indicate that targets situated beyond the arm's reach or in rather close proximity to the user's body may present difficulties due to the additional movements required, such as maintaining an extended arm posture or engaging in forward-leaning to sustain contact with the target [74]. While our results generally revealed a decline in performance as target distance increased, this trend was not universal for all users, particularly those with longer arm lengths. For these individuals, the closest distance (e.g., 0.45 m) proved to be less comfortable, inadvertently imposing heightened physical demands on the user and potentially compromising the overall usability and ergonomic efficiency of the system. Consequently, it is recommended to implement a calibration process for general VR systems that measures each user's arm span and adjusts application settings accordingly, thereby optimizing the user experience.

DR3: Incorporating multi-modality to make VR interaction techniques more inclusive and accessible. We found that older participants tend to linger around the targets before clicking the selection button, which might introduce extra physical demand and result in lower accuracy for the selection. Hence, future interaction techniques could incorporate other forms to assist the interaction besides using hands as input. For example, incorporate eye gaze as selection input [55, 75] or additional visual or haptic feedback [38] that notified users of the exact timing of making confirmed selections, which could make VR interaction become more inclusive.

DR4: Future mid-air interaction should use the virtual plane that is easily perceived and operated by the users as the primary interaction surface. Empirical evidence gleaned from our research findings indicates that participants tend to encounter challenges when engaging in mid-air interactions under conditions where their hand movements are not visually perceptible. Consequently, designing systems that emphasize the user's sight of view and facilitate clear visibility of their hand gestures could remarkably enhance the efficiency and overall user experience of mid-air interaction technologies [76].

DR5: Reducing bi-manual interaction in future interaction and gesture design. We also found that older participants have difficulties in performing tasks that need to coordinate two hands. Age-related changes in sensory and perceptual functions significantly enlarge challenges faced by older adults in coordinating two-handed interactions. For instance, diminished vision and proprioception may hinder their ability to accurately perceive the position and movement of their hands at the same time, thereby making it difficult to carry out tasks that require precise spatial coordination and alignment.

6 LIMITATION AND FUTURE WORK

We identified that there were five older participants who quit during the user studies (three for User Study 1 and two for User Study 2). The recorded reasons for dropping out include motion sickness caused by the virtual environment (85, M; 62, F; 68, F), physical fatigue caused by prolonged task time (65, F), difficulties in comprehending the interaction in VR (63, F), and tedious repeated tasks (65, F). These imply the current practice of VR might not be suitable for all older adults.

In this study, our evaluation was limited to the interaction in a seated posture. However, it is important to consider other postures, including standing and walking, which are frequently encountered in virtual reality (VR) interactive scenarios. Specifically, older adults with mobility issues who are unable to go out for extended periods may benefit from using travel-based VR applications to explore the world [58, 62]. Additionally, investigating the effects of relaxing postures, such as lying down, could be beneficial, as it may reduce physical strain associated with prolonged sitting and standing. The follow-up designs could promote greater inclusivity in VR by enabling bed-bound users, such as patients, to experience the immersive world [66].

Besides, we only included healthy older adults into our study. Nevertheless, it is common for older adults to suffer from age-related health deterioration and diseases, such as mobility disabilities with heavy knee-related issues, which require sitting in a wheelchair to finish their daily activities. Previous research suggested that the use of VR in a wheelchair contains substantial usability issues [79]. Hence, it would be worth investigating the challenges and experiences of older adults with different kinds of disabilities while using VR.

7 CONCLUSION

Research on object selection and manipulation techniques is crucial in VR studies, particularly in understanding human behavior and enhancing user experience in immersive environments. However, insufficient attention has been given to developing comprehensive comprehension for specific user groups and addressing accessibility needs. Through two empirical studies, we revealed the motor control and interaction performance under aging-related influences in immersive environments. In addition, our study uncovered potential barriers and challenges that older adults may encounter in VR interactions. Based on the above analyses and findings, we derived five design recommendations with inclusive considerations and

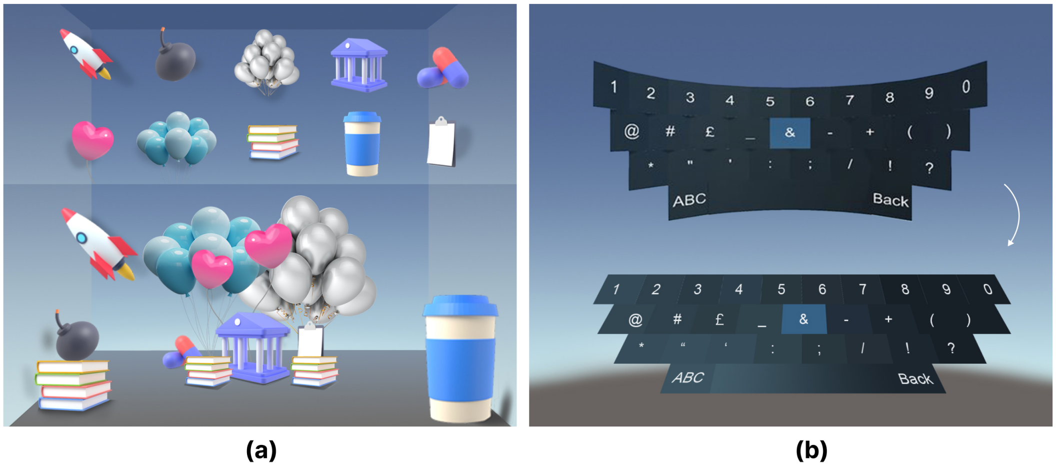


Figure 10: Demonstration scenarios: (a.top) provide an example of object alignment. (a.bottom) provide an enhancement of the alignment as DR1 and DR2 suggested, where the objects clustered at comfortable regions and augmented the objects at less convenient positions. (b) The keyboard at the top shows the less convenient surface and the keyboard at the bottom shows the more comfortable typing surface according to DR4

prototyped potential applications for enhancing and smoothing interaction experiences with older adults in VR.

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