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# A Hand Age-Swap Proteus Effect on Memory and Movement

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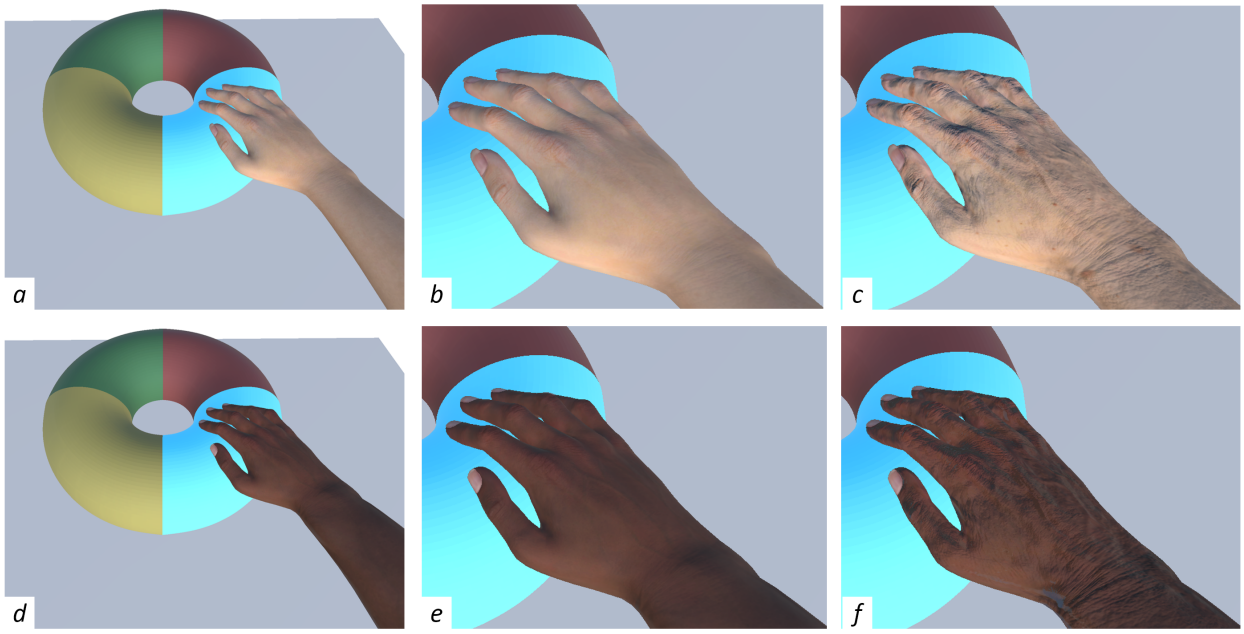



Figure 1: Sample frames from our VR study (*a, d*) and magnified fragments (*b, c, e, f*). Participants in the 18-35 age range were asked to play back from memory a sequence of colors they had just seen by pressing the four buttons on the wheel in the correct order. Each participant plays the game twice, once with age appropriate avatar hands, i.e., with a young appearance, and once with age incongruent avatar hands, i.e., with an old appearance (*b* vs. *c*, *e* vs. *f*). Results show that with the avatar hands with an old appearance, the participants' cognitive and motor behavior shifts towards that commonly associated with older participants.

**Abstract**— This paper describes an initial investigation of an approach for gathering data on older VR participants indirectly, not by actually enrolling older participants in the study, but rather by attempting to modify the cognitive and motor behavior of younger participants for it to resemble that of older participants. The behavior modification relies on the Proteus effect, a well-documented change in the behavior of a user of a VR application when provided with an incongruent self-avatar. A user study asked N = 30 participants in the 18 to 35 age group to play a memory game in VR, twice: once with virtual hands with a young appearance, in line with the actual participant age, and once with virtual hands with an old appearance, in contradiction with the actual participant age. The game plays a growing sequence of lights that the participant has to play back from memory by pressing buttons on the game wheel. The results show that when presented with older-looking hands, participants recalled shorter sequences and their hands did not reach as far as when presented with age-congruent hands. The study brings evidence of simultaneous cognitive and motor manipulation of VR user behavior. Specifically, the study shows that both the cognitive and motor behavior of young VR users can be shifted towards behavior commonly associated with older participants.

**Index Terms**—Memory game in VR, age Proteus effect, avatar hand manipulation, memory and motor changes.

## 1 Introduction

People are living longer than ever before, and the proportion of older persons in the population is increasing across the globe [66]. Caring for aging populations comes with many challenges as aging causes decreases in both mental and physical ability. Conversely, supporting both memory and physical health in aging populations can increase life expectancy and quality of life. Technology, including virtual reality (VR), is a promising tool that can support memory and physical health. For example, when considering older populations, computer games have been shown to promote cognition and improve memory [3, 68], and VR systems have been developed as physical therapy applications [19].

Older populations are a promising user group who could benefit from VR applications, yet VR systems are often tested only on younger populations [54]. Not developing or testing systems for diverse participants, including diversity in age, can lead to system bias and unusable systems for these populations [52]. As researchers and practitioners investigate and implement the VR human-computer interfaces and applications needed to concretize VR's potential for massive societal impact, the evaluation of VR innovations with diverse users remains an important

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bottleneck.

Running VR user studies with participants from an older demographic, e.g., aged 65 and older, is particularly challenging. Older participants can have mobility issues, making it harder for them to travel to the laboratory where the study is run. Addressing this challenge by having the research team travel to each participant's home raises additional important challenges regarding logistics and privacy. Older participants can also present a higher risk of participation in VR user studies, due to a potentially more precarious balance, which can lead to falls when wearing a VR headset. Consequently, most VR studies opt to bypass this challenging participant demographic, with the consequence that little is known in terms of whether, which, and under what conditions VR interventions can benefit the older members of our society.

VR places users into fully immersive computer generated environments that can include full-body self-avatars such that the user can experience a body-ownership illusion [39], which can increase VR application efficacy. When experiencing a body-ownership illusion, users have been shown to take on the characteristics of their self-avatar, VR behavior modulation known as the Proteus effect [67]. For example, people negotiate more aggressively when their self-avatar is taller [67], have reduced implicit racial bias when experiencing a racial-swap illusion [53], and perform better on a cognitive task when embodying Einstein [10]. Furthermore, just having a self-avatar and being able to move one's virtual hands has been shown to improve cognitive load [60]. When considering the Proteus effect and age, studies have explored physical changes with age-swap illusions including walking, exercising, and hand-grip strength [55, 62, 64]. However, we are only aware of one study that investigates the impacts of age-swaps and cognition as measured through word recall [64]. These Proteus effect age studies employed full-body swap illusions that change the user's identity (i.e. different face) with virtual mirrors used to induce embodiment [24]. Little work has been done to investigate the effects age-swapping by only changing the appearance of the user's hands and arms, without changing their virtual identity.

In this paper we conduct an initial investigation of an indirect approach for improving age representation in VR studies by leveraging the Proteus effect in a task that measures both memory and physical movement simultaneously. Specifically, we investigate whether providing younger participants with age-incongruent avatar hands modifies both their mental and motor behavior to exhibit characteristics associated by prior research with older participants. We conducted a user study with N = 30 participants in the 18 to 35 age range. The user study was approved by the ethics boards of our institutions. Participants played a memory game in VR, which asked them to reproduce light sequences of increasing length (Fig. 1). Each participant played the game in two conditions, young or old appearing hands. In addition to the game score given by the length of the longest sequence recalled correctly, we also recorded the participant's head and hand motions. Participants had better recall when embodying younger hands compared to older hands. Additionally, movement patterns of both the head and hands mimic expected age behaviors of younger and older populations. This provides initial evidence in support of the effectiveness of an indirect approach for evaluating a VR intervention's effect on older participants, bypassing the challenges of actually enrolling older participants in the study. The participants played the game while seated, which is an important if not the main way in which the elderly are likely to want to experience VR. Therefore, our study's focus on seated VR is not only justified, but also of highest relevance. We also refer the reader to the video accompanying our paper.

## 2 Background

With the growing number of people above the age of 65, it is imperious that innovations across domains be also designed and validated for this important user demographic group. Conducting research with older participants is challenging. Members of the geriatric profession began investigating safe ways to conduct research in nursing homes to accurately provide care and medical assistance to older populations. Their findings illustrate the difficulties involved in conducting research in nursing home facilities because of factors like the rigid nature of the daily schedules and the challenges involved in working with the older population [33]. Researchers have documented the most effective ways of navigating these difficulties when conducting research [29], the best ways of gaining informed consent from people in nursing homes or their proxies and respecting the human rights of the elderly during the research process [46], and finally, the best ways of collecting and assessing data gained from research in nursing homes while accounting for factors like fatigue and memory loss in the elderly [18].

### 2.1 The Elderly in Virtual Reality

In the same light, it is of great importance that new and upcoming technologies perform test trials involving the older population. This is because, while the focus of new technologies is placed on people below the age of 65, these technologies offer the opportunity to also make the lives of the older population easier, including for those in assisted living facilities. A first step is to investigate the reaction of the elderly to VR. Such studies explored the hesitant initial reactions as well as the positive final thoughts of older adults when placed in virtual environments [32, 61]. Studies also highlighted the difficulties that were faced, such as dizziness from head-mounted displays (HMDs), physical strain from handheld controllers, and overall mobility constraints. Another study used Samsung Gear VRs with independently living older adults and found VR to be a viable source of entertainment, exploration, and education [17]. They noted the need for special consideration of frailty and preexisting conditions like head and neck pain. A different group of researchers explored the use of VR as a source of socialization among older adults living in residential care homes, where two control groups were used to determine the effectiveness of using virtual reality as a potent entertainment source. Despite the small geographic scope the researchers had access to, they found the use of VR as an entertainment source for older adults living in assisted care to be a viable option [8,44].

VR may also support a unique means of socialization within older adult communities. Haase et al. found that older adults reacted positively to social VR environments finding them to be a great opportunity to meet new people [28].

Research has also shown that the benefits of VR for the elderly extend beyond social life and into geriatrics. A systematic review [47] inventories the potential use of VR to enhance health recovery outcomes and reduce recovery times for older patients with serious illnesses. VR was used to create distractions during treatment, to relieve anxiety, to distract from stress, and to improve motor reactions in older patients during treatment. Another study [58] provided insights into the use of virtual reality as a means of improving the cognitive health and responses of the geriatric population. Their review reported positive findings of the use of virtual reality as a good clinical aid in cognitive testing and training among the older population.

Barker et al. [8] reports on using VR technologies with older adults living in residential age care to study how the elderly react to VR, and the benefits and challenges involved with using VR in these facilities. The VR technology generally received positive reactions, providing an extra array of daily activities for the inhabitants of those residential facilities. However, hardware aspects like the design of the headset and of the hand-held controllers made VR technology difficult to use for these participants. Although newer headsets [48] now provide anatomically-complete hand tracking with 27 degrees of freedom, bypassing the need of using handheld controllers, the headset form factor has not yet improved sufficiently.

Previous research highlights that elderly populations may benefit from, and enjoy using VR. However, current systems are not studied on or designed for older populations [52]. VR research on older populations is challenging and finding innovative ways to better design for and support this group is essential for developing usable VR systems for the elderly.

### 2.2 The Proteus Effect

The Proteus Effect, first introduced by Yee et al. [67] identified that VR users behave differently in social situations based on the physical appearance of their avatar. For example, participants who's self-avatar

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had a more attractive face would reduce their proximity to other avatars compared to those with a less attractive face. Additionally, participants whose avatar was taller behaved in a more dominant way than participants with a shorter avatar. The behavior modification towards alignment with an incongruent self-avatar was dubbed the Proteus effect, to which subsequently substantial research was devoted (we also refer the reader to a relatively recent meta review [13]).

It has been shown that certain avatars can carry preconceived opinions about physical and cognitive abilities. For example, when users were put into the body of Albert Einstein, they performed better on a Tower of London (TOL) assessment of executive functioning skills [10]. This suggests that because Albert Einstein is associated with high cognitive abilities, embodying him leads users to take on similar attributes to him as quantified by high performance on the TOL tasks. Similarly, when users are put into the body of the Christian God, they respond more calmly to simulated stressful situations, in particular when the ground around them collapses, compared to participants who were not embodied in a Christian God-like avatar [23]. Additionally, muscular self-avatars have been shown to increase physical endurance such as jumping farther or holding weights longer [23, 42].

A VR user's behavior can also be impacted by the apparent age of their self-avatar. Reinhard et al. [55] showed that when embodied in an older avatar users took longer to maneuver the environment. Surprisingly, When users exited the environment and walked down a hallway they initially walked slower, continuing the behavior acquired while in the virtual environment. There is also evidence that the Proteus Effect can depend on a user's implicit biases. One study [64] found that when young participants embodied older avatars, their memory and physical abilities were worse than when embodied in younger appearing avatars. However, when age group stereotypes were added as a co-variate in their analysis, their findings regarding physical and mental abilities were no longer significant, suggesting that stereotypes could have caused this difference in performance.

Further work investigating self-avatars and age by Tammy et al. [62] examined how older VR users embody younger avatars compared to avatars of their age. The findings show that older men using a younger avatar perceived more exertion from the same amount of physical activity compared to when using an age-congruent avatar. On the other hand, female participants who used younger avatars reported a greater self-efficacy and performed more physical activity. Female participants appeared to be more influenced by avatar age than their male counterparts and were more motivated and engaged in varied aerobic activities.

These Proteus effect age studies employed full-body swap illusions that change the user's identity by changing the appearance of the user's face and body using virtual mirrors used to induce embodiment [24]. To date, little work has been done to investigate the effects of age-swapping by only changing the appearance of the user's hands and arms, without changing their virtual identity. It is not yet known if an age Proteus effect can be induced by only changing the appearance of the user's arms and hands. This may be critical in studying the Proteus effect for older populations who find avatar appearance self-similarity and natural movements to be important [7].

### 2.3 Hand Representation

Feeling a sense of ownership over a hand has been shown through the Rubber Hand Illusion (RHI) where a rubber hand, in the sight of the participant, is stroked at the same time as the participant's own hand [15]. Participants report a sense of ownership over the rubber hand when the stroking action is synchronous rather than asynchronous [20]. In extension of this sense of ownership in a physical environment, the same effect has also been shown in VR, called the Virtual Hand Illusion (VHI) [20].

Another point of interest is user experience and performance due to hand representations. A realistic hand representation has been shown to invoke a greater sense of ownership than other, more abstract wooden block representation during the VHI [45, 69]. Further, when a user's hands closely resemble their own, they can make more accurate estimations of object size [36]. Specifically in a video game environment, users had the most enjoyable experience while using a hand representation compared to a sphere or a controller representation [9]. Additionally, in a different test participants had to grab a ball inside of a box where the front was opening and closing. It was found that participants performed best when they were using a virtual gloved hand compared to a virtual representation of the joystick [65]. Hands have been shown to be ideal representations in circumstances where hand interaction is necessary. Experience also can depend on the kind of hand and its similarity to the user's actual hand. When a hand is too similar looking to a user's actual hand, they can experience the Uncanny Valley Effect, which can lower the user's enjoyment [21]. Additionally, a user's sense of agency over the virtual hand is important when the virtual hands do not move exactly how users might expect. But ultimately, decreased agency was not enough to lower the user's overall sense of avatar ownership [6].

Overall, virtual hands are an important visual representation in virtual body-ownership illusions. However, it is not clear if the appearance of virtual hands alone, without a full-body swap and seeing oneself in a mirror, can induce an age-swap Proteus effect illusion.

### 2.4 Movement and Memory in the Elderly

Age is associated with a decline in both mental and physical health. Memory and recall ability decline as people age [59] such that elderly perform worse on a memory recall task compared to younger people. Additionally, the aging process influences physical ableness and movement such as reduced flexibility, joint integrity, and reduced limb range of motion [35]. Considering movement, older adults exhibit greater postural sway (i.e., increased back-and-forth head motion) compared to younger adults [41]. They also show greater head acceleration and larger head pitch than younger adults [34]. Head-tracked XR systems afford the collection of tracking data at multiple frames per second that enables nuanced data analysis including looking at variations in head movement patterns [26]. For example, increased back-and-forth head motion could be measured by the standard deviation of back-and-forth head movement, i.e. head-yaw such that older adults would be expected to ave a higher head yaw standard deviation compared to younger adults. Similarly, head-pitch would be greater in older adults compared to younger adults.

Older adults have reduced flexibility and limb range of motion [35]. In addition, arm movements in older adults tend to be slower and more irregular [4]. Reaching kinematics differ with age as well such that wrist trajectories are typically more curved in younger adults but straighter in older adults [50]. Finally, joint range of motion generally declines with age, which can reduce how far individuals are able to reach [22]. These differences in limb movements can be explored by comparing the arm and hand movement data that can be collected from hand-held tracking devices. Specifically, we would expect younger adults to reach farther than older adults.

## 3 Study Design

Our goal is to investigate whether young participants presented with a self-avatar with an older appearance modify their behavior in a VR application to adopt behavior commonly associated with older people. We investigate the simultaneous modification of both motor behavior, i.e., the way participants move, and cognitive behavior, i.e., the way participants performed a memory task.

*One study design consideration* is how to convey to the participant the appearance of their avatar. One option used in prior work is to insert mirrors in the virtual environment that allow the participant to see themselves [24]. The placement of the mirror and the fact that the motions of the avatar seen in the mirror are tethered to the user motions make the user associate the avatar to their own body, despite appearance incongruence. Whereas virtual mirrors can be fitted in the narrative of tasks used in a user study, virtual mirrors are not always suitable for a VR application's narrative, which could limit what is being learned in the study. Therefore, we choose to convey to the user the appearance of their avatar exclusively through the appearance of their virtual hands. A VR user who performs a task that requires manual interaction will naturally look at their avatar's hands, the same way humans look at

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their real world hands. Furthermore, humans are very familiar with the appearance of their own hands, so they are likely to respond strongly to any appearance incongruence. In other words, relying on the avatar hands promises both generality and effectiveness.

*A second design consideration* is to decide on the participant motion to investigate. Due to reduced mobility, precarious balance, and ergonomics the elderly are far more likely to opt for extended use of VR applications while seated. For example, an older user of VR technology will be seated during a VR visit with their doctor, as they socialize with a distant friend, or as they play a board game. Furthermore, a seated VR user is much more likely to perform actions in which they see their avatar hands, such as gesturing while talking, or moving their hands in front of them to interact with the virtual environment and its interface. Related to the first design concern, having the VR user see their avatar's hands frequently will provide the opportunity for effective hand appearance manipulation. As such, we have opted for the VR participant to be seated, and we will focus our motion investigation on the participant's movement of their arms, forearms, and hands, as well as of their head.

*A third design consideration* is to decide on the cognitive task. The task has to be general, to not require specific skill sets or background knowledge. The task should also have malleable difficulty, to allow for calibration to specific user ability. Based on these considerations we have opted for a memory task, which is both general and of malleable complexity. A memory task also has the advantage that memory is an essential aspect of the cognitive health of the older population and memory decline is a sign of aging [30].

*A fourth design consideration* is to achieve a fine grain interleaving of the motor and cognitive tasks in an engaging activity in which participants behave naturally, potentially losing awareness of participating in a research study and even of using VR technology. This way, any response to the hand appearance manipulation has the potential to be genuine and therefore informative to our investigation. We measure recall memory and user head and hand movement looking for known age differences between the elderly and younger adults.

We formulate the following research hypotheses. Compared to when assigned hands with an appropriate (young) appearance, when assigned avatar hands with an old appearance, young participants will:

**RH1** have worse performance on the memory task;

**RH2** have slower performance on the memory task;

**RH3** have different head movement, i.e., greater back-and-forth motion, larger pitch;

**RH4** have different hand movement, i.e., have a shorter reach length, more irregular movements, straighter trajectory.

Finally, we have opted for a within subject design, which, given a number of participants, maximizes the number of participants per condition. Confounding learning effects are not a concern since we will use a new instance of the memory task for each trial.

## 4 Methods

We have conducted a user study with the approval of the ethics commissions of our institutions. As this work is exploratory, we did not consider preregistration of the study to be necessary. Results should be interpreted as exploratory and not confirmatory.

### 4.1 Participants

Our study specifically targets young participants with the age between 18 and 35. As such, we recruited (N = 30) participants from the undergraduate and graduate student population of our institution of higher education using email and flyers. Participants verified that they met all inclusion criteria: age between 18 and 35, no history of epilepsy or simulator sickness, in a general state of good health, normal/corrected to normal vision, not color blind, and with the ability to use both hands. Participant gender distribution was 13 female and 17 male. 28 participants reported having used a VR headset at least once before and 13 that they are familiar with the Simon memory game. The median answer to the "I think I have great memory" question was a neutral 3 on a 1 to 5 scale. Participants were not frequent memory game players, with a median answer of 2 on the same 1 to 5 scale. An apriori power analysis of linear multiple regression with one predictor, with an error of .05 and power of .8, supports that 25 participants are needed for large effects and up to 55 participants for medium effects. Our sample of 30 is ample for identifying large effects and adequate for identifying medium effects.

### 4.2 Task

As discussed in Sec. 3, our study requires a task that presents natural opportunities for the participant to see their hands, that the participant performs while seated, that includes a memory challenge with malleable complexity, and that interleaves with fine granularity the memory and motor demands from the participant. We have opted for a memory board game that the participant plays while seated, providing the answers to the memory challenges not verbally, but through physically reaching and tapping the interface.

We developed a virtual reality version of the Simon game, which was originally developed by Ralph H. Baer and Howard J. Morrison in 1978. The participant is seated at a physical table and puts on a VR headset. The participant sees a virtual table, which is aligned to the physical table, for the physical table to provide haptic feedback when tapping. The participant sees their virtual, gender and skin-tone matched forearms and hands (Fig. 1). The fingers and hands are tracked by the VR headset and move synchronously with the user's movements. The participant sees a virtual wheel placed on the table. There is no physical counterpart for the wheel. The wheel is divided into four sectors of colors red, blue, yellow, and green. The wheel plays back a sequence of colors. The corresponding sector lights up and a color specific sound is played back. After the wheel plays back the sequence, the participant has to recreate the sequence from memory by pressing the sectors in order, with either of their hands. As the participant presses a sector, the sector lights up and the sector's sound is played back. The sound is useful to the participant as a dual encoding of the sequence. The initial sequence is of length one and sequences grow by one every time the participant plays back a sequence correctly. When the participant plays back a sequence incorrectly, the trial ends and the participant score for the trial equals the length of the longest sequence played back correctly.

### 4.3 Conditions

Participants played the game in two conditions, presented in counterbalanced order. In the "young condition" (Young) the avatar hands had a young appearance, as appropriate for the age demographic of our participants. In the "old condition" (Old) the avatar hands had an old appearance, incongruent with the true age of the participant.

*Avatar hands.* We developed $2 \times 2 \times 3 = 12$ pairs of (left/right) avatar hands for all {young, old} $\times$ {female, male} $\times$ {light skin tone, medium skin tone, dark skin tone} combinations. A participant was assigned the young and old avatar hands with the gender and skin tone matching the participant. We designed the hands starting from the same 3D avatar model. The initial hands were modified in length and finger thickness to create the male/female variations. The hands' texture was modified to obtain the skin tone variations. The young/old variation was obtained by adding color non-uniformity, sun spots, and wrinkles to the skin texture, and by adding a slight misalignment of the phalanges evocative of hand deformations that can be caused by arthritis. Images *a, b, c* in Fig. 1 show female light skin tone avatar hands, and *d, e, f* show male dark skin tone avatar hands.

### 4.4 Measures

We measured memory and movement performance with objective metrics, and we measured embodiment and the Simon VR experience with several questionnaires.

#### 4.4.1 Memory performance

We quantified participant memory performance objectively through the score for each trial. In addition to the score for the trial, we also recorded the time the participant took to press each button (latency),

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for each sequence, including for the sequences played back correctly. Sequences shorter than two were removed from analysis. Additionally, latency outliers (1.5*IQR) were removed from the data.

#### 4.4.2 Movement performance

Participant movement was recorded by saving the head, right hand, and left hand position (x, y, z) and orientation (yaw, pitch, roll) at a rate of five times per second, i.e., 5 Hz. Participant movement data was analyzed using the measures and methods defined by Guth et al. [26]. We investigated movements with known differences between younger adults and the elderly (see Section 2.4).

**Head Yaw SD.** Older adults have increased back-and-forth head motion and head acceleration. To investigate the effect of the hand age-swap we looked at head yaw standard deviation (Yaw SD) for each trial. We hypothesize that participants with old hands will have greater Yaw SD compared to young hands.

**Head Pitch 95.** Older adults have a greater head pitch compared to younger adults. To consider the difference in head pitch between ages we looked at the 95% range—the total range of head pitch with the upper and lower 2.5% of measurements removed. We hypothesize that participants with old hands will have a greater Pitch 95 compared to when they have young hands.

**Hand Reach SD.** Wrist trajectories are typically more curved in younger adults but straighter in older adults. To investigate the hand age-swap we looked at hand standard deviation along the z-axis, the forward reaching axis, in front of the participant, towards the game board. We hypothesize that participants with old hands will have lower reach SD, compared to participants with young hands.

**Hand Reach 95.** Older adults have a reduced range in hand reach motion. To investigate the hand age-swap we looked at the hand reach 95% range along the z-axis. We expect participants to have a shorter reach length with old hands compared to young hands.

#### 4.4.3 Embodiment and Simon VR User Experience

We gauged participant embodiment differences between the young and old avatar hand conditions with the Avatar Embodiment Questionnaire (AEQ [51]), which participants completed after each condition.

We gauged the participants' perception of the Simon VR game experience through a custom user experience questionnaire with nine questions:

**Q1** You played the Simon memory game twice. Each time you were given a different avatar. Which avatar seemed younger?

**Q2** Which avatar matched your age more closely?

**Q3** When do you think you had a higher score?

**Q4** I did not fully understand how to play the game.

**Q5** I frequently pressed the wrong button inadvertently.

**Q6** The headset felt uncomfortable.

**Q7** I enjoyed playing the Simon game in VR.

**Q8** I would love to have a VR headset to play the Simon game.

**Q9** I would love to have a VR headset to play VR games.

Q1, Q2, and Q3 had binary "[First/Second]" answers, Q4 had a binary "[Yes/No]" answer, and Q5-Q9 had answers on a five-point Likert scale, i.e., "Strongly disagree", "Disagree", "Neither agree nor disagree", "Agree", "Strongly agree".

Additionally, we also investigated the participants' perception of the Simon VR game experience through four standard questionnaires that participants completed once, at the end of the study session: system usability scale (SUS [16,40]), simulator sickness questionnaire (SSQ [38]), iGroup presence questionnaire (IPQ [57]), and task load index (NASA TLX [31]).



Figure 2: Virtual environment used in the study. Participants sat at the desk and played the Simon memory game in front of them.

### 4.5 Equipment

The system was developed using Unity 3D 2022.3.16f1 [2] and deployed on a Meta Quest 3 VR headset [48]. The avatar hands were designed using Character Creator v4.53 [1], with modified texture and normal map drawn manually within Photoshop [5]. The house interior virtual environment was obtained from the Unity Asset Store.

### 4.6 Procedure

Upon registering for the study, participants confirmed eligibility and registered for a study session. Once a participant arrived at the testing site in our laboratory, the researcher again confirmed with the participant that they meet the inclusion criteria. Participants then read and signed the consent form. Participants were given the option to ask questions from the experimenter before signing. The consent form asks the participant to remove the headset at the onset of any discomfort such as motion sickness symptoms. Furthermore, the consent form informs the participant that they will be compensated in full even if they have to stop early, to encourage the participant to report early any symptoms of discomfort. All participants completed the entire experiment.

While the participant was completing the consent form, the experimenter set up the experiment by selecting the avatar gender, age and skin tone. Participants also received a verbal description of the Simon memory game based on a physical VR game, and were given the opportunity to ask questions. The experimenter then introduced participants to the HMD and handheld controllers. Participants then donned the HMD and saw themselves in a virtual house interior, sitting at a table. The Simon game was placed on the table, in front of the participant. The virtual environment is shown in Fig. 2.

Participants completed two experimental blocks, Young and Old, in counterbalanced order to mitigate learning and fatigue effects. Each block was the same except for the appearance of the virtual hands and arms. In the Young condition participants' self avatar was an age-matched avatar. In the Old condition participants' had an age mismatched avatar with old appearing hands. In all conditions the avatar hands were gender and skin-tone matched to the participant.

During each experimental block participants played the Simon game for 12 consecutive minutes. Participants completed trials where they built memory sequences of colors by reaching out and tapping the game. A trial began when the first color of the sequence flashed and ended when the the participant made a mistake. The total number of trials varied by participant. At the end of 12 minutes that game stopped and participants removed the HMD. Participants then completed the AEQ and the nine custom questions on a tablet.

Participants then put the HMD back on and completed the second experimental block in the other experimental condition, Young or Old. After block two participants then completed the usability questionnaires and basic demographic information. Participants were debriefed to the purpose of the study, thanked for their time, and compensated with a $40 US gift card. The entire procedure took approximately 60 minutes.

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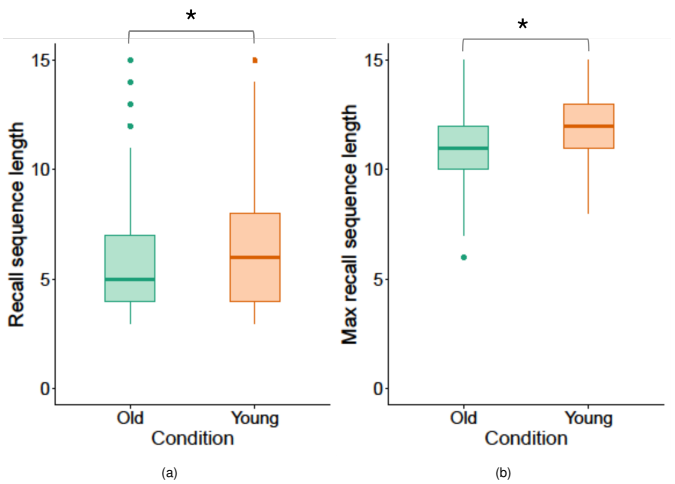



Figure 3: Memory performance: (a) recall sequence length and (b) maximum recall sequence length for the Old (green, left) and Young (orange, right) conditions. The differences between conditions are significant.

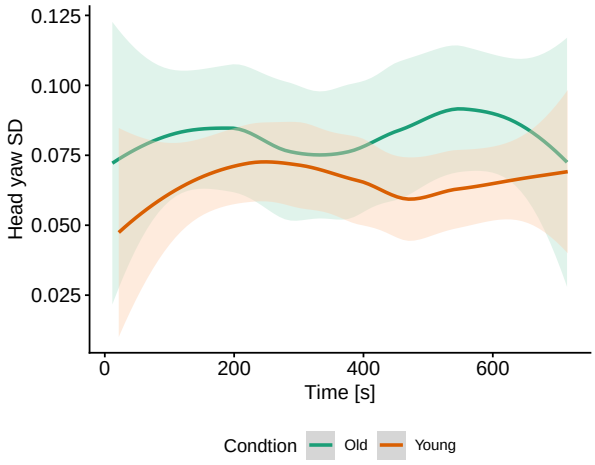



Figure 4: Movement performance: Head yaw SD for the Old (green) and Young (orange) conditions.

## 5 Results

All analysis was performed in the R software statistical package, version 4.5.2.

### 5.1 Memory Performance

Memory performance was measured per trial as the longest sequence recalled correctly in each trial. Sequence length was analyzed with a linear model with Condition (Young, Old) as a within-participant factor. On average (Fig. 3a), participants had longer trial lengths in Young ($M = 6.68$, $SE = .26$) compared to Old ($M = 6.04$, $SE = .27$), ($F(1,20.69) = 5.30$, $p = .03$, $\eta^2 = .20$).

Memory performance was also measured as the length of the maximum sequence, i.e., the longest sequence recalled correctly over all trials in the same condition. The results are shown in Fig. 3b. The maximum sequence for the Young condition ($M = 12.3$, $SE = .44$) was significantly longer than for the Old condition ($M = 11.1$, $SE = .48$), with medium effect ($F(1,29) = 4.33$, $p = .046$, $\eta^2 = .06$).

The results show that in the Young condition participants performed better both on average and in terms of highest score, compared to when they were in the Old condition. The older appearing avatar hands reduced the participants' ability to recall the sequences in the Simon VR game. This supports **RH1**, i.e., that participants with an old hand appearance will perform worse on the memory task compared to when they had a young hand appearance.

No significant difference was found in response latency between Young and Old. We found no evidence that the appearance of the avatar hands impacted the speed at which participants pressed buttons during the Simon VR memory game, and thus we found no support for **RH2**, i.e., that participants with an old hand appearance would have slower performance on the memory task.

### 5.2 Movement Performance

The movement performance data was analyzed with a linear mixed-effects model with Condition (Young, Old) as a within-participant factor. Significant differences were found in how participants physically moved based on their avatar's hand appearance in the expected ways based on the age appearance of the virtual hand.

**Head Yaw SD.** The results are shown in Fig. 4. As predicted, participants with old hands had a greater yaw SD compared to those with young hands. Participants in Old had a higher yaw SD ($M = .08$, $SE = .009$) compared to participants in Young ($M = .07$, $SE = .007$), with medium effect ($F(1,64.37) = 4.08$, $p = .048$, $\eta^2 = .06$). When participants had Old hands they moved their heads back and forth more compared to when they had Young hands. This matches the physical differences in age that older people have higher head frequencies compared to younger people [34].

**Head Pitch 95.** No significant differences in head pitch were found between Young and Old, $F(1,29.13) = 0.21$, $p = 0.65$.

**Hand Reach SD.** The results are shown in Fig. 5a. Significant differences were seen in the dominant hand movements, i.e., the hand used to press the buttons on the game wheel. Wrist movements differ between young adults and the elderly, with the elderly having straighter movements [50]. Participants in Old had a lower reach SD ($M = .08$, $SE = .006$) compared to participants in Young ($M = .09$, $SE = .006$), with large effect ($F(1,27.68) = 5.64$, $p = .02$, $\eta^2 = .17$).

**Hand Reach 95.** The results are shown in Fig. 5b. As expected, participants in Old did not reach as far with their dominant hand as participants in Young. Participants had a larger hand range 95 in Young ($M = .29$, $SE = .02$) compared to Old ($M = .25$, $SE = .02$), with large effect ($F(1,28.08) = 5.86$, $p = .02$, $\eta^2 = .17$).

### 5.3 Embodiment and Simon VR User Experience

**AEQ.** The results are shown in Fig. 6. Avatar embodiment questionnaire scores were in an acceptable range for both Young ($M = 3.65$, $SD = .94$) and Old ($M = 3.58$, $SD = 1.06$) [51]. No significant difference was found between conditions for AEQ total scores ($F(29) = .33$,

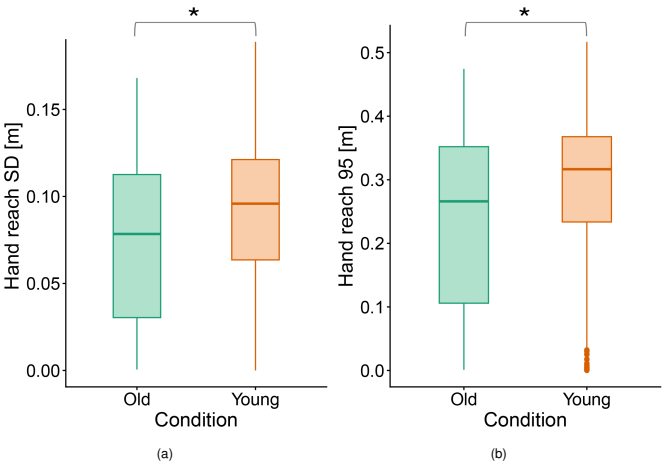



Figure 5: Movement performance for the Old (green, left in each graph) and Young (orange, right in each graph) conditions. The differences between conditions are significant.

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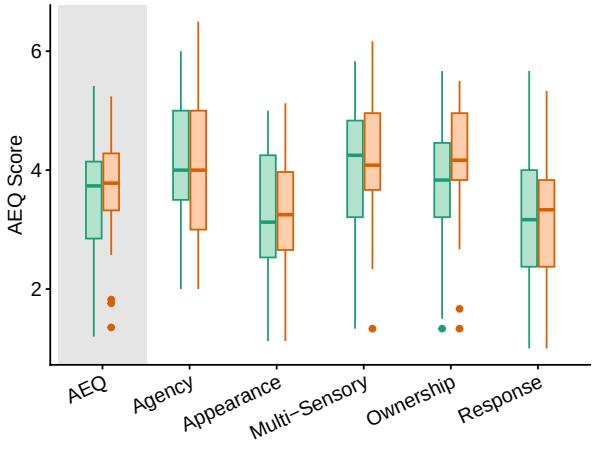



Figure 6: The AEQ total and submeasure scores for the Old (green, left) and Young (orange, right) conditions.

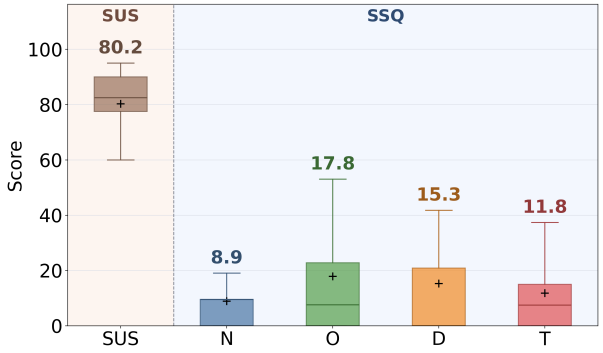



Figure 7: Boxplots of SUS and SSQ nausea (N), oculomotor (O), disorientation (D), and total (T) scores for our Simon VR game. The means are shown with a line in the box and provided numerically above each box. Usability is "Excellent" [11] and there are no cybersickness concerns [14].

$p = .57$, $\eta^2 = .001$). However, there was a significant difference in the subjective ownership submeasure with Young having greater ownership than Old with weak effect ($F(29) = 5.69$, $p = .02$, $\eta^2 = .03$). No other significant differences between the AEQ submeasures were found. Overall, there were no notable differences between Young and Old regarding the subjective sense of embodiment of the self-avatar.

**Simon VR user experience.** Q1 asked participants which avatar they thought appeared younger. We consider this a sanity check question. One participant did not answer the question. Of the 29 remaining participants 90% correctly selected the young hand. This supports that the age-swap with hands was effective. Additionally, 100% of participants selected the same avatar for Q1 and Q2 indicating that the avatar that they thought was younger also matched their age more closely. Additionally for Q3, 79% of participants thought they had the higher score when the avatar age matched their own age. Most participants (i.e., 93% or 28 out of 30, answered for Q4 that they understood how to play the game. Participants were not excluded based on their self-reported understanding of how to play the game.

To create a usability score specifically for our Simon VR game we grouped questions Q5, Q7, and Q8 (Q5 negatively encoded) and averaged their scores, with acceptable reliability ($\alpha = .72$). Participants Simon usability was above average ($M = 3.09$, $SD = .88$), however improved design considerations may need to be considered to use the VR game with the elderly.

Overall, participants had mixed opinions on headset comfort, with Q6 scores evenly distributed between the 1 to 5 values. Finally, Q9 was likely unreliable due to the leading phrasing asking if participants "would love to have a VR headset", with minimal response disparity and all responses in the high range.

**Usability and Cybersickness.** Fig. 7 shows the SUS and SSQ scores assigned by participants to our Simon VR game. The average SUS score of 80.2 corresponds to the 88th percentile, to the letter grade of A-, to the highest acceptability rating of "Acceptable", to the highest net promoter score of "Promoter", and to the adjective qualifier of "Excellent" [11, 56]. We conclude that our Simon VR virtual environment had a sufficient level of usability to not interfere with the investigation of the participant behavior modification based on avatar hand appearance. The average SSQ score of 11.82 and the subscale scores of 8.93 for Nausea, of 17.85 for Oculomotor, and of 15.27 for Disorientation do not raise cybersickness concerns [14].

**Presence.** The IPQ scores [57] are given in Fig. 8. We use a -3 to +3 seven-point scale, and not the original 0 to 6 scale, for improved reliability [63]. The (overall) presence score of 0.9 indicates a moderate sense of presence in the Simon VR virtual environment. The spatial presence score of 0.6 indicates that participants likely found the virtual environment intuitive enough to feel "inside it", yet the feeling was not particularly strong. The low involvement (-0.2) score indicate that participants were not fully engaged in the virtual environment and remained aware of the physical surroundings. The low experienced realism score of -0.5 indicates that participants felt that the virtual environment did not match their expectations of the real world. Although our virtual environment is a house interior of reasonable complexity (Fig. 2), We made the deliberate choice of placing the participant at a desk against the wall, with not much other than a plain wall and a plain desk in view (Fig. 1). While this helps the participant concentrate on the Simon game, it also fails to convey to the participant a strong sense of immersion into the virtual world and disconnection from the physical world, as reflected by the IPQ scores.

**User task load.** The NASA TLX scores are given in Fig. 9. The total score of 44 is in the optimal workload range of 26-50 where the user is engaged but not overwhelmed [25]. The mental load of 51 is at the border between optimal (26-50) and high (51-75) workload. This confirms the malleability of the complexity of the memory task in the Simon game–sequences grow longer until the user makes a mistake, adapting to each user's ability. The physical demand of 24 is at the high end of the low workload range of 0-25, indicating a disparity between the more difficulty memory challenge and the simpler movement challenge. Temporal demand is well calibrated. The performance score of 63 indicates that participants are satisfied with their performance, i.e., they feel that the task is challenging, yet that they complete it successfully. This is also corroborated by the optimal/high effort of 57 and the low frustration score of 31: participants push themselves relatively hard and succeed at the task. We conclude that the study task is well calibrated.

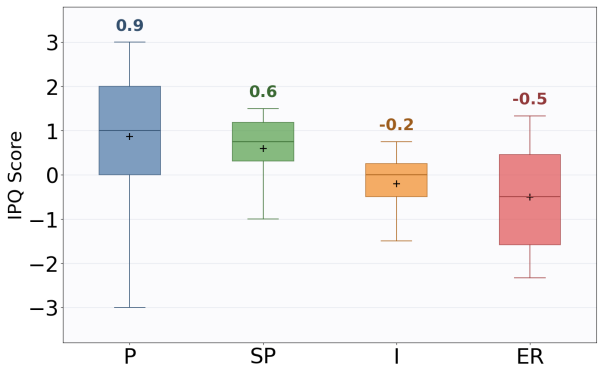



Figure 8: IPQ scores for presence (P), spatial presence (SP), involvement (I), and experienced realism (ER).

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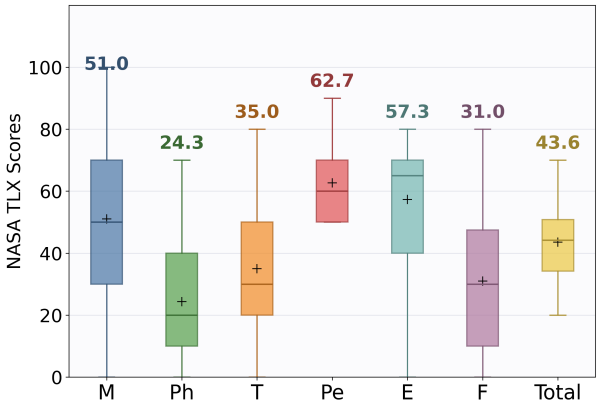



Figure 9: NASA TLX scores for total task load (Total) and for each subscale, i.e., mental demand (M), physical demand (Ph), temporal demand (T), performance (Pe), effort (E), and frustration (F).

## 6 Discussion

The study results clearly show that our young participants, age 18-35, modify both their cognitive and movement behavior in the Simon VR game when experiencing a body-ownership illusion with avatar hands with an old appearance. Furthermore, the behavior modification is in alignment with behavior previously documented for the elderly. Specifically, elderly populations have memory and recall decline compared to younger populations [59]. We see a similar Proteus effect with participants having shorter average recall length across all of their trials and a shorter maximum recall length when embodying old appearing hands compared to young appearing hands. It is possible that hands that are different from the user's hands may cause this effect, and that it is not merely due to the age manipulation. However, further support that an age Proteus effect occurred is seen in the analysis of hand movement data matching movement effects that are associated with aging and the elderly. For example, when participants were in the Old condition they had a reduced range of motion compared to when they were in the Young condition, mimicking an older population's reduced range of limb motion [35].

When considering head movement, the elderly have increased back-and-forth movements compared to younger populations [41]. We see a similar result in our data: participants head yaw SD was greater when they were embodied in old hands compared to young hands. Even though we saw greater variation in the back-and-forth head movement, we did not see any difference in head pitch. Previous work identified that the elderly have an increased head-pitch, however this was measured when participants had their eyes closed [34] which is different from our experiment where participants were not asked to close their eyes. Interesting future work might consider differences in head pitch with eyes closed when embodying an elderly appearing avatar compared to having eyes open. The change in head pitch would be an inverse result to the strong body studies [23, 42] where embodying a strong body increased physical performance.

Hand movements also demonstrated movement patterns associated with the elderly. Reaching trajectories are typically more curved in younger adults and straighter in older adults [50]. We again see a similar age Proteus effect pattern when participants used the young hand such that their hand range SD was greater compared to when they used the old hand. This supports a difference in hand trajectory such that in Old participants hands moved in more straight lines with less back-and-forth variation compared to Young. Finally, joint mobility decreases with age [22, 35]. We see that the hand reach range is shortened with the old hand compared to the young hand. These results support that, the older hand modified participant cognitive and physical abilities to match those expected of the elderly.

The two-fold cognitive and movement Proteus effect observed in our study is triggered with an intervention limited to the user's hands, which supports generalization. Though initial body-swap studies started with only the hand [15] research quickly changed to full-body illusions [39]. Interventions on the avatar's face or avatar body require integrating in the narrative of the VR application mechanisms for the user to see their face or body, such as virtual mirrors. These interventions also require changing the user's identity unless a look-alike avatar is created [49]. Limiting the intervention to the avatar's hands broadens applicability as the user is likely to see their hands in many if not most VR applications.

Another important element in support of the broad applicability of the VR user behavior modification reported in our study is the availability of anatomically-complete 27-degree-of-freedom hand tracking, even on low-end VR headsets, such as the Quest 3 and 3S. Although hand tracking accuracy can be improved, it is sufficient to free the user from the encumbrance of hand-held controllers, and to replace the generic gloved VR hands with hand models. These tracked hand models can render complex appearance and motion that is near synchronous to the user's real hands. When considering the AEQ agency submeasure (Fig. 6), the agency scores were relatively high for both hand conditions with means above the total AEQ score for both hand conditions. This supports that the Oculus Quest 3 used in this experience supported adequate hand tracking for users.

In conclusion, the results show that young participants modify their cognitive and motor behavior in the Simon VR game, and that these modifications introduce characteristics associated by prior research with the behavior of older VR participants. These results are an encouraging first step of the investigation into whether the response of older users to a VR intervention can be estimated indirectly, using young participants who are given an age incongruent avatar.

## 7 Limitations and Future Work

Our study opens the door to promising future work in multiple directions. An obvious such direction is to repeat our study with other tasks that place both movement and cognitive demands on the user. As noted in the discussion of the IPQ results, we placed the participant in the virtual environment in a way that avoids visual distractions, which also brought only a moderate sense of presence. Future work should investigate scenarios in which the participant is immersed in a visually complex part of the virtual environment, to examine the interplay between the Proteus effect on one hand and visual complexity and sense of presence on the other. As noted in the discussion of the task load index results, the Simon task complexity is somewhat skewed towards the memory challenge, with a simpler movement challenge. Future studies could increase the complexity of the movement challenge, for example by reducing the size of the game, by adding time constraints when playing back the memorized sequence, or by changing the game altogether. In our study the participants were seated, which is the preferred, safest, and thus most frequent way in which older participants experience VR. Future work could examine tasks performed while standing, which could increase the motor challenge. We have investigated movement performance through a detailed analysis of position and orientation, and future work should also examine the first (speed), second (acceleration), and higher (jerk) derivatives of these signals. Whereas we could easily sample position and orientation at a higher rate, e.g., at 72 Hz or once per frame, robust higher order motion and orientation analysis is likely to require also higher tracking accuracy.

The potential to modify study participant behavior through differences in preliminary exposure has been known long before VR and the Proteus effect. One study primed participants by having them read terms either related to old age or neutral, to find that the first group walked slower down the corridor after the experiment [12]. However, the results of this study proved difficult to replicate. Whereas the Proteus effect has been confirmed by numerous replication studies, the similarity between the earlier study and ours emphasizes the importance that future work attempt to replicate our findings.

Another direction of future work is to investigate manipulating user hand appearance in extended reality (XR), where the user sees their actual hands. This brings the heightened technical challenge of aging the appearance of the user's hands in the live video stream of the XR headset running in passthrough mode. It also brings the promise of a

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stronger user response to the modification, which the user is likely to associate more vividly to their own hands. This hypothesis is supported by prior evidence that the just noticeable difference thresholds for positional redirection of the user hands are more tolerant in XR compared to VR [43].

True to a Proteus effect study design, our work only modified the appearance of the avatar hands, and did not attempt to limit the mobility of the older hands. The relationship between virtual hands and agency is an active and open research area [6,27]. Future work should investigate abandoning the one-to-one mapping between the user hand motion and that of the avatar hands, for example to minimize joint mobility in the older hands. This will allow for an implementation of a decrease in dexterity for the older avatar hands, which could help seed and enhance the user behavior modification. This hypothesis is supported by prior work in pseudo-haptics that showed users cooperate when the arms of their avatar were limited to slower motion underwater, as expected from the effect of water resistance [37]. In the work presented here, a small misalignment of the phalange was applied for the visual suggestion of an arthritic hand. Future work should investigate enforcing kinematic limits of the old avatar hand.

This work was also limited by only testing two different hand ages, young adult and elderly adult. Child hands, and non-human hands were not included in this work. Future research could investigate memory and movement differences when embodying a child's hand vs. a young adult or elderly hand. Furthermore, our approach is limited by the aspects of older VR user behavior that can be induced through a Proteus effect. For example the precarious balance effect of a VR application on older users cannot be investigated indirectly through a Proteus effect. This precludes gathering complete information on older VR participants relying solely on young study participants.

In this work we collect objective and subjective measures and our statistical analysis performs many tests to investigate our research hypotheses. Each additional statistical test performed increases the chance to commit a Type I error in at least one of the tests. Due to this increased risk of Type I error, results should be interpreted with caution. As it is always the case with exploratory work like ours, future work is called upon to collect follow-up confirmatory evidence in replication studies to firm up the support of the research hypotheses and to strengthen any conclusion drawn.

Our study demonstrates modification of the behavior of young VR users towards behavior that has been associated with older VR users by prior work. This is just a preliminary step, and not a demonstration that the response of older users to a VR intervention can be estimated indirectly, using younger participants. Future work is needed to establish a mapping between the amount of hand appearance manipulation and the targeted age. Indeed, our study modified the avatar hands for them to appear "as old as possible". Future work should resort to different degrees of manipulation and to attempt to correlate them to the degree of user behavior modification. Such work will ultimately need to enroll actual older participants to confirm any such correlation.

## 8 Conclusion

We have presented a VR study that suggests the possibility of using young participants to estimate the response of older participants to a VR application. Our approach has potential for broad applicability: the intervention is limited to the avatar's hands, and does not require the availability or modification of a full-body avatar, nor placing constraints on the application narrative to create opportunities for the user to see their avatar beyond its hands. Our work is inscribed in the general effort of expanding the human subject pools of VR studies, towards realizing VR's immense and still largely untapped potential to benefit the older members of our society. Despite the challenges of evaluating and deploying VR interventions to an older demographic, the older members of our society stand to benefit just as much—if not more—from VR. Indeed, the more old-age constraints make more and more real-world experiences less and less accessible to aging individuals, the more important it is to present them with alternatives that can be experienced from the safety and comfort of their home, and this is precisely one of the great strengths of VR.

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