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ORIGINAL ARTICLE

The REAsmash serious game for the post-stroke diagnosis of distractor inhibition: contrast between immersive and non-immersive virtual reality test versions

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ABSTRACT

BACKGROUND: Virtual reality (VR) Serious Games (SG) offer greater sensitivity and specificity than traditional diagnostics. The playfulness of the SG reduces stress, enhancing motivation and reliability. We developed immersive (iVR) and non-immersive (niVR) versions of REAsmash, a SG based on Feature Integration Theory (FIT) to assess distractor inhibition attention.
AIM: The aim of this study was to verify the transfer of the REAsmash FIT diagnostic properties across VR devices with different degrees of immersion.
DESIGN: Cross-sectional clinical study.
SETTING: Inpatient, outpatient and healthy controls.
POPULATION: Post-stroke and healthy individuals.
METHODS: The REAsmash involves searching for a (target) mole with a red miner's helmet. The target is either presented alone (baseline), or presented with distractors (11, 17 or 23) that contrast the target by high or low saliency (moles with blue miner's and horned helmets vs blue miner's and red horned helmets). Stimuli appeared randomly from a 24-molehill grid. Participants (15 with and history of cortical-subcortical stroke and 15 age matched controls) hit the target with their response hand in niVR and with a virtual hammer in iVR. Post-stroke participants used their less impaired hand, controls their dominant hand. ANOVA tested VR type (niVR vs iVR), group (post-stroke vs healthy), saliency (high vs low) and distractor number (11, 17, 23), with the interaction between saliency and distractor number defining FIT. The dependent variable was relative mean response time, calculated by subtracting the mean baseline response time from each response to targets presented with distractors, for each participant. This variable exemplifies the costs to response time cause by the manipulation of independent variables.
RESULTS: We found significant main effects and an interaction for saliency and distractor number, confirming FIT. Group and VR type main effects were significant, with slower responses for post-strokes and for iVR, but with no interactions.
CONCLUSIONS: To evaluate performance across acute to chronic post-stroke phases, diagnostic measures must be transferable between test devices, ensuring compatibility from hospital to outpatient settings.
CLINICAL REHABILITATION IMPACT: Our results demonstrated that the REAsmash diagnostic properties were consistent across immersive and non-immersive VR, as well as within both groups of participants.

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KEY WORDS: Virtual reality; Stroke; Rehabilitation; Attention; Outcome and process assessment, health care.

There are an estimated 80 million disabled stroke survivors worldwide,[1] making stroke the leading cause of long-term disability in high-income countries.[2] With increased innovations in health care and longer average life expectancy, a 35% increase in stroke prevalence is expected by 2030.[3, 4] Because of these two factors, it is paramount to develop new and improved diagnosis and neurorehabilitation methods for stroke care.

Currently, the estimated prevalence of post-stroke cognitive impairments is uncertain, with estimates varying from 24% to 96%.[5] Part of this variance is explained by the different domains of cognition that can be affected by stroke. However, another contributor to this variance results from routine evaluation of cognitive deficits being overlooked in most clinics.[6, 7] Even though the literature clearly demonstrates the impact of cognitive deficits on global post-stroke recovery, and makes frequent calls for more comprehensive, precise and routine evaluations of cognition during post-stroke diagnosis of impairments.[8, 9]

The use of virtual reality (VR) and serious games (SG) methods provide promising reliable tools for cognitive assessment and rehabilitation.[10] VR is defined as a computer-generated immersive experience.[11] It ranges from non-immersive (niVR) to fully immersive (iVR).[11] In niVR, participants typically interact with content via input peripherals (*e.g.*, keyboard, touchscreen or hand tracker) and an output device (*e.g.*, screen or tablet).[12] Fully iVR generally refers to technology that recreates an interactive three-dimensional and multisensorial experience using a head mounted display (HMD), large screen projection system (SPS) or cave automatic virtual environment (CAVE).[13] The HMD is a wearable device equipped with two small screens positioned near the eyes, typically within goggles or a helmet. It includes a head-tracking sensor that adjusts the visual display according to head movements, and it has headphones for delivering auditory feedback.[13] The SPSs are large displays that project the virtual environment onto a screen. The CAVE consists of a room featuring four to six screens, which when used with 3D glasses, provide an immersive and continuous visualization of virtual spaces. This setup is further enhanced by a head-tracking sensor and speakers to deliver audio stimuli.[13]

SG are games designed with a primary purpose other than pure entertainment, such as education and training.[14] As suggested by Tong *et al.*, specially adapted SG can be leveraged to create an interactive and engaging tool that promotes patient-centered cognitive assessment.[15] The primary objective of a SG using VR for cognitive assessment is to motivate the participant to perform the task. The SG incorporates challenging goals and are fun to play.[16] SG promotes maximized user performance (the best ability of the player), increasing test/re-test reliability[17] and allowing the collection of large amounts of digital measurement data, boosting measurement sensitivity and specificity. Furthermore, as for all computerized assessments,[18] the possibility of randomizing the presentation of the stimuli allows the SG to diminish practice effects, while maintaining control and standardization across individuals.

The impact of the degree of immersion in VR is a topic that is still not fully understood, especially in post-stroke populations. Immediately post stroke, patients tend to have increased anxiety[19] caused by a change to personal routine and future uncertainty, which typically dissipates with time. Anxiety can moderate user experience when using VR technology.[20] For example, studies on cognitive assessment have demonstrated that VR naïve relative to experienced participants show more difficulties when performing tasks in iVR than niVR, explained by anxiety.[21] A similar effect is reported for age, with aged relative to young participants showing more difficulties in iVR relative to niVR,[22] again explained by anxiety. However, despite these results, recent research with iVR on older adults with cognitive decline has shown good acceptance, possibly due to the use of new HMDs that minimize cyber sickness and allow immersive experiences more closely resembling real life.[23] Nevertheless, iVR effects on sense of presence, flow, and the transfer of skills or knowledge to real-world contexts remain a matter of debate in the academic literature.[24] Taking the overall results, it may be the case that niVR relative to iVR is better suited to acute and sub-acute post-stroke patients who are naïve in the use of VR technology, regardless of patients' age, and that with increased time, there becomes no difference in user experience between niVR and iVR, making a transition to iVR possible for sub-acute to chronic patients. This pathway of technology would allow use of niVR in clinical settings, transitioning to the use of iVR in outpatient and home-based settings.

From a broader clinical standpoint, the economic implications of device selection remain a pivotal consideration. In resource-limited regions, as well as within healthcare systems of low- and middle-income countries, the financial investment in diagnostic technologies cannot be overlooked.[25] This is particularly relevant given the substantial cost differential, ranging from tens of thousands of euros for niVR devices to mere hundreds of euros for iVR solutions. Our study contributes to the discussion about the appropriateness of choosing one type of VR over another already in the diagnostic field.

Recently we developed the REAsmash,[26] a SG adaptation of the classic fairground and arcade game, Whac-A-Mole. The objective was to create a new assessment tool that systematically evaluates distractor inhibition attention. Although the disruptive effect of distracting stimuli (*i.e.*, irrelevant information[27]) has a known impact on performance,[28] with many replications of the effect in the literature,[29] there is currently no validated diagnosis test for distractor inhibition impairment that is routinely used in clinical practice. The REAsmash aims to address this unmet need. The SG was validated for full iVR with healthy participants (REAsmash-iVR),[26] and has recently been tested with different groups of post-stroke participants.[30] The REAsmash SG is based on Feature Integration Theory (FIT) by Treisman and Gelade,[28] which contrasted response time performance to two target-distractor contrast conditions. In a high saliency target-distractor contrast condition, the target differed by one salient feature from the distractors (*e.g.*, a red target presented with blue distractors), leading to "parallel search" where the target "pops-out" from the distractors.

This effect shows that attention is directly drawn to the target stimulus. In contrast, in a low saliency target-distractor condition, the target differs from the distractors by a conjunction of features (*e.g.*, a red circular target presented with blue circular and red square distractors, with red and circle features shared with the distractors). This condition leads to "serial search," where the participant spatially scans the stimuli one at a time, attentionally inhibiting the distractor stimuli until they find the target. Treisman and Gelade showed that in parallel search, increasing numbers of distractors did not change response time. However, response time in the serial search condition was influenced by distractor number, with increased numbers of distractors increasing response time. Therefore, the diagnosis criteria for measuring distractor inhibition relies on the interaction effect between salience and distractor number.

The REAsmash aims to replicate the FIT paradigm using gamified animated complex stimuli in both niVR and iVR, showing: 1) overall longer response times to accomplish the task in low compared to high salience conditions; and 2) an interaction effect, with no effect of distractor number for the high salience condition and increased time to find the target with increased distractors in the low salience condition. In earlier preliminary studies using the iVR version,[30] post-stroke participants were contrasted to healthy controls. No participants were enrolled in both the preliminary and the study concerned in this article. Post-stroke participants showed particularly pronounced difficulties in low-salience target-distractor levels, where they exhibited substantially prolonged response times and higher rates of errors and omissions. This finding suggests a specific impairment in serial search and distractor inhibition in this population, distinguishing them from healthy controls.

Few studies in the literature have compared the same cognitive task in different degrees of VR immersion, and we found no studies exploring this issue in relation to tests of distractor inhibition.

In our main experiment, we tested a group of post-stroke participants and an age-matched group of healthy controls on the REAsmash presented in niVR and iVR. The main objective was to verify the transfer of the FIT effect across devices with different degrees of VR immersion. We thus hypothesized to replicate our preliminary research findings, showing a significant saliency by distractor number interaction effect (demonstrating FIT), and no differences, or interactions between use of niVR and iVR (particularly for the diagnostic criteria). As a secondary objective we explored possible differences between groups to investigate possible interactions between VR types (iVR *vs.* niVR), cognitive demand (parallel *vs.* serial research) and groups. Prior to the main experiment described in this paper, we ran a preliminary study on healthy participants playing with both niVR and iVR REAsmash SG, testing possible differences in hand use (dominant *vs.* non-dominant) on outcomes. Our hypothesis was that, because of a consistent neutral starting position (in the center of the playing field), response times, as well as error and omission rates, would not be affected by the hand used.

Materials and methods

Study design

This study uses a cross-sectional clinical study design and followed the STROBE guidelines.[31] The protocol was approved by the Saint Luc-UCLouvain clinical ethics committee (Belgium) (2015/10FEV/053) and registered on clinicaltrial.gov (NCT04694833). Details on the design of the study are reported in the following sections.

Participants

To determine the required sample size, an a priori power analysis using G*Power® (version 3.1.9.7) was performed on previous data testing the FIT effect with 60 healthy participants. The power analysis was conducted considering a

single group, as the primary objective was to establish the necessary sample size to detect the FIT interaction effect across different VR technologies. This data showed the hypothesized significant interaction between target-distractor saliency contrast and distractor number ($F(2.114)=117.58$, $P<0.001$, $\eta^2=0.67$), and an effect size (Cohen's f) of 1.425. Using these parameters, the G*Power analysis indicated that a total sample size of 4 participants is required to show the FIT effect interaction, with a power of 0.80 for detecting the specified effect size at an alpha of 0.05. For our study, which involved contrasting a group of post-stroke participants with healthy participants, we decided to increase the sample size to 15 participants per group. Retrospectively, a sample size of 15 participants per group was deemed sufficient to detect a significant between-group effect ($\eta^2=0.96$).

Post-stroke participants were recruited from the physical medicine and rehabilitation department of the *Cliniques universitaires Saint-Luc* in Brussels and were either currently hospitalized or already discharged. Recruitment took place from December 2022 to March 2024. The post-stroke participants were selected using the following inclusion criteria: 1) adult participants (*i.e.*, minimum age of 18 years old); 2) presence of an ischemic or hemorrhagic first cortical and/or sub-cortical stroke, diagnosed by CT or magnetic resonance imaging; and 3) a good understanding of the task instructions. The exclusion criteria were: 1) uncorrected vision deficiencies; 2) MoCA[32] score less than 20 out of 30 points; 3) presence of other neurological conditions (*e.g.*, major neurocognitive disorder or extrapyramidal disorders) that could bias the outcomes; 4) medication-resistant epilepsy; 5) orthopedic dysfunction that could influence upper extremity function and; 6) too poor trunk control to sustain the trial. Points (5) and (6) were clinically evaluated by a physical medicine and rehabilitation specialist in the week preceding the VR sessions. The post-stroke group (N.=15; 14 males) had a mean age of 58.4 years (SD=12.4; range: 21-71) and a mean height of 175.5 cm (SD=6.5). Most participants were VR naïve (93%), 54% reported the less impaired hand (*i.e.*, the response hand) was their pre-stroke dominant hand. The average time since stroke was 7 months (range: 1-132 months), 7 participants were in sub-acute phase (*i.e.*, within 6 months from the stroke) and 8 in chronic phase, with 12 ischemic and 3 hemorrhagic strokes. Lesions were located on the right hemisphere in 9 participants and on the left in 6, primarily affecting the Sylvian regions. The mean MoCA score was 26.2 (SD=2.4; range: 20-30). Rehabilitation status varied, with 8 participants still undergoing neuropsychological, occupational, and/or physical therapy at the time of testing.

Healthy controls were recruited between November 2021 and March 2024 through the University of Louvain participation panel and social media groups. The participants were selected using these inclusion criteria: 1) they should have normal or corrected to normal vision; and 2) no neurological, psychiatric or orthopedic disorders potentially affecting compliance or limiting upper limb functionality. Difficulty in understanding French (the language of the task instructions) was an exclusion criterion.

The healthy control group (N.=15; 7 males) had a mean age of 58.1 years (SD=14.4; range: 21-81) and a mean height of 170.3 cm (SD=8.1), showing no significant age and height differences to the control group. Although gender ratio was different between groups, we expected no gender effects for FIT (with males and females showing equal ability to inhibit visual distractors). Most participants were VR naïve (86%). Further details, including individual participant data, are provided in Supplementary Digital Material 1 (Supplementary Table I, Supplementary Table II). All the participants volunteered to participate in the study, providing written informed consent before participation.

Materials

The "REAsmash" Serious Game (SG) was created using Unity 2019.3 software (in C# language). The REAsmash presented a visual display of 24 molehills displayed in a cartoon-like garden (organized into 6 columns and 4 rows). The grid of molehills was aligned with an active surface of 100 x 50cm in both the niVR and iVR devices. The stimuli presented to participants was organized by 7 blocks of 24 trials (game levels). The participant was instructed to "smash" (hit) the target stimulus that pseudo-randomly appeared from one of the 24 molehills, making the 24 trials for each block/level. The target stimulus was a mole wearing a red miner's helmet. In the baseline level 1 trial block, no distractors were presented. In the remaining trial block levels, distractors were presented with the target mole. The distractor moles wore different helmets and were used to create high versus low saliency contrasts to the target mole (creating a measure of distractor inhibition demands). In the high saliency target-distractors contrast condition, the target was presented with distractor moles wearing blue helmets (miner's or horned) (levels 2, 3 and 4). In the low saliency target-distractors contrast condition, the target was presented with distractor moles wearing either blue miner's or red horned helmets (levels 5, 6 and 7). In the high salience condition, the target differed

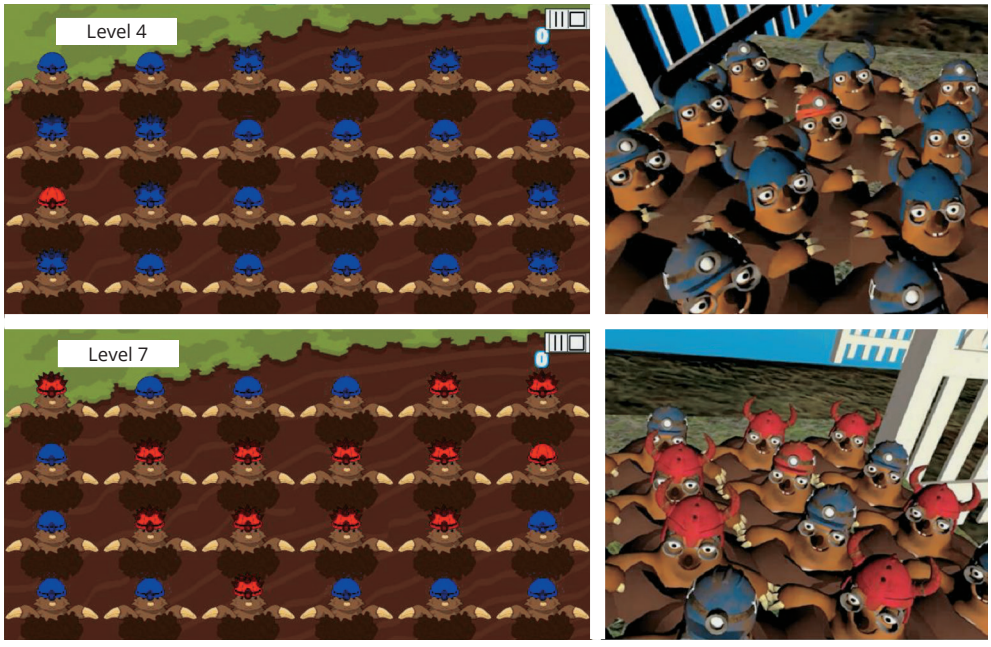

Figure 1.—The REAsmash target-distractor search stimuli.
Examples of stimuli settings. The upper images show level 4 (high salience) with 23 distractors wearing horned or miner's blue helmets. The lower images show level 7 (low salience) with 23 distractors, wearing red helmets with horns and blue miner's helmets The two images on the left column represent the stimuli as they appeared in the REAsmash-niVR version of the SG, while the images on the right are taken from the REAsmash-iVR SG.

from the distractors by color, whereas in the low salience condition, the target differed from the distractors by a conjunction of features (both color and helmet shape). In each of the two target-distractor salience conditions, 11, 17 or 23 distractors accompanied the target, making stimuli sets of 12, 18 and 24 stimuli (corresponding to levels 2, 3 and 4, and levels 5, 6 and 7; Figure 1).

The REAsmash-niVR ran on the REAtouch® (Axinesis®) interactive medical device. This was composed of a touch-sensitive screen (43", 95x53 cm) incorporated in a motorized structure that allowed customized screen lifting and inclination tilting. The REAtouch® provides multisensory and real-time performance feedback and is designed to allow uni- or bi-manual interaction by direct hand-contact with the screen. The hardware for the REAsmash-iVR consisted of an immersive VR headset (Oculus Quest 2) and one Oculus Quest motion controller. When the virtual hammer hits the mole helmet, Oculus Quest 2 provides

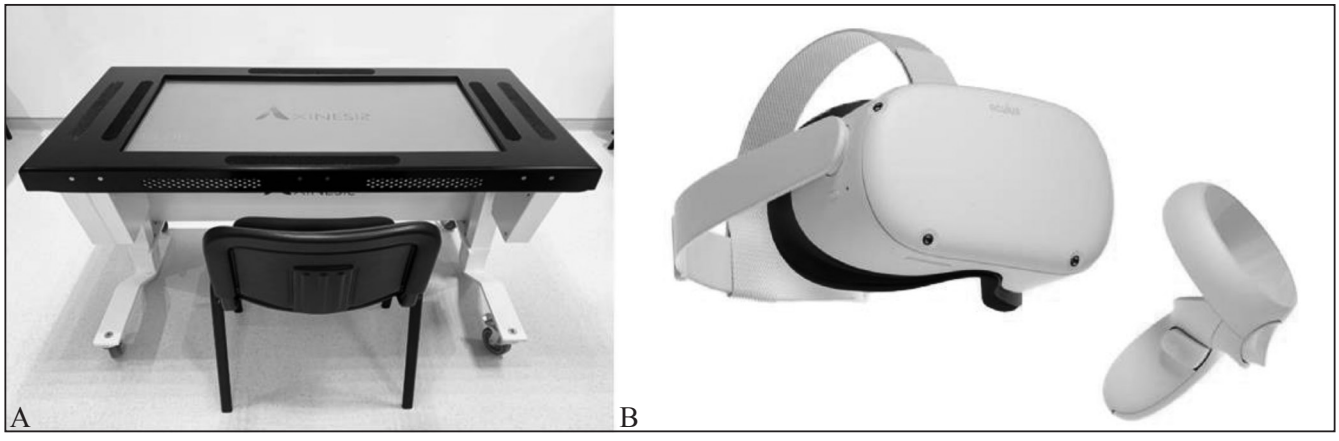

Figure 2.—The non-immersiveVR and immersiveVR devices.
A) The REAtouch® (Axinesis®), a touch-sensitive 43" screen tablet with multisensory and real-time performance feedback. The height and inclination of the touch-sensitive screen can be adjusted. In the present study the inclination was the same as that presented here (*i.e.*, 0°). B) The Oculus Quest 2®, the immersive VR headset (with a per-eye resolution of 1832×1920, and a refresh rate of 120 Hz), and one Oculus Quest motion controller (left or right according to the response hand), used for manual responses.

a real-time performance acoustic feedback, and the respond controller vibrates. The experiment was monitored through a live stream from the Oculus App (Figure 2).

Procedure

The study was run in controlled laboratories at the Cliniques Universitaires Saint-Luc of Brussels (Belgium) and at the University of Louvain (UCLouvain). All sessions were conducted by a PMR specialist, who was the intervention provider for the project. Before the study, participants were given instructions regarding the experimental design, and they were invited to sign a consent form. They were informed that they could withdraw from the study at any time.

When playing the REAsmash-niVR SG, participants were asked to sit on a chair positioned in front of the REAtouch® and aligned with the central sagittal axis of the interactive touch-sensitive screen (Figure 2), with their feet placed on the ground. The screen was adjusted to a suitable height, allowing the participant to make responses to all parts of the screen, and making their position comfortable for the experiment. The touch-sensitive screen was presented at a horizontal angle of zero degrees relative to the ground. Participants were instructed, by means of a superimposed message on the playing field that was also verbally spoken by the software, to touch the target as quickly as possible with their playing hand. To begin each trial, the participant had to touch an "X" stimulus that appeared at the mid-lower edge of the touchscreen. This was used to provide a consistent starting point prior to each trial response. After touching the start position, the trial would begin.

The format of the REAsmash-iVR SG experiment matched that of the REAsmash-niVR SG. Participants were invited to sit on a chair, wearing the iVR headset and hold the controller in their response hand. Multimodal (*i.e.*, written and verbal) instructions were played at the beginning of the SG, instructing the participants to hit the target stimulus as fast as they could, using a virtual hammer that was controlled with the iVR controller. As in the case of niVR, the height of the playing field could be adjusted for comfort, allowing participant to interact with all parts of the display. Before each trial, to provide a consistent starting point, two red squares were displayed floating in front of the participants, aligned with the central sagittal axis of the playing field and placed on the edge nearest to the player (matching the location of the X in the niVR display). One square had a pictogram of an eye, and the second had a pictogram of a hammer. The participants had to simultaneously fixate on the eye-square and place the hammer on the hammer-square to initiate each trial. When the participant's head and virtual hammer positions were correctly located, the two red squares turned green, and the trial began (Figure 3). Note that the iVR used head tracking to measure head rather than eye position.

In the case of participants in wheelchairs, the wheelchair was appropriately positioned aligning the participants to the same playing conditions as the other participants. A 10-trial practice session was used to familiarize participants with the devices before each session. A 20-second rest period was provided between each game level. The 7 levels were run from easy to difficult (levels 1-7 in sequence).

All mole stimuli appeared for a maximum time of 7 seconds. If the participant made no response, the trial was considered as an omission, while if they responded to a distractor stimulus, the trial was considered as an error response. If a correct response was made within 7 seconds, the trial was terminated, and the next trial was initiated.

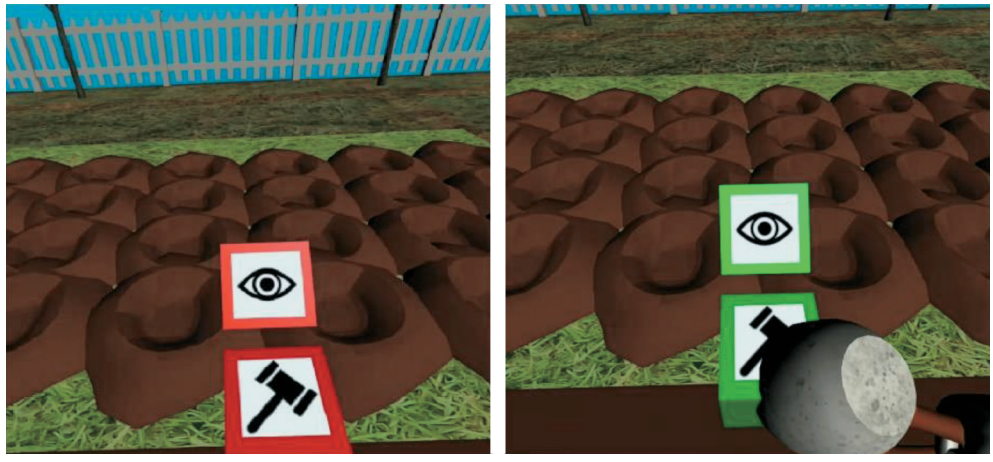

Figure 3.—The starting position in iVR.
When the cubes with the eye and hammer pictogram turned from red (left frame) to green (right frame), both the position of the head and the response hand were correctly placed and the trial was initiated.

The playing hand, in the case of post-stroke subjects was the less impaired hand. In current clinical cognitive diagnosis tests, post-stroke individuals are frequently asked to use their less impaired (ipsi-lesional) hand for making responses. This is carried out to reduce the influence that motor impairments have on the interpretation of cognitive impairments.

Prior to the main experiment, we conducted a preliminary experiment on healthy participants to verify the hand used had no effect on response times. In this preliminary study, 10 healthy participants (average age 60 years, SD 10.6) performed the REAsmash with both hands, randomizing the hand order. These data are presented in the Results section.

All participants performed the two versions of the REAsmash (niVR and VR). The order of the two sessions were randomized and took place with a maximum of one week separation to minimize potential cross-platform practice effects.

Outcomes

The following behavioral outcomes were measured in this paper, constituting the dependent variables.

For the preliminary experiment, the primary outcome was absolute mean response time (AT), consisting of the mean response time between target appearance and manual response (*i.e.*, the virtual hammer hits the mole helmet) in successful trials.

For the main experiment, we introduced relative mean response time (RT) for successful trials. This outcome was calculated by subtracting the mean response time of baseline level (level 1) from the mean response times recorded in levels 2 to 7. RT highlights the temporal cost of different task conditions, isolating the cognitive demands of distractor inhibition from individual variability in absolute response time. The dependent variables RT was introduced to control for individual variability intra- and inter-group.

In both experiments, two further outcomes were collected: 1) Error Rate, defined as responses made to distractor stimuli instead of the target; and 2) omission rate, defined as the failure to respond to the target within the 7-second time limit. Both error and omission rates were calculated as proportions out of the total number of trials for each condition.

Data analyses

Data analyses were performed using SPSS 27.0 (IBM®). The normality of the data was investigated using the Shapiro-Wilk Test, and then repeated measures ANOVAs. *Post-hoc* analyses were performed with Bonferroni corrections for multiple comparisons.

For the preliminary experiment on healthy participants contrasting hand use, the dataset consisted of 3360 trials (*i.e.*, 7 levels x 24 trials x 10 participants for the dominant and non-dominant hand) for each VR type. The independent variables were hand (dominant *vs.* non-dominant) and game level (7 levels), with a separate ANOVA for each VR type (as the intention here was to isolate differences for hand used).

For the main experiment, we focused on target-distractor saliency and number of distractors, comparing groups and type of VR. Each participant group was composed of a total dataset of 5040 trials (*i.e.*, 7 levels x 24 trials x 15 participants x 2 VR type). The independent variables were VR type (iVR *vs.* niVR), target-distractor saliency (high *vs.* low), distractor number (11, 17 and 23) and group (post-stroke vs healthy controls).

Availability of data and materials

The datasets used during the current study are openly available in the open data archive of University of Louvain (https://dataverse.uclouvain.be/dataset.xhtml?persistentId=doi:10.14428/DVN/OM0TIM).

Results

The post-stroke group included 1 female, and all participants were right-handed, with an average age of 58.4 years (SD 12.4). The control group included 8 females and 4 left-handed participants with an average age of 58.1 years (SD 14.4) (Supplementary Digital Material 1: Supplementary Table I and Supplementary Table II). The post-stroke and control groups were mean age matched, with a *t*-test showing no significant difference in age between the two groups (t (28)=-0.125, P=0.902).

No participants withdrew before the end of the study. No adverse events occurred during the experiment. The sessions were well tolerated and overall described as non-stressful and engaging. No participants asked to stop the experiment prematurely or to extend the rest periods.

The preliminary experiment testing hand differences in healthy participants

Concerning the preliminary experiment, the niVR dataset, there were 12 omissions (0.3%), 11 errors (0.3%), 5 anticipatory responses (0.1%) (*i.e.*, responses imitating in less than 250 ms) and 48 outliers (1.4%) (defined by a three standard deviation confidence interval). In the iVR data-

set, there were 24 omissions (0.7%), 19 errors (0.6%), 0 anticipatory responses and 67 outliers (2%).

The ANOVA on AT for the niVR dataset showed a significant main effect of game level, F (6.54)=300.7, P<0.001, η^2=0.97, but no significant main effect of the response hand F (1.9)=0.235, P=0.639, η^2=0.03, and no interaction between level and response hand F (6.54)=0.340, P=0.913, η^2=0.04. Similarly, the ANOVA for the iVR dataset showed a significant main effect of game level, F (6.54)=238.347, P<0.001, η^2=0.96, but no significant effect for response hand F (1.9)=0.001, P=0.982, η^2=0.000, and no significant interaction F (6.54)=0.364, P=0.899, η^2=0.04. Therefore, these data showed that starting from a consistent central position, the response showed no differences between hand used to respond to a spatial target.

The main experiment

For the post-stroke group, in niVR, there were 71 omissions (1.4%), 10 errors (0.2%) and 4 anticipatory responses (0.07%), and in iVR, there were 89 omissions (1.8%), 30 errors (0.6%) and 0 anticipatory responses. For the healthy control group, in niVR, there were 9 omissions (0.2%), 7 errors (0.1%), 5 anticipatory responses (0.1%) and 37 outliers (0.7%), and in iVR, they made 29 omissions (0.6%), 15 errors (0.3%), 0 anticipatory responses and 51 outliers (1%).

The ANOVA for RT showed significant main effects of target-distractors saliency F (1.28)=630.15, P<0.001, η^2=0.96, distractor number F (2.56)=82.62, P<0.001, η^2=0.75, VR type F (1.28)=99.18, P<0.001, η^2=0.78 and group F (1.28)=12.25, P=0.02, η^2=0.96). Multiple inter-

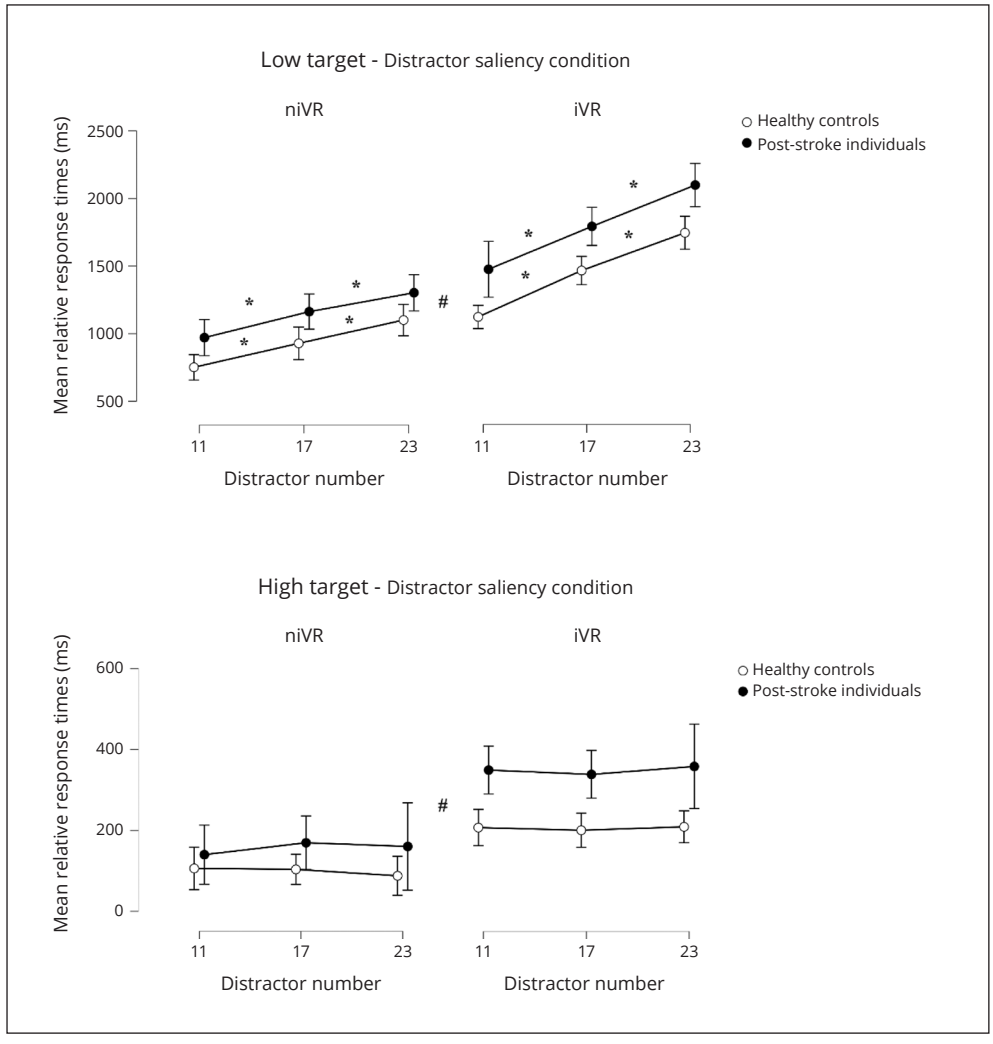

Figure 4.—Mean relative response time for independent variables of target-distractor saliency, number of distractors and group (milliseconds).
The upper plots show the low saliency conditions while the lower plots show the high saliency conditions. On the left, the results in niVR and on the right, the results of the iVR. The error bars show the 95% confidence interval. Black-filled circles represent post-stroke participants;
Outlined circles represent healthy controls.
"*" represent significant main effect for distractor number; "#" represent significant main effect for VR type.
The results for both VR types showed the classic FIT effect, with the number of distractors showing no differences for high target-distractors saliency, but a significant increase in mean relative response time with increased number of distractors in the low target-distractors saliency. The post-stroke group was significantly slower than the healthy controls group. The iVR responses were significantly slower than the niVR responses (relative to baseline).

actions were also statistically significant: 1) saliency and distractor number, F (2.56)=79.26, P<0.001, η^2=0.74; 2) VR type and saliency, F (1.28)=58.19, P<0.001, η^2=0.68; 3) VR type and distractor number, F (2.56)=8.31, P<0.001, η^2=0.23; and 4) VR type, saliency and distractor number F (2.56)=7.13, P=0.002, η^2=0.20 (Figure 4). No significant interaction was found between VR type and group F (1.28)=2.19, P=0.150, η^2=0.07, and there were no other significant interactions.

We first focus on the interaction between target-distractor saliency and distractor number. To analyze the interaction, we ran two separate ANOVAs for each target-distractor saliency condition (high and low). As predicted, the high saliency condition showed no significant differences for numbers of distractors F (2.56)=0.07, P=0.935, η^2=0.002, whereas for the low saliency condition, there was a significant effect F (2.56)=86.198, P<0.001, η^2=0.755, with RT increasing with increased numbers of distractors (M=1081.54 ms, SD 46.86; M=1340.18 ms, SD 58.80 and M=1565.73 ms, SD 50.65 with 11, 17 and 23 distractors respectively).

We next focus on the three-way interaction between VR type, target-distractor saliency and distractor number (*i.e.*, the FIT effect versus VR type), which encompasses the interaction effects between VR type and saliency, and VR type and distractor number. Separate ANOVAs were run for each saliency condition, testing distractor number and VR type. For the high saliency target-distractors condition there was a significant effect of VR type (F (2.28)=24.95, P<0.001, η^2=0.471), with slower responses for iVR relative to niVR. No other statistically significant results were found for high saliency condition. For the low saliency target-distractors condition, there was a significant effect of numbers of distractors F (2.56)=86.20, P<0.001, η^2=0.75 (showing increased RT with increased numbers of distractors) and VR type F (1.28)=112.05, P<0.001, η^2=0.80 (showing slower relative response time for iVR than niVR), as well as a significant interaction between VR type and numbers of distractors F (2.56)=8.90, P<0.001, η^2=0.241. We further separated the low saliency condition by distractor number and found significant main effects of VR type in all the three distractor conditions (F (1.28)=41.63, P<0.001, η^2=0.598; F (1.28)=74.88, P<0.001, η^2=0.728 and F (1.28)=117.94, P<0.001, η^2=0.808 for 11, 17 and 23 distractors respectively) with longer RT in iVR than niVR (M=860.80 ms, SD 47.17 *vs.* M=1302.27 ms, SD 67.15; M=1045.53 ms, SD 53.69 *vs.* M=1634.83 ms, SD 79.70 and M=1201.75 ms, SD 56.64 *vs.* M=1929.71 ms, SD 64.57 with 11, 17 and 23 distractors in niVR relative to iVR respectively).

Discussion

From a general perspective, this paper adds new understanding on the use of VR in SG for improving the cognitive diagnosis of distractor inhibition, for which there is currently no objective clinical diagnosis test used in clinical practice.

Firstly, the preliminary study on 10 healthy participants confirmed that the design of our SG and the choice of introducing a consistent neutral and central starting position in both types of VR minimized differences between the hand used for the task. This was demonstrated by the data showing no performance difference between use of the dominant compared to non-dominant hand. However, the potential problem with this decision is that some patients will make responses with their pre-stroke dominant hand, whereas others will now make responses with their pre-stroke non-dominant hand, potentially causing differences in response efficacy. To improve diagnosis tests requiring manual responses, we suggest that a consistent starting position is necessary to eliminate subjacent differences that are not stroke-related, such as making responses with the former dominant compared to former non-dominant. Such differences of hand dominance are removed with the central starting position.

The main objective of this paper was to verify the transfer of the FIT effect between iVR and niVR versions of the SG, contrasting post-stroke participants with healthy age-matched controls. For this purpose, we used the dependent variable of RT. This modified measure (relative to the usual AT) adds a second new value to the diagnosis literature proposing a strategy to minimize potential differences introduced by different VR devices, where one requires direct hand interaction, and the other uses an iVR controller.

For the main objective of the study, the contrast between types of VR (iVR *vs.* niVR), we found a significant main effect of VR type, with RT slower in iVR than niVR. We also found interactions between VR type and the FIT effect. The interaction is likely explained by increasingly greater F ratios, all being significant, with increasing numbers of distractors in low saliency condition for both VR types. *Post-hoc* analyses demonstrated the FIT effect in both types of VR, as explained above, but also a consistent effect of slower RT for iVR than niVR for contrasts in saliency and distractor number, with none of the interactions showing more effects. These results suggest that the degree of VR immersion has increased cognitive cost. Currently, there is no literature comparing the same cognitive inhibition task in different degrees of VR

immersion. However, our results are in line with Makransky *et al.*,[33, 34] who demonstrated reduced performance in immersive compared to non-immersive environments, arguing that immersive VR adds extraneous cognitive load (*i.e.*, increased task demands relative to the individual's cognitive capacity[35]). This may be explained by the iVR creating a more absorbing experience than niVR.

A final interesting value of the present study was the significant effect of group, but with no interactions between group and the other variables. Although the purpose of this article was not to validate the REAsmash as an assessment tool, this result is particularly interesting in this respect. The REAsmash seems able to maintain the FIT characteristics in high and low cognitive load VR environments, replicating results from healthy participants. The stability of the FIT effect, irrespective of the speed of response, the two devices, and for different populations, makes the REAsmash an ideal candidate for a clinical evaluation tool. Overall, these results support the ability to transfer diagnosis tests between two different devices. This consistency in diagnostic characteristics allows a strategy where one could use niVR in the acute to sub-acute phase post-stroke, transitioning to iVR in the sub-acute to chronic phase. This allows for increased neurorehabilitation possibilities for post-stroke individuals, potentially extending rehabilitation to telemedicine methods, and use of iVR in the home or in outpatient settings. In the case of extended neurorehabilitation, the REAsmash can be used as an independent test to verify progress in treatment.

Limitations of the study

The present study has some limitations. The preliminary study conducted on 10 healthy participants provides limited evidence, and its findings should not be generalized to the broader population without further validation. Additionally, while the results suggest that the starting position effectively reduces variability related to handedness in this specific task, contrasting findings in the literature warrant caution in extending these conclusions beyond the context of this study.

We decided not to segregate participants by post-stroke phase, resulting in a single group of post-stroke participants in different recovery phases (from one month to 11 years since the stroke). Since the results suggest a higher cognitive load in iVR than niVR, further research on REAsmash should investigate differences caused by post-stroke phase (sub-acute vs chronic), to verify whether niVR is more suitable for the sub-acute phase.

The absence of proper haptic and force feedback in the iVR setting is a limitation, particularly for the stroke group, where the lack of feedback may have influenced task performance by reducing sensory-motor integration demands. Future iterations of this study could explore the inclusion of haptic technologies in iVR, which might better leverage the immersive medium's capabilities and provide additional insights into user responses.

This study did not match participants by gender as no effects for the primary task based on FIT have been reported in the literature, demonstrating that cognitive and attentional processes are unlikely affected by gender differences.[28] Therefore, controlling gender was considered unnecessary for the scope of this research. Nonetheless, we acknowledge that gender differences might provide valuable insights for other contrasts, such as use of technology. Future research should balanced gender representation to better understand cognitive performance and task engagement.

Another limitation is that we included both VR naïve and non-naïve participants. As our study used a cross-sectional clinical design, not having prior experience with VR might have influenced the outcome results.[21] Future studies which aim to clinically validate the REAsmash as a diagnostic tool should take this into account.

Observation during the sessions led to the realization that trunk control, especially in iVR, played an important role in task execution. The iVR sessions induced the participant to maintain postural control of the response upper limb. As there is no true contact between the hammer and mole's helmet, no external forces stopped the movement once the helmet had been hit. The participant therefore had to actively control the movement throughout the entire trial. Even when the response hand was the less impaired (as in our experiment), the trunk played an important role in balancing forces and stabilizing posture, but also in the execution of the movement, which includes torsion movements of the trunk to reach the furthest targets. Future studies on the REAsmash would benefit from the introduction of a trunk control measure, such as a rating scale (*e.g.*, the Trunk Impairment Scale[36, 37]) or an objective motion tracking measure of trunk movement, integrated into the assessment.

Conclusions

As we hypothesized, and in accordance with what has been theorized in the literature, we demonstrated that while the type of VR immersion influenced response time, the diagnostic criteria of the REAsmash test was

unaffected by type of VR. To successfully evaluate cognitive performance across different post-stroke phases, it is important to develop measures that are transferable between test devices, providing diagnostic compatibility from hospital to outpatient settings (for example, from bulky niVR to wearable and more ecological iVR devices). Our results demonstrated that the diagnostic properties of REAsmash were consistent across the two types of VR, as well as within both groups of participants. The REAsmash is a useful new assessment tool able to systematically evaluate distractor inhibition attention in both niVR and iVR. Future SG with search tasks should consider the transferability of the test diagnostic criteria for different types of VR immersion, providing more value to patient clinical care.

References

1. Duncan PW, Bushnell C, Sissine M, Coleman S, Lutz BJ, Johnson AM, *et al.* Comprehensive Stroke Care and Outcomes: Time for a Paradigm Shift. Stroke 2021;52:385–93.

2. Phipps MS, Cronin CA. Management of acute ischemic stroke. BMJ 2020;368:l6983.

3. Pu L, Wang L, Zhang R, Zhao T, Jiang Y, Han L. Projected Global Trends in Ischemic Stroke Incidence, Deaths and Disability-Adjusted Life Years From 2020 to 2030. Stroke 2023;54:1330–9.

4. Fan J, Li X, Yu X, Liu Z, Jiang Y, Fang Y, *et al.* Global Burden, Risk Factor Analysis, and Prediction Study of Ischemic Stroke, 1990-2030. Neurology 2023;101:e137–50.

5. Douiri A, Rudd AG, Wolfe CD. Prevalence of poststroke cognitive impairment: South London Stroke Register 1995-2010. Stroke 2013;44:138–45.

6. Einstad MS, Saltvedt I, Lydersen S, Ursin MH, Munthe-Kaas R, Ihle-Hansen H, *et al.* Associations between post-stroke motor and cognitive function: a cross-sectional study. BMC Geriatr 2021;21:103.

7. Montero-Odasso M, Almeida QJ, Bherer L, Burhan AM, Camicioli R, Doyon J, *et al.*; Canadian Gait and Cognition Network. Consensus on Shared Measures of Mobility and Cognition: From the Canadian Consortium on Neurodegeneration in Aging (CCNA). J Gerontol A Biol Sci Med Sci 2019;74:897–909.

8. Shimada H, Makizako H, Doi T, Park H, Tsutsumimoto K, Verghese J, *et al.* Effects of Combined Physical and Cognitive Exercises on Cognition and Mobility in Patients With Mild Cognitive Impairment: A Randomized Clinical Trial. J Am Med Dir Assoc 2018;19:584–91.

9. VanGilder JL, Hooyman A, Peterson DS, Schaefer SY. Post-stroke cognitive impairments and responsiveness to motor rehabilitation: A review. Curr Phys Med Rehabil Rep 2020;8:461–8.

10. Maggio MG, Latella D, Maresca G, Sciarrone F, Manuli A, Naro A, *et al.* Virtual Reality and Cognitive Rehabilitation in People With Stroke: an Overview. J Neurosci Nurs 2019;51:101–5.

11. Wohlgenannt I, Simons A, Stieglitz S. Virtual Reality. Bus Inf Syst Eng 2020;62:455–61.

12. Ventura S, Brivio E, Riva G, Baños RM. Immersive Versus Non-immersive Experience: Exploring the Feasibility of Memory Assessment Through 360° Technology. Front Psychol 2019;10:2509.

13. Demeco A, Zola L, Frizziero A, Martini C, Palumbo A, Foresti R, *et al.* Immersive Virtual Reality in Post-Stroke Rehabilitation: A Systematic Review. Sensors (Basel) 2023;23:1712.

14. Charsky D. From edutainment to serious games: A change in the use of game characteristics. Games Cult J Interact Media. 2010;5:177–98.

15. Tong T, Chignell M, Tierney MC, Lee J. A Serious Game for Clinical Assessment of Cognitive Status: validation Study. JMIR Serious Games 2016;4:e7.

16. Bergeron BP. Developing Serious Games. Hingham, MA: Charles River Media; 2006.

17. van der Kuil MN, Visser-Meily JM, Evers AW, van der Ham IJ. A Usability Study of a Serious Game in Cognitive Rehabilitation: A Compensatory Navigation Training in Acquired Brain Injury Patients. Front Psychol 2018;9:846.

18. Oliveira RS, Trezza BM, Busse AL, Jacob-Filho W. Learning effect of computerized cognitive tests in older adults. Einstein (Sao Paulo) 2014;12:149–53.

19. Rafsten L, Danielsson A, Sunnerhagen KS. Anxiety after stroke: A systematic review and meta-analysis. J Rehabil Med 2018;50:769–78.

20. Rmadi H, Maillot P, Artico R, Baudouin E, Hanneton S, Dietrich G, *et al.* Tolerance of immersive head-mounted virtual reality among older nursing home residents. Front Public Health 2023;11:1163484.

21. Srivastava P, Rimzhim A, Vijay P, Singh S, Chandra S, Desktop VR. Desktop VR Is Better Than Non-ambulatory HMD VR for Spatial Learning. Front Robot AI 2019;6:50.

22. Plechatá A, Sahula V, Fayette D, Fajnerová I. Age-Related Differences With Immersive and Non-immersive Virtual Reality in Memory Assessment. Front Psychol 2019;10:1330.

23. Arlati S, Di Santo SG, Franchini F, Mondellini M, Filiputti B, Luchi M, *et al.* Acceptance and Usability of Immersive Virtual Reality in Older Adults with Objective and Subjective Cognitive Decline. J Alzheimers Dis 2021;80:1025–38.

24. Høeg ER, Povlsen TM, Bruun-Pedersen JR, *et al.* System Immersion in Virtual Reality-Based Rehabilitation of Motor Function in Older Adults: A Systematic Review and Meta-Analysis. Front Virtual Real 2021;2.

25. Mugambi ML, Peter T, F Martins S, Giachetti C. How to implement new diagnostic products in low-resource settings: an end-to-end framework. BMJ Glob Health 2018;3:e000914.

26. Ajana K, Everard G, Lejeune T, Edwards MG. A feature and conjunction visual search immersive virtual reality serious game for measuring spatial and distractor inhibition attention using response time and action kinematics. J Clin Exp Neuropsychol 2023;45:292–303.

27. Lustig C, Hasher L, Zacks RT. Inhibitory deficit theory: Recent developments in a "new view." In: Inhibition in Cognition. American Psychological Association; 20071. P. 45-162.

28. Treisman AM, Gelade G. A feature-integration theory of attention. Cogn Psychol 1980;12:97–136.

29. Erez AB, Katz N, Ring H, Soroker N. Assessment of spatial neglect using computerised feature and conjunction visual search tasks. Neuropsychol Rehabil 2009;19:677–95.

30. Ajana K, Everard G, Sorrentino G, Lejeune T, Edwards MG. Cognitive inhibition difficulties in individuals with hemiparesis: Evidence from an immersive virtual reality target-distractor salience contrast visual search serious game. Research Square; 2023.

31. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. J Clin Epidemiol 2008;61:344–9.

32. Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, *et al.* The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc 2005;53:695–9.

33. Makransky G, Terkildsen TS, Mayer RE. Adding immersive virtual reality to a science lab simulation causes more presence but less learning. Learn Instr 2019;60:225–36.

34. Makransky G, Petersen GB. The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based

Model of Learning in Immersive Virtual Reality. Educ Psychol Rev 2021;33:937–58.

35. Chandler P, Sweller J. Cognitive Load Theory and the Format of Instruction. Cogn Instr 1991;8:293–332.

36. Verheyden G, Nieuwboer A, Mertin J, Preger R, Kiekens C, De Weerdt W. The Trunk Impairment Scale: a new tool to measure motor impairment of the trunk after stroke. Clin Rehabil 2004;18:326–34.

37. Sorrentino G, Sale P, Solaro C, Rabini A, Cerri CG, Ferriero G. Clinical measurement tools to assess trunk performance after stroke: a systematic review. Eur J Phys Rehabil Med 2018;54:772–84.

Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions
Gregorio Sorrentino designed the presented study, analyzed the data, interpreted the results and wrote the paper; Khawla Ajana, Gauthier Everard, Thierry Lejeune, Martin G. Edwards created the REAsmash, interpreted the results of the present paper, and helped write the paper; Florence Vanhoof interpreted the results of the present paper and helped write the paper. All authors contributed to editorial revisions in the manuscript. All authors read and approved the final manuscript. All authors have participated actively in the work and accepted responsibility for all aspects of the work.

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SUPPLEMENTARY DIGITAL MATERIAL 1

Supplementary Table I.—The demographic characteristics of the post-stroke subjects.

ID	Sex	Age (years)	Height (cm)	VR naïve	Was the response hand the dominant one before the stroke?	Months between stroke and VR sessions	Stroke type	Brain lesion side	Brain lesion location	MoCa score	Current Rehabilitation
P1	M	69	172	Yes	Yes	7	Hem	Right	Sylv+Deep	26	Nps+OT+PT
P2	M	65	176	Yes	No	3	Isch	Left	MCA	25	Nps+OT +PT
P3	M	62	183	Yes	Yes	1	Isch	Right	MCA	26	Nps+OT+PT
P4	M	53	173	Yes	No	4	Isch+Hem	Left	Sylv	20	Nps
P5	M	65	180	Yes	No	132	Isch	Left	MCA	26	Finished
P6	F	52	166	Yes	No	19	Isch	Left	Sylv	26	PT
P7	M	52	178	Yes	Yes	32	Isch	Right	Sylv	28	Finished
P8	M	62	164	Yes	No	16	Hem	Left	MCA	25	Finished
P9	M	64	181	Yes	Yes	75	Isch	Right	Sylv	27	PT
P10	M	54	180	Yes	Yes	48	Isch+Hem	Right	Sylv	30	Finished
P11	M	21	172	No	Yes	7	Hem	Right	Sylv	28	Nps+OT+PT
P12	M	60	182	Yes	Yes	2	Isch	Right	Sylv	26	Nps+OT+PT
P13	M	71	173	Yes	No	2	Isch	Left	MCA	30	PT
P14	M	66	178	Yes	Yes	1	Isch	Right	MCA	27	Nps+OT+PT
P15	M	60	184	Yes	No	5	Isch	Left	Sylv	27	Nps+OT+PT

F = Female, M = Male; Isch= Ischemic, Herm= Hemorragic; MCA= Middle cerebral artery, Sylv= Sylvian Segment of MCA; MoCA=Montreal Cognitive Assessment[25]; Nps= neuropsychological therapy, OT= Ocupational therapy, PT = Physiotherapy.

Supplementary Table II.—The demographic characteristics of the healthy controls.

ID	Sex	Age	Height (cm)	VR naïve	Dominant hand
HS1	M	48	180	No	Right
HS2	F	21	168	Yes	Left
HS3	M	45	178	Yes	Left
HS4	F	54	166	Yes	Left
HS5	F	67	174	Yes	Right
HS6	F	69	160	Yes	Right
HS7	M	51	181	Yes	Right
HS8	M	75	178	Yes	Left
HS9	M	65	173	Yes	Right
HS10	F	55	164	Yes	Right
HS11	M	61	180	Yes	Right
HS12	F	64	165	Yes	Right
HS13	F	64	163	Yes	Right
HS14	F	81	164	Yes	Right
HS15	M	52	184	No	Right

F = Female, M = Male.