Self-adaptive over progressive non-adaptive immersive virtual reality serious game to promote motor learning in older adults – A double blind randomized controlled trial.

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ABBREVIATIONS

Immersive Virtual Reality = iVR

Feature Integration Theory = FIT

Speed/Accuracy Trade-off = SAT

Response Time = RT

Montreal Cognitive Assessment = MoCA

Test d'Evaluation des Membres Supérieurs de Personnes Agées = TEMPA

Deary-Liewald Reaction Time = DLRT

Deary-Lieward Simple Reaction Time = DLRT-S

Deary-Lieward Choice Reaction Time = DLRT-C

Spectral Arc Length = SPARC

Arm Displacement = Lpath

Repeated Measures General Linear Model = RM-GLM

ABSTRACT

Older adults often experience cognitive and functional decline, which can be mitigated by innovative interventions like immersive virtual reality (iVR). Self-adaptive serious games, which dynamically adjust task difficulty, may provide additional benefits by tailoring challenges to individual performance. However, the comparative effectiveness of self-adaptive versus progressive non-adaptive iVR interventions on motor learning in older adults remains underexplored. This randomized controlled trial primarily aimed to compare the effects of self-adaptive and progressive non-adaptive iVR interventions on motor learning in older adults. A total of 33 older adults were randomly assigned to either a self-adaptive (n=17) or progressive non-adaptive (n=16) iVR group. Both interventions involved an iVR serious game requiring unimanual reaching, target selection, and distractor inhibition under increasing difficulty over three days. Performance was evaluated pre- and post-intervention using a standardized iVR task, consisting of hitting a virtual target while ignoring distractors. This task features five levels of difficulty (level 0: no distractors; level 4: 17 low-saliency distractors). Primary outcomes, assessed during the standardized task, included changes in speed-accuracy trade-offs (SAT) and relative response time (RT, compared to level 0). Both participants and assessors were blinded to the intervention. After the intervention, both groups exhibited significant SAT improvements at level 1, 3 and 4 ($P<0.05$) and RT gains at level 3 and 4 ($P<0.05$). The self-adaptive group demonstrated significantly greater SAT ($P=0.049$) and relative RT ($P=0.004$) improvements at level 4. Findings suggest that older adults can achieve motor learning in iVR, particularly with self-adaptive serious games, highlighting potential for self-rehabilitation.

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Keywords: Virtual Reality; Aged; Upper Extremity; Kinematics; Attention; Randomized Controlled Trial

HIGHLIGHTS

- Immersive virtual reality (iVR) enhanced speed-accuracy trade offs (SAT).
- Both self- and non-adaptive iVR enhanced SAT and relative RT across levels.
- Self-adaptive iVR led to greater SAT and relative RT at the hardest level.
- Both groups improved movement linearity and peak speed at the easiest level.
- Upper limb activity and motor coordination improved in both groups.
- Movement smoothness, manual dexterity or reaction time did not improve.

INTRODUCTION

On average, older adults spend a significant portion of their waking hours (around 70%) in sedentary and socially isolated states (Harvey et al., 2015). These behaviours create a cycle of decreased engagement and growing dependency (Botö et al., 2021), which not only worsen functional and cognitive decline but also increases the risk of chronic diseases and mortality (Pantell et al., 2013; Park et al., 2020). With the global population of older adults projected to reach nearly 22% by 2050, there is an urgent need for innovative approaches that can enhance functional performance and improve quality of life (Wasay et al., 2016).

Traditional leisure-time activities, though beneficial, often require substantial caregiver involvement (Arem et al., 2015). To address this challenge, serious games and virtual reality present an innovative alternative. Serious games are defined as games designed for a primary purpose beyond pure entertainment, such as education, training, or rehabilitation (Michael and Chen, 2006). These games are intentionally developed to achieve specific outcomes and can be used in various fields including health care and geriatric rehabilitation (Saragih et al., 2022).

Virtual reality systems can be divided into different categories: (i) non-immersive virtual reality, where users remain aware of their physical surroundings and interact through a 2D display, and (ii) immersive VR (iVR), which allows complete submersion in the virtual environment through a head mounted display, a panoramic projection or a large curved screen (Huygelier et al., 2021). The iVR systems are increasingly used in rehabilitation and geriatric care (Doré et al., 2023; Everard et al., 2024), offering interactive and immersive environments that can be accessed remotely and autonomously (Pedram et al., 2020), and by providing a cost-effective solution (Pot-Kolder et al., 2020) for engaging older adults that promote physical and cognitive activities (Appel et al., 2019). iVR technologies can provide opportunities to facilitate motor learning (Lang et al., 2018), a process that involves the improvement of skills through practice. This process engages both cognitive and motor systems, with skills acquired through motor learning being retained and applied across different contexts (Krakauer et al., 2019; Muratori et al., 2013). Research has shown that combining motor and cognitive challenges in virtual reality can enhance the overall effectiveness of interventions, as both aspects are interrelated and impact one another (Buele and Palacios-Navarro, 2023).

From a motor point of view, iVR and serious games can simulate complex motor tasks and environments that promote motor learning (Saragih et al., 2022; Saragih et al., 2024). This process typically involves practicing skills that improve kinematic aspects such as movement speed, coordination, and accuracy. In the literature, kinematics indices, such as the speed-accuracy trade-off (SAT) function, are often used as markers of motor learning (Gathy et al., 2024; Gerardin et al., 2022; Riga et al., 2022). The SAT represents the relationship between the speed of a movement and its accuracy as individuals strive to perform faster, the accuracy of their movements typically decreases, and vice versa. A shift in the SAT function can be interpreted as evidence of skill acquisition and motor learning, reflecting the ability to optimize movement strategies to meet task demands (Molina et al., 2019). Other kinematic measures, such as the coefficient of linearity and spectral arc length of the instantaneous velocity (SPARC), can also provide valuable insights into motor performance. The coefficient of linearity assesses the straightness of a movement trajectory, with higher values indicating more efficient and controlled movements. SPARC, on the other hand, is a movement smoothness index, providing information about the quality of movement in relation to its continuity and the absence of interruptions.

Virtual reality interventions can be designed to progressively challenge motor abilities, thereby facilitating motor learning through repetitive and varied practice in a controlled virtual setting (Levac et al., 2019). Several studies have provided evidence that the provision of haptic and visual feedback in iVR positively influences movement smoothness, accuracy, and rapidity, thereby contributing to improved motor learning outcomes (Bugdadi et al., 2019; Everard et al., 2023). Haptic feedback, which involves tactile sensations, may help users adjust their movements with greater precision and coordination, while visual feedback allows for the provisioning of real-time information on movement performance (Everard et al., 2024). However, the extent to which improvements in motor skills and kinematics within iVR transfer to standardized functional assessments and real-world tasks remains uncertain (Levac et al., 2019). The effects of iVR interventions on functional outcomes, such as motor coordination and manual dexterity, when measured outside of the virtual environment, have yet to be clearly established.

From a cognitive point of view, research based on feature integration theory (FIT) (Treisman and Gelade, 1980) provides valuable insights into how inhibitory attentional processes can be integrated into iVR and rehabilitation (Ajana et al., 2023). Treisman and Gelade (1980) demonstrated that attention is automatically captured by a target when it differs from distractors (irrelevant stimuli) by a high salience contrast (e.g., color; red target and blue distractors), causing a "pop-out" effect (Treisman and Gelade, 1980). The target stands out against distractors, allowing for rapid and parallel search processes (Duncan and Humphreys, 1989; Treisman and Gelade, 1980). Conversely, when a target has a low salience contrast from distractors (e.g., color and shape), search processes become serial and effortful. Attention must shift sequentially across stimuli, which is more demanding on cognitive resources, resulting in longer response times (RT) (Treisman and Gelade, 1980). In such cases, relative RT, which is the difference in RT between tasks with and without distractors, can be a key measure to quantify the added cognitive load and the efficiency of attentional shifts in iVR-based rehabilitation tasks (Steinhauser and Hübner, 2007).

This understanding of inhibitory attentional processing can be leveraged in iVR rehabilitation to design tasks that simultaneously challenge motor and cognitive systems, enhancing both motor skills and inhibitory attention. Our previous study demonstrated the feasibility of designing an iVR software involving both motor and cognitive functions (Ajana et al., 2023). In this serious game, participants engaged with three-dimensional animated stimuli where they used a virtual hammer to hit targets and avoided responding to distractors. Our findings demonstrated that the game's design, which includes tasks requiring high and low salience target-distractor searches, replicated FIT. Specifically, we observed that performance in finding and responding to a target having a high salience difference from distractors was fast, and that increasing distractor number had no influence. In contrast, performance in finding and responding to a target with a low salience difference from distractors was slow, and performance decreased with increasing numbers of distractors, indicative of the heightened cognitive load associated with more complex visual search. Kinematic analyses showed variations in movement smoothness, further demonstrating the impact of cognitive demand on motor performance.

Another key area of interest in iVR and motor learning is the development of self-adaptive serious games. The self-adaptability refers to the ability of a system to adapt its behaviour in response to variations in the environment and the user's condition (Macías-Escrivá et al., 2013). In rehabilitation, these games dynamically adjust the difficulty of tasks in real-time based on the user's performance, offering personalized challenges that enhance engagement and efficacy (Doumas et al., 2025). This adaptive process operates independently of any intervention by the therapist, making it particularly valuable for home-based or self-training (Bouatrous et al., 2023). The literature suggests that adaptive difficulty is crucial for maintaining motivation and optimizing learning outcomes (Hocine et al., 2014). For instance, Afyouni et al. conducted a feasibility trial demonstrating that participants with neck pain who followed a self-adaptive virtual reality intervention reported high levels of motivation and engagement, with performance outcomes similar to traditional rehabilitation approaches (Afyouni et al., 2020). Similarly, Wang et al. developed an iVR system where participants were required to trace curves as accurately as possible. The game offered a self-adaptive and non-adaptive condition (Wang et al., 2024). Their results indicated that healthy individuals reported higher satisfaction in the self-adaptive condition although performance metrics such as accuracy and range of motion were similar between the self-adaptive and non-adaptive conditions.

While several studies have explored self-adaptive interventions, significant gaps remain in the literature. Notably, no randomized controlled trials have compared the effects of self-adaptive versus progressive non-adaptive iVR interventions on both motor performance and attentional functions. Furthermore, the impact of self-adaptive serious games on older adults' functional performance, particularly in terms of motor and cognitive function, remains underexplored and debated. There is ongoing uncertainty regarding the extent to which skills acquired in iVR can be transferred to real-world functional tasks. Our study aims to address these gaps by conducting a double-blind randomized controlled trial comparing two iVR interventions in older adults: one using a self-adaptive system, which adjusts difficulty based on real-time performance, and another using a progressive, non-adaptive program with fixed difficulty increments. We will assess their effectiveness in improving key motor learning outcomes, including unimanual reaching SAT, as well as cognitive attentional functions, such as relative (to baseline) RT. We hypothesize that the self-adaptive iVR serious game will lead to greater improvements in both SAT and relative RT than the progressive non-adaptive intervention, due to its personalized and dynamic challenge levels. Secondary outcomes will include the transfer of iVR skills to functional performance such as motor coordination, upper limb activity, manual dexterity as well as the effect of iVR on reaction time when measured outside the virtual environment.

EXPERIMENTAL PROCEDURES

Study design

This randomized controlled trial was conducted in alignment with the declaration of Helsinki. The protocol received approval from the *Recherche Sectorielle en Réadaptation and*

Intégration Sociale Ethics Committee (#2020-1909), and the study was prospectively registered on clinicaltrials.gov (NCT 06141642). Written informed consent was obtained from all participants prior to their involvement in the trial. The study adhered to CONSORT guidelines, and the data supporting the findings of this work are available from the corresponding author upon reasonable request.

Participants

All participants were recruited between January and June 2024 among the Canadian population (in Quebec), and in senior home residences in Quebec (Canada).

To be eligible for this study participants had to meet the following inclusion criteria: (1) having a normal or corrected-to-normal vision, (2) obtaining a score greater than 24 on the Montreal Cognitive Assessment (MoCA), and (3) being 65 years of age or older. Individuals were excluded from participation if they had (1) severe comprehension issues that could have impeded their ability to understand or follow the study instructions, (2) a history of seizures, or (3) prior experience with serious games in iVR environments.

Randomisation and masking

After providing consent to participate and before beginning the experiment, participants were randomly assigned in a 1:1 ratio to either a self-adaptive (experimental group) or progressive non-adaptive (control group) iVR serious game-based motor learning intervention. Randomization was conducted using opaque, sealed envelopes, with stratification based on age and sex. Only the intervention provider was informed of the group assignments to ensure the correct intervention mode (self-adaptive or progressive non-adaptive) was administered. Both the participants and the outcome assessors were blinded to the group assignments.

At the conclusion of the experiment, participants were asked to indicate their certainty about which group they believed they were assigned to by choosing one of the following options: no idea, thought they were in the self-adaptive group, or thought they were in the progressive non-adaptive group. For the latter two responses, participants were also requested to rate their confidence level in their response on a five-point Likert scale, ranging from 1 (not confident at all) to 5 (completely confident).

Procedure and interventions

The protocol lasted three days. On the first day, participants received detailed explanations regarding the trial, oral instructions explaining the operation of the various tests, and how to interact with the iVR system. Throughout the experiment, participants remained seated and performed actions with their non-dominant hand. We chose to focus on the non-dominant hand, assuming that it would exhibit a higher margin of improvement compared to the dominant hand (Stöckel and Weigelt, 2012).

The intervention consisted of playing a shortened version of the iVR serious game (REAsmash-iVR) for 20 minutes during three consecutive days (Ajana et al., 2023). The REAsmash-iVR involves detecting and striking, as quickly as possible, a virtual mole wearing a red miner's helmet, which is presented among various distractors. In the parallel search condition, the distractor moles wore a blue miner's helmet and a blue horned helmet. In the conjunction search condition, the distractor moles wore a blue miner's helmet or a red horned helmet. The intervention was delivered using the Meta Quest 2 device (Facebook®) using one haptic controller and a head-mounted display. All the software were internally designed on Unity 2020.3.3 (C# language).

In the self-adaptive group, the REAsmash-iVR game automatically adjusted difficulty based on participants' performance to maintain a 75% success rate (number of target moles correctly hit divided by the total number of trials, where each trial referred to a single instance of locating and hitting a target mole). The starting level of the game was set as very easy (e.g., high salience), and as participants improved, the game became more challenging (i.e., low salience with increasing numbers of distractors), requiring more frequent and precise reaching movements (see Figure 1). The game adapted continuously through an infinite sequence of trial blocks. A block was a set of multiple trials, ranging from 1 to 24, depending on the participant's performance level. After each block, the difficulty was adjusted according to the success rate. If the rate was above 75%, the game was made harder; if below 75%, it was made easier. As presented in Figure 1, adjustments were based on various factors, including the success rate, number and location of omissions (missed targets), number of false positives (hit distractors) and their locations, which influenced parameters like target lifetime (the duration it remained), distractor types and number, and working area. A detailed explanation about the regulation of the game is available in Supplementary Material 1.

Figure 1. Regulation of the self-adaptive intervention

In the progressive non-adaptive group, the REAsmash-iVR game difficulty was not self-adaptive. The challenge was progressively heightened by gradually increasing the saliency difference between the target and distractor moles, as well as the number of distractor moles. The location of both the target and distractors were randomly selected in each trial, and the types of distractors were randomly displayed. In the progressive non-adaptive mode, the target mole's lifetime was fixed to 7 seconds throughout the session.

Standardized evaluations

All complete standardized assessments were done on day 1 (before the intervention) and day 3 (after the completion of the intervention). Kinematics, RTs, omissions and false positives were measured in iVR using the REAsmash-iVR standardized test. To ensure participants had a consistent evaluation each day, level 0 of the REAsmash-iVR standardized test (which is described in the next section) was also administered on day 2 and day 3 before the intervention.

To test the transfer of iVR skills to performance in everyday activities, standardized functional assessments were conducted pre- and post-intervention. Manual dexterity was assessed with the Box and Block Test, upper limb activity was assessed with the glass subscale of the *Test d'Evaluation des Membres Supérieurs de Personnes Agées* (TEMPA), and motor coordination was assessed with the Finger-Nose Test. We also evaluated the effect of iVR on reaction time when measured outside the virtual environment using the Deary-Liewald Reaction Time (DLRT) task. The whole procedure, which includes all testing and interventions, is presented in Figure 2.

Standardized evaluations – iVR outcomes

The REAsmash-iVR standardized test allows for the measurement of RT, number of omissions and false positives, and kinematics (see kinematics section) during a task involving detecting and striking, as quickly as possible, a virtual mole wearing a red miner's helmet, which is presented among various distractors (Ajana et al., 2023). The current version was shortened to consist of five levels, each comprising 18 trials. In each trial, the target mole appeared randomly in a 6 × 3 array. We added a level 0 to serve as a baseline, where only the target was presented with no distractors. Level 1 introduced 11 distractors, 5 with a blue miner’s helmet and 6 with a blue horned helmet. Level 2 increases the number of distractors to 17, 8 with a blue miner’s helmet and 9 with a blue horned helmet. Level 3 presented 11 distractors, 5 with a blue miner’s helmet and 6 with a red horned helmet and Level 4 presented 17 distractors, 8 with a blue miner’s helmet and 9 with a red horned helmet. Each trial required participants to strike the target mole while ignoring the distractors. The design aimed to progressively challenge participants' attention and reaction skills by varying the number and types of distractors, while keeping the molehill grid layout consistent. Performance data, including success or failure to detect and hit the target (success, omission, or false positive hit to the distractor), RT (the interval between target appearance and successful hit), and 3D controller position is recorded in a .csv file on the headset. This allowed to compute kinematics (described in the kinematics section) and relative RT, subtracting the mean baseline RT (targets without distractors) ($RT_{level\ 0}$) from absolute RT. Computing the relative RT enabled to remove individual differences in RT and isolate the cognitive dimension of inhibition cost to RT.

$$Relative\ RT_{level\ x} = RT_{level\ x} - RT_{level\ 0}$$

Standardized evaluations – functional assessments and reaction time measurements

The Box and Block Test was used to evaluate the transfer of iVR performance to gross manual dexterity. This test was deemed valid and reliable (Desrosiers et al., 1994). The test involves grasping and displacing as many wooden blocks as possible from one side of a box to the other within one minute.

The TEMPA was used to evaluate the transfer of iVR performance to upper limb activity. The TEMPA is a valid and reliable test for assessing upper limb function in older adults, encompassing the performance of nine everyday upper limb activities (Desrosiers et al., 1995; Desrosiers et al., 1993). In this study, we only performed the glass-subscale of the test, consisting of pouring a glass with water and bringing it to the mouth. The score corresponds to the time required to complete the task.

The Finger-Nose Test was used to evaluate the transfer of iVR performance to motor coordination. In this test, participants are required to alternately touch their nose and a 3 cm square target positioned 30 cm away on a wall, within the horizontal plane. The goal is to complete as many repetitions as possible within 20 seconds without missing either the nose or the target. This test is valid and reliable (Gagnon et al., 2004).

The DLRT was used to test the effect of both iVR interventions on reaction time when measured outside the virtual environment. The DLRT is a computerized assessment comprising two subtests designed to evaluate different aspects of reaction time (Deary et al., 2011). The first subtest (DLRT-S) measures simple reaction time, where participants respond as quickly as possible to a visual stimulus by pressing a button. The second subtest assesses choice reaction time (DLRT-C), requiring participants to decide and respond to one of several possible stimuli presented randomly. Both subtests aim to capture various dimensions of reaction speed and decision-making efficiency.

Kinematic analysis

The kinematic data were analysed using a custom program developed in Python. Three-dimensional positions of the controller, recorded during both the assessment and serious game in virtual reality were extracted from export files (.csv) at a sampling rate of 60 Hz. For each participant, a preliminary visual inspection was performed to confirm accurate data acquisition, followed by signal smoothing using a Butterworth filter (sampling frequency = 60 Hz; cut-off frequency = 10 Hz). The following kinematic indices were calculated for each trial: arm displacement (Lpath), mean velocity, peak velocity, coefficient of linearity, coefficient of variation of the velocity, spectral arc length (SPARC) and speed/accuracy trade-off (SAT). For each of these kinematic indexes, an average score was computed for each level (for the REAsmash-iVR standardized test) or block (for the REAsmash-iVR game), excluding trials where the target mole was not hit.

Our primary outcome was the SAT. The SAT is a motor learning metric that quantifies improvements induced by training (Fitts, 1992). In this study, SAT was computed as the ratio between velocity and error using the equation:

$$SAT = C \times \frac{Mean\ velocity}{Pathway\ error}\ (where\ C = 10\ m.s^{-2})$$

We also computed relative SAT to remove individual differences in SAT.

$$Relative\ SAT_{level\ x} = SAT_{level\ 0} - SAT_{level\ x}$$

Here, mean velocity was defined as the mean of the first derivative of controller position, while the pathway error was measured by dividing the controller's displacement to the ideal path (shortest distance between the target and the controller’s positions). For SAT computed during the intervention, since the conditions were not standardized as the parameters differ across blocks and between interventions arms, we used a backward stepwise model to adjust SAT (in-game-SAT) according to the observed parameters of the block (see Supplementary Material 2). In-game-SAT was therefore computed using the following equation:

$$In - game - SAT = SAT + (0.794 \times Presence\ of\ distractors)$$
$$-(0.0561 \times \#Blue\ horned\ distractors)$$
$$+(0.0867 \times \#Red\ horned\ distractors)$$

Here, the presence of distractors was set to 0 if there were no distractors and to 1 if there was at least one distractor).

Mean velocity corresponds to the ratio between the arm displacement and the movement duration. Peak velocity corresponds to the maximal instant velocity within a trial. The coefficient of linearity is the ratio between the shortest distance between the controller and the target at the moment of its appearance (i.e., the length of the ideal route) and the arm displacement. This metric ranges from 0 to 100%. A higher score indicates a better linearity. The coefficient of variation of the velocity, another smoothness index, is computed as the ratio between the standard deviation of the instant velocity and the mean velocity. This index ranges from 0 to 100%. A lower value corresponds to a smoother movement. The SPARC is a smoothness metric ranging from -∞ to 0 and computed as the spectral arc length of the normalized instant velocity signal (Balasubramanian et al., 2015). A higher SPARC value corresponds to a smoother movement.

Figure 2. Experimental protocol

Functional and reaction time assessments were conducted at baseline (day 1, before the intervention) and at the end of the intervention (day 3). Kinematic data, response time, number of omissions, and false positives were recorded across all five levels of the REAsmash-iVR assessment at baseline (day 1) and post-intervention (day 3). Additionally, performance at level 0 was assessed before the intervention on day 2 and 3. Using the in-game SAT computation, participants' kinematic progression during gameplay was also analyzed throughout the intervention. BBT = Box and Block Test; DLRT = Deary Liewald Reaction Time task; FNT = Finger Nose Test; iVR = immersive virtual reality; RT = response time; SAT = speed/accuracy trade-off; TEMPA = *Test d'Evaluation des Membres Supérieurs de Personnes Agées*; UL = upper limb.

Outcome

The primary motor outcome was changes in SAT from baseline to post-intervention assessment. To evaluate the effect of both interventions on motor learning, in-game-SAT was compared over time (first block of day 1 vs last block of day 1 vs first block of day 2 vs last block of day 2 vs first block of day 3 vs last block of day 3). The primary cognitive outcome was change in relative RT from baseline to post-intervention.

The secondary outcomes were changes in the number of omissions and false positives, SPARC, coefficient of linearity, mean velocity, peak velocity, coefficient of variation of the velocity, Lpath, and the scores of the Box and Block Test, the TEMPA, the Finger Nose Test and the DLRT.

Statistical analysis

We conducted all statistical analyses using IBM SPSS Statistics 25, setting the significance threshold at $\alpha=0.05$. The normality of the data was evaluated using the Shapiro-Wilk test and Q-Q plot. Equivalence between group characteristics at baseline were assessed using the Mann-Whitney U test, z-scores, and t-tests.

For the primary outcome measures, a Repeated Measures General Linear Model (RM-GLM) was used with SAT and relative RT as dependent variables, time (day 1 to day 3) as a within-subject factor, and group (self-adaptive vs progressive non-adaptive) as a between-subjects factor. When sphericity was violated, Greenhouse-Geisser (for $\varepsilon < 0.75$) or Huynh-Feldt corrections (for $\varepsilon \geq 0.75$) were applied. To account for multiple pairwise comparisons, Bonferroni corrections were applied to adjust the significance level. If the residuals did not follow a normal distribution, a Wilcoxon Signed Rank Test (or a Friedman's Analysis of Variance by Ranks if more than 2 repeated measures) was used to assess the effect of time, and a Mann-Whitney U test comparing changes between baseline and post-intervention scores was used to assess the interaction effect between time and group.

For the secondary outcome measures, RM-GLMs with time and group as within- and between-subjects factors, respectively, were also used. Wilcoxon Signed Rank and Mann-Whitney U tests were also applied for non-continuous measures and for data whose residuals did not follow a normal distribution.

A modified intention-to-treat approach was used, including all participants who engaged in the study without major protocol violations, regardless of the group to which they were assigned and the amount of intervention completed.

As this was a pilot randomized controlled trial, no formal sample size calculation was conducted. However, it was estimated that a sample size of 30 participants would be required to detect an effect size of Cohen's d > 0.8 (Power = 0.8; β = 0.2) when comparing SAT between the first and third days.

RESULTS

Between January 9, 2024, and June 5, 2024, a total of 45 participants were screened for eligibility (see Figure 3). Five participants did not meet the eligibility criteria, and nine withdrew before beginning the protocol. Of the 33 participants randomly assigned to the intervention, 17 were placed in the self-adaptive group, while 16 were assigned to the progressive non-adaptive group. All 33 participants completed the study intervention. However, two participants used their dominant hand during the whole protocol (which was considered as a major protocol violation) and were subsequently excluded from the modified intention-to-treat analysis.

Figure 3. Flow chart diagram

There were no major protocol deviations that impacted participants' rights, safety, well-being, or the study's scientific integrity. Additionally, no serious nor non-serious adverse events occurred. The baseline demographics are presented in Table 1, and the groups were evenly matched at baseline.

Table 1. Baseline demographics

	Self-adaptive (n=17)	Progressive non-adaptive (n=16)	p-value
Age (years)	74.3 (6.41)	75.2 (6.18)	0.698
Sex (M/F)	15/2	14/2	0.639
Height (feet)	5.3 [5.00 – 5.40]	5.3 [5.20 – 5.50]	0.267
MoCA (/30)	26 [25.25 – 27.75]	28 [26.00 – 29.00]	0.099
BBT (#blocks)	64 [57.8 – 65.00]	59 [54.0 – 71.0]	0.937
FNT (# mvts)	24 [22.0 – 27.0]	24 [23.0 – 29.0]	0.499
TEMPA (s)	12.3 (2.53)	11.3 (3.05)	0.318
Baseline SAT	1.49 (0.256)	1.57 (0.283)	0.432
Baseline RT (s)	3.44 [3.094 – 3.695]	3.30 [3.042 – 3.599]	0.353

MoCA = Montreal Cognitive Assessment; BBT = Box and Block Test; mvts = movements; FNT = Finger Nose Test; TEMPA = *Test Evaluant la Performance des. Membres supérieurs des Personnes Agées*; SAT = Speed Accuracy/Trade-off; RT = Response Time; Age, TEMPA and Baseline SAT are presented as means (standard deviations), other variables are presented as median [first quartile – third quartile]. Baseline SAT and baseline RT are presented for Level 0.

Figure 4. Evolution of the success rate over time

The x-axis represents the block number of the REAsmash-iVR intervention, while the y-axis shows the participants' success rate. The central lines indicate the medians, and the envelopes around the lines represent the interquartile range. Results for the progressive non-adaptive group are shown in red with a solid line, and results for the self-adaptive group are shown in turquoise with a dotted line.

Participants in the experimental and control group performed a similar mean number of movements per session (experimental group: 302 [SD 29.9]) movements; control group: 299 [SD 25.1] movements). Over the three days, the median success rate was of 80 [68.4 – 91.7] % in the self-adaptive group and 100 [100 - 100] % in the non-adaptive progressive group (see Figure 4). The evolutions of distractors number and target lifetime per group are presented in Figure 5.

Figure 5. Evolution of distractors number and target lifetime over time.

A. In this plot, each line represents the evolution of the median number of distractors (y-axis) in relation to the time (x-axis). Results for the progressive non-adaptive group are shown in red and results for the self-adaptive group are shown in turquoise. Distractors with blue horned helmet are plotted using a continuous line, distractors with a red horned helmet are plotted using a dashed line, and distractors with a regular blue miner helmet are plotted using a dotted line.

B. In this plot, the lifetime of the target (y-axis) is presented in relation to the time (x-axis). The central lines indicate the medians, and the envelopes around the lines represent the interquartile range. Results for the progressive non-adaptive group are shown in red with a solid line, and results for the self-adaptive group are shown in turquoise with a dotted line.

In both plots, on the x-axis, First 1, First 2 and First 3 correspond the first three blocks of each day. Last 3, Last 2 and Last 1 correspond to the last three blocks of each day.

Primary motor outcome

As presented in Figure 6, the effect of experimental and control group on SAT were similar across levels, except at the most difficult level (level 4; low salience-high numbers of distractors). At this level, the effect of the self-adaptive group showed a significantly ($F = 4.21$; $P = 0.049$) greater SAT improvement (mean change = 0.38 [SD 0.076]) than the progressive non-adaptive group (mean change = 0.15 [SD 0.078]) (between group difference 0.22; 95% CI 0.001 – 0.446; see Table 2). Except for levels 0 and 2, SAT scores significantly improved over time from baseline to post-intervention assessment ($P < 0.05$). Regarding relative SAT, as presented in Supplementary Material 3, the self-adaptive group exhibited significant larger improvements than the progressive non-adaptive group for level 3 ($F = 10.08$; $P = 0.004$) and 4 ($F = 8.68$; $P = 0.006$).

Figure 6. Evolution of Speed/accuracy trade-off over time.

The x-axis represents the block number of the REAsmash-iVR intervention, while the y-axis shows the participants' speed/accuracy trade-off. The central lines indicate the medians, and the envelopes around the lines represent the interquartile range. Results for the progressive non-adaptive group are shown in red with a solid line, and results for the self-adaptive group are shown in turquoise with a dotted line. Significant effects of time are presented with continuous blue brackets and significant interactions of time x group are presented with green dotted brackets. On the x-axis, First 1, First 2 and First 3 correspond the first three blocks of each day. Last 3, Last 2 and Last 1 correspond to the last three blocks of each day. "Post" stands for post-intervention assessment.

As presented in Figure 6, in-game-SAT scores significantly improved between the first and last block of day 1 ($F = 49.18$; $P < 0.001$) with retention at day 2 ($F = 32.55$; $P < 0.001$), between the first block of day 1 and the last block of day 2 ($F = 42.93$; $P <0.001$) with retention at day 3 ($F = 48.26$; $P < 0.001$), and between the first block of day 1 and the last block of day 3 ($F = 45.17$; $P < 0.001$). However, no significant difference ($P > 0.05$) was found between the effect of both groups.

Primary cognitive outcome

The effect of groups on relative RT were not significantly different, except at level 4. At this level, the self-adaptive group exhibited a significantly ($U = 49.0$; $P = 0.004$) larger improvement (median change = -0.71 [-0.942 – 0.498] s) than the progressive non-adaptive group (median change = -0.18 [-0.567 – -0.430] s) (Table 2). Furthermore, relative RT showed a significant reduction over time from the baseline to the post-intervention assessments across levels 3 ($W = -414.0$; $P < 0.001$) and 4 ($W = -416.0$; $P < 0.001$) (Table 2).

Table 2. Effect of time and group assignment on speed/accuracy trade-off and response time.

	Baseline Mean (SD)	Post-intervention Mean (SD)	Time p-value	Time*Group p-value
SAT – Level 0				
Self-adaptive	3.14 (0.459)	3.22 (0.420)	0.072	0.562
Progressive non-adaptive	3.04 (0.553)	3.27 (0.564)		
SAT – Level 1				
Self-adaptive	2.67 (0.490)	2.84 (0.393)	**0.019**	0.966
Progressive non-adaptive	2.63 (0.362)	2.80 (0.385)		
SAT – Level 2				
Self-adaptive	2.79 (0.534)	2.93 (0.405)	0.075[a]	0.599[b]
Progressive non-adaptive	2.79 (0.480)	2.89 (0.426)		
SAT – Level 3				
Self-adaptive	1.76 (0.359)	2.02 (0.256)	**<0.001**[a]	0.572[b]
Progressive non-adaptive	1.77 (0.275)	1.97 (0.339)		
SAT – Level 4				
Self-adaptive	1.49 (0.256)	1.87 (0.285)	**<0.001**	**0.049**
Progressive non-adaptive	1.57 (0.283)	1.72 (0.346)		
Relative RT (s) – Level 1				
Self-adaptive	0.34 (0.153)	0.28 (0.107)	0.142[a]	0.470[b]
Progressive non-adaptive	0.32 (0.153)	0.30 (0.143)		
Relative RT (s) – Level 2				
Self-adaptive	0.33 (0.212)	0.27 (0.110)	0.071[a]	0.830[b]
Progressive non-adaptive	0.32 (0.259)	0.33 (0.196)		
Relative RT (s) – Level 3				
Self-adaptive	1.38 (0.517)	1.02 (0.205)	**<0.001**[a]	0.626[b]
Progressive non-adaptive	1.35 (0.342)	1.10 (0.300)		
Relative RT (s) – Level 4				
Self-adaptive	2.06 (0.465)	1.35 (0.374)	**<0.001**[a]	**0.004**[b]
Progressive non-adaptive	1.87 (0.419)	1.62 (0.432)		

SAT = Speed/Accuracy Trade-off; RT= Response Time. P-values are issued from the General Linear Model except for [a] = p-values are issued from the Wilcoxon Signed Rank Test as residuals did not follow a normal distribution; [b] = p-values are issued from the Mann-Whitney U Test as residuals did not follow a normal distribution.

Secondary outcomes

Regarding kinematics, as presented in Supplementary Material 4, statistical analyses suggest that SPARC, coefficient of variation of velocity and Lpath did not significantly change over time (P > 0.05). Mean velocity was increased for level 0 ($\chi^2 = 11.94$; P = 0.008), level 3 (W = 179.0; P = 0.04) and level 4 (W = 276.0; P = 0.003). Coefficient of linearity ($\chi^2 = 8.92$; P =

0.03) and peak velocity (F = 4.194; P = 0.008) also significantly changed over time but only for level 0. No significant interaction between time and group was found (P > 0.05).

The number of false positive significantly decreased over time for levels 1 (W = -67.0; P = 0.005) and 3 (W = -197.0; P < 0.001), as did the omissions for level 3 (W = -21.0; P = 0.03). The effect of self-adaptive over progressive non-adaptive intervention was not significant (P > 0.05).

Regarding the transfer to performance on functional tests, as presented in Table 3, iVR serious games interventions led to improved TEMPA (F = 7.37; P = 0.011) and Finger Nose Test scores (W = 207.0; P < 0.001) but did not affect BBT, DLRT-S and DLRT-C scores (P > 0.05). No significant interaction between time and group was found (P > 0.05).

Table 3. Transfer to performance on functional tests.

	Baseline Mean (SD)	**Post-intervention Mean (SD)**	**Time p-value**	**Time*Group p-value**
BBT (# blocks)				
Self-adaptive	61 (6.5)	63 (6.9)	0.247	0.475
Progressive non-adaptive	62 (8.8)	62 (8.7)		
TEMPA_glass (s)				
Self-adaptive	12.3 (2.53)	10.8 (2.15)	**0.011**	0.414
Progressive non-adaptive	11.3 (3.05)	10.5 (1.81)		
FNT (# mvts)				
Self-adaptive	24.8 (4.55)	27.0 (4.59)	**<0.001**[a]	0.572[b]
Progressive non-adaptive	25.7 (4.22)	27.3 (3.89)		
DLRT-S				
Self-adaptive	294.6 (35.04)	308.8 (47.26)	0.240[a]	0.520[b]
Progressive non-adaptive	362.8 (179.21)	327.5 (45.70)		
DLRT-C				
Self-adaptive	606.3 (82.14)	589.6 (95.01)	0.094[a]	0.935[b]
Progressive non-adaptive	578.9 (124.8)	554.1 (93.65)		

BBT = Box and Block Test; TEMPA_glass = glass subscale of the *Test d'Evaluation des Membres Supérieurs de Personnes Agées*; FNT = Finger Nose Test ; DLRT-S = Deary-Liewald simple Reaction Time ; DLRT-C = Deary-Liewald choice Reaction Time; mvts = back and forth movements; P-values are issued from the General Linear Model except for [a] = p-values are issued from the Wilcoxon Signed Rank Test as residuals did not follow a normal distribution; [b] = p-values are issued from the Mann-Whitney U Test as residuals did not follow a normal distribution.

Treatment allocation

Four participants (25%) in the self-adaptive group and six participants (40%) in the progressive non-adaptive group had no idea in what group they were allocated. Additionally, eight participants in the self-adaptive group and four in the progressive non-adaptive group incorrectly identified their treatment allocation, with a certainty coefficient of 3.5 [3 - 4] and 3

[2.75 - 3.25], respectively. Conversely, four participants (25%) in the self-adaptive group and five (33%) in the progressive non-adaptive group correctly identified their treatment allocation, with certainty coefficients of 3 [2.75 - 3] and 4 [3.5 - 4], respectively.

DISCUSSION

Between January and June 2024, 33 participants were included in the study (17 in the self-adaptive group, 16 in the progressive non-adaptive group), with two excluded due to protocol violations. Both groups showed significant improvements on SAT and relative RT across most levels, with the self-adaptive group demonstrating significantly greater gains at the most challenging level (level 4) for both SAT and relative RT. Kinematic outcomes, such as mean and peak velocity, improved over time without significant differences between groups, while errors (false positives and omissions) significantly decreased at various levels. In terms of functional performance, both interventions led to improvements in TEMPA and Finger Nose Test scores ($P < 0.05$), though no significant effects were observed for the Box and Block Test nor DLRT.

Neutral effect with enhanced performance at the highest difficulty level

In this study, both the self-adaptive and progressive non-adaptive groups showed significant improvements in motor and cognitive performance, yet a notable distinction emerged at the most challenging level of difficulty (level 4). This showed that the self-adaptive group outperformed the progressive non-adaptive group at level 4, even though the evolution of effect in both groups followed a similar trajectory of improvement (as presented in Figure 4A). This demonstrates that control intervention was also effective in enhancing participants' inhibitory attention, likely due to its structured progression that provided incremental challenges. This possible effect of the progressive nature of the control intervention is supported by literature demonstrating that gradually increasing task difficulty in iVR, as seen in traditional rehabilitation approaches, can effectively enhance learning and performance (Levin et al., 2015). For example, studies have shown that progressive interventions lead to significant improvements in cognitive and motor skills by systematically introducing more complex tasks as participants' abilities improve (Schmidt et al., 2018). Similarly, in a study where participants trained on a visuomotor tracking task over four consecutive days, those in the progressive practice group demonstrated superior performance at the skill task level and transfer of performance compared to those practicing at a constant difficulty level (Christiansen et al., 2018). These findings align with the observed results, indicating that while the self-adaptive group showed a greater improvement in the most challenging level, the structured progression used in the progressive non-adaptive group also fostered notable improvements in attentional and motor outcomes.

However, the adaptive nature of the experimental intervention, with its rapid adjustments to increasing distractor load and reduced target lifetime, likely provided additional benefits by challenging participants to enhance their motor and attentional performance under more variable and difficult conditions, reflecting its potential for optimizing motor learning in more dynamic scenarios. In fact, the rapid exposure to the most challenging target-distractors salience contrast in the self-adaptive group, combined with the early reduction in target lifetime (to around 3 seconds), may have played a pivotal role in preparing participants for the increased difficulty at level 4. These dynamic adaptations likely pushed participants in the self-adaptive group to process stimuli and react more quickly and perform movements more accurately, particularly in complex conditions requiring heightened cognitive and motor control. This is supported by literature highlighting that adaptive interventions are beneficial in environments that require substantial cognitive and motor engagement. For instance, Pedulla et al., found that adaptive and personalized training had greater effect in sustained attention than non-adaptive training (Pedullà et al., 2016).

Another hypothesis could be that in the self-adaptive intervention, older adults were presented with easier levels during the first day, followed by periodic reductions in task difficulty, allowing them to adjust gradually and optimize motor learning. In contrast, the control group followed a strictly progressive difficulty increase without adjustments based on individual performance. While progressive training can enhance motor learning (Christiansen et al., 2018), research suggests that excessive task difficulty may hinder skill acquisition in older adults by increasing motor output variability (Akizuki and Ohashi, 2015). In fact, older adults who practiced an easier motor task demonstrated greater skill retention and transfer compared to those who trained with a more difficult version (Onushko et al., 2014). This implies that strategically lowering task difficulty at key moments may help maintain an optimal challenge level, facilitating sustained improvements in motor performance without overwhelming sensorimotor control mechanisms.

Performance acquisition and retention

In both intervention groups, in-game-SAT significantly improved from the first to the last block of day 1, suggesting that participants in both the self-adaptive and progressive non-adaptive groups experienced rapid performance acquisition over time. Notably, these improvements were retained, as evidenced by the enhanced SAT scores when comparing the first block of day 1 to the first blocks of day 2 and the first blocks of day 3. These findings align with prior research demonstrating that older adults can achieve motor learning and skill acquisition when provided with virtual reality interventions. For instance, dos Santos Mendes et al. (2012) demonstrated that older adults, including those with Parkinson's disease, could learn new motor skills through virtual reality-based interventions, with improvements not only in motor performance but also in skill retention (dos Santos Mendes et al., 2012).

The retention of performance is crucial for validating the efficacy of iVR interventions, as skill retention is a hallmark of successful motor learning (Schmidt et al., 2018). The ability to retain motor skills, particularly in an older population, suggests that iVR can foster durable motor learning outcomes, especially when tasks are appropriately structured to align with participants' cognitive and physical capacities.

Discrepancy of iVR effect on kinematics

The secondary outcomes related to kinematic measures yielded mixed results. While improvements were observed in linearity, mean velocity and peak velocity at certain levels (e.g., level 0, 3, and 4), other kinematic indices such as SPARC (smoothness), coefficient of variation of velocity, and arm displacement (Lpath) did not show significant changes over time. A possible explanation for this discrepancy lies in the complexity and specificity of the kinematic measures. Metrics such as velocity may reflect gross motor improvements linked to task completion speed, which can increase rapidly with repetition. In contrast, movement smoothness measures such as SPARC are more subtle indicators of fine motor control, which might require more extended periods of intervention or a specific type of feedback (e.g., visual) (Everard et al., 2023) to show noticeable improvement.

Furthermore, research suggests that changes in movement smoothness are highly dependent on the nature of the task. For example, Gulde et al. (2019) indicated that the intermittency of movement—reflected by velocity peaks—varies significantly based on task complexity, especially in older adults. In discrete and linear tasks, velocity tends to remain more consistent, while in more complex, circular movements, frequent changes in direction lead to greater velocity variability (Gulde et al., 2019). In our study, the tasks involved relatively straightforward and linear movements, which may not have been complex enough to evoke significant changes in smoothness, particularly in participants without notable motor impairments. This could explain why finer motor control measures, like SPARC, did not show substantial change over time. The absence of significant changes in these more nuanced kinematic metrics also suggests that while gross motor performance improved, finer aspects of motor control may require either more complex tasks, longer intervention durations, or additional feedback mechanisms to achieve meaningful progress.

Differences in motor reserve may also have influenced changes in movement smoothness. While a systematic definition for motor reserve has not been provided yet, the concept refers to the motor system's capacity of some individuals to maintain better motor function despite a certain level of decline (Giustiniani and Quartarone, 2024). Participants with higher motor reserve may have already achieved an optimal level of movement smoothness at baseline, requiring little to no compensatory movement, whereas those with lower reserve may rely more on compensatory mechanisms and need longer adaptation to refine finer movements. Since SPARC reflects movement quality and compensation, its lack of improvement could stem from motor reserve differences rather than an inability to enhance smoothness. Future studies should examine baseline motor reserve as a moderating factor in motor learning interventions, integrating neurophysiological assessments or behavioral outcomes.

Transfer to functional performance and reaction time

The transfer to functional performance, as assessed through standardized tests, revealed some improvements but not across all tests. Notably, the Finger-Nose Test and TEMPA scores improved significantly over time, while no significant effects were observed for the BBT or the DLRT tasks (DLRT-S and DLRT-C). One potential explanation for these results is the nature of the tasks themselves. The Finger-Nose Test and TEMPA involve coordinated, fluid upper-limb movements similar to those practiced in the iVR tasks, whereas the BBT requires more manual dexterity and fine motor skills, which were not specifically trained in the iVR interventions. The lack of improvement in BBT could be attributed to the absence of direct hand-grasping tasks in the virtual environment, while improvements in the Finger-Nose Test and TEMPA reflect the gains in reaching and coordination that were targeted in the intervention.

The lack of significant improvements in the DLRT, which assesses simple and choice reaction times, could be attributed to the nature of the iVR intervention. Although the REAsmash-iVR task involved responding to virtual moles quickly, the cognitive demands of the game were likely more focused on spatial attention and distractor inhibition rather than simple reaction times. Moreover, previous studies have shown that reaction time improvements, particularly in older adults, can be modest due to age-related declines in neurological processing speed (Kempermann et al., 2002). Additionally, motor reserve may have influenced these outcomes, as participants with higher reserve might have already exhibited efficient reaction times at baseline, leaving little room for improvement, whereas those with lower reserve may require more intensive or prolonged training to show noticeable gains (Giustiniani and Quartarone, 2024).

Implications

The findings of this study carry significant clinical and research implications. Clinically, they suggest that iVR interventions, especially self-adaptive and progressive serious games like REAsmash-iVR, hold promise as a novel and engaging approach to promoting motor and cognitive learning in older adults. The use of virtual reality-based interventions in rehabilitation programs could provide an innovative way to combat sedentariness and age-related motor decline, offering tailored rehabilitation solutions that can be delivered autonomously. Supporting this, a recent study involving 293 older adults demonstrated that a mixed motor-cognitive intervention in virtual reality led to significant improvements in global cognition and frailty compared to traditional therapy, highlighting the potential of these approaches to enhance both physical and cognitive health in aging populations (Kwan et al., 2024). Self-adaptive systems, offer the potential for efficient self-rehabilitation, as they can continuously adjust difficulty levels based on individual performance, providing real-time feedback and motivating users to improve. For example, a study found that individualized iVR training for driving resulted in more effective learning and retention compared to traditional virtual reality, video-based, and manual training methods (Lang et al., 2018). This flexibility could make iVR interventions accessible for home-based and self-rehabilitation, enabling older adults to take an active role in their own care. Moreover, the integration of social interaction features, such as virtual group exercises or collaborative tasks within the virtual reality environment, could further enhance engagement, especially for older adults at risk of social isolation. Virtual reality platforms offer the potential to foster social connectivity, which are critical in addressing both the physical and emotional well-being of older adults. Studies have shown that virtual environments can enhance social engagement, helping to reduce isolation and improve mental health (Lin et al., 2018) in older adults (Matsangidou et al., 2023).

From a research perspective, our results highlight the need for larger controlled studies to examine the long-term retention of motor learning and explore the optimal parameters for delivering VR-based interventions, such as difficulty regulation and task complexity. Future studies could also assess the effect of these interventions on older adults with more pronounced motor or cognitive impairments.

Limitations

This study has several limitations that should be considered. First, incorporating a third group with no intervention could have provided valuable insights into whether the observed improvements were attributable to the specific interventions or simply due to familiarization with the VR tool. A control group with no intervention would help distinguish between genuine learning effects and those resulting from the mere use of the VR system. Second, the relatively small sample size limited our ability to perform more complex analyses, such as examining interactions between group, time, game levels, and covariates such as age and Montreal Cognitive Assessment scores. Larger sample sizes would enable more robust statistical analyses and a better understanding of how these factors influence intervention outcomes. Third, including a follow-up period would have been beneficial for assessing long-term retention of skills acquired during the intervention. This would provide insights into the durability of the improvements and whether they persist beyond the immediate post-intervention period. Finally, it would be valuable to extend this research to older adults with more pronounced motor and cognitive impairments. Evaluating the effects of these interventions in this population could offer deeper insights into their efficacy and adaptability for individuals with varying levels of functional capacity. Future studies addressing these limitations could enhance our understanding of the potential benefits and applications of self-adaptive and progressive VR interventions in geriatric care.

In conclusion, this randomized controlled trial demonstrated that both self-adaptive and progressive non-adaptive iVR interventions effectively enhanced motor and cognitive learning in older adults, with the self-adaptive approach showing greater benefits at higher attentional difficulty levels. While gross motor improvements were significant, finer motor control metrics showed limited change, suggesting the need for longer or more complex interventions. These findings highlight the potential of iVR-based interventions in rehabilitation, especially for promoting motor learning, self-rehabilitation and addressing age-related declines in motor and cognitive function.

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