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A non-immersive virtual reality serious game to assess distractor inhibition and spatial attention in post-stroke individuals

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A R T I C L E I N F O

Keywords:
Visual search
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Non immersive virtual reality

A B S T R A C T

Background: REAsmash, a non-immersive virtual reality serious game based on Feature Integration Theory (FIT) was used to evaluate distractor inhibition and spatial attention.
Methods: Participants (15 post-stroke and 15 age matched healthy controls) performed the visual search REAsmash task with manipulations of high and low target-distractor salience and distractor number. Dependent variables included frequency of errors and omissions and mean correct response time.
Results: Post-stroke participants made more errors ($\chi^2(1) = 19.452$, $p < 0.001$) and omissions ($\chi^2(1) = 55.108$, $p < 0.001$), and responded slower ($F(1,28) = 17.957$, $p < 0.001$, $\eta^2 = 0.391$) than controls. FIT significant effects showed salience ($F(1,28) = 497.626$, $p < 0.001$, $\eta^2 = 0.947$), distractor number ($F(2,56) = 24.968$, $p < 0.001$, $\eta^2 = 0.471$), and a salience and distractor number interaction ($F(2,56) = 26.616$, $p < 0.001$, $\eta^2 = 0.487$), with increased distractor number slowing response time in the low salience condition. A salience-by-group interaction ($F(1,28) = 7.794$, $p = 0.009$, $\eta^2 = 0.218$) indicated greater post-stroke difficulties in low salience conditions. A target-hand congruency (Simon) effect was observed only in post-stroke participants ($F(1,28) = 4.499$, $p = 0.043$, $\eta^2 = 0.138$).
Conclusion: REAsmash-niVR replicated FIT results, confirming its validity for assessing distractor inhibition and spatial attention in post-stroke populations. Future research will compare individuals with and without visual neglect and explore rehabilitation applications to improve spatial attention and motor responses.

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1. Introduction

Stroke is the leading cause of long term disability in developed countries (Phipps & Cronin, 2020), with an estimated 80 million survivors worldwide living with disabilities (Duncan et al., 2021), and with expectations for a 35 % increase in stroke prevalence between 2020 and 2030 (Fan et al., 2023; Pu et al., 2023). Motor limitations are the most common post-stroke impairments, with an estimated prevalence of 83–90 % in acute/sub-acute stages (Bogousslavsky et al., 1988; Dutta et al., 2022; Lawrence et al., 2001). Cognitive impairments resulting from stroke are less obvious, with prevalence in the acute/sub-acute stages estimates varying from 24 to 80 % (Sun et al., 2014). Stroke survivors are often faced with enduring difficulties following clinical interventions in one or more cognitive functions, including attention, concentration, spatial awareness, inhibition, perception, memory, praxis, and executive functioning (Aben et al., 2013; Bour et al., 2011; Bowen et al., 2013; Hurford et al., 2013; Stamenova et al., 2010). Several factors contribute to this variability in prevalence estimation, including the heterogeneity of post stroke cognitive deficits, with clinical scenarios that can range from clear deficits of a specific cognition to, more commonly, conditions where several cognitive functions are involved (Jokinen et al., 2015; Laakso et al., 2019). Furthermore, it is common to consider the motor impairments as independent to the cognitive impairments, presenting a limitation in understanding.

Executive functions, such as selective attention and cognitive inhibition are deeply involved in motor relearning processes (Barrett & Muzaffar, 2014; Hochstenbach & Mulder, 1999; McEwen et al., 2009; Tennant et al., 2004) and seem to have a direct association to poor motor performance (D'Imperio et al., 2021; Kim et al., 2021; Nijboer et al., 2014). Furthermore, ecological (real-world) motor interaction tasks integrate cognitive load and double-task demands, requiring cognitive inhibition in order to perform the task efficiently (Lowrey et al., 2022; Mullick et al., 2015; VanGilder et al., 2020). Even though the literature clearly shows the impact of cognition on post-stroke recovery (Shimada et al., 2018; VanGilder et al., 2020), the routine assessment of cognitive deficits remains underrepresented in the clinic (Einstad et al., 2021; Montero-Odasso et al., 2019), unless the patient shows clearly observable cognitive impairments.

Differences in spatial task performance among post-stroke individuals may also reflect altered motor planning or execution, particularly when reaching across the midline (Fang et al., 2007). The effect may be explained by the Simon effect (Simon, 1990). The Simon effect refers to the phenomenon whereby reaction times are faster, and responses more accurate, when the spatial location of a stimulus corresponds to the side of the response hand, even if stimulus location is irrelevant to the task. This effect is thought to arise from automatic spatial coding of stimuli and subsequent response conflict and has been used as an index of executive function and motor planning (Cespón et al., 2020). From a motor perspective, the effect may be linked to a requirement of greater postural control or coordination of the trunk and upper limb (i.e., driven by motor plan complexity). In this context, stimulus-response hand congruency may offer additional insight into the interplay between spatial and inhibitory attention.

Based on recent calls to improve neuropsychological evaluations using new technologies, our team recently developed REAsmash-iVR (Ajana, Everard, Lejeune, & Edwards, 2023), a new immersive Virtual Reality (iVR) Serious Game (SG) with the aim to simultaneously evaluate distractor inhibition and spatial attention using measures of target omissions and response time during an immersive virtual experience (head-mounted display). The REAsmash-iVR is an adaptation of the classic fairground and arcade game Whac-A-Mole, and based on Feature Integration Theory (FIT) (Treisman & Gelade, 1980). FIT, by Treisman and Gelade, contrasted response time performance to two target-distractor contrast conditions. In a high saliency target-distractors 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 pre-attentive cognitive effect shows that attention is directly drawn to the target stimulus. In contrast, in a low saliency target-distractors 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 of the target shared with the distractors). This stimuli 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 the numbers of distractors did not change response time (Treisman & Gelade, 1980). However, the serial search condition was influenced by distractor number, with increased numbers of distractors increasing response time. The REAsmash-iVR replicates the FIT paradigm using animated complex 3D stimuli (Ajana, Everard, Lejeune, & Edwards, 2023).

The novelty of the REAsmash lies in applying the well-established FIT attentional principles within a SG format for the concurrent assessment of spatial attention (contrasting time to select a left versus right targets, a common test paradigm for neglect) and distractor inhibition. This integration allows for the identification of co-occurring (spatial and inhibitory) attentional deficits. The aim of this novel combination is to enable patient stratification based on attentional profiles, identifying individuals with hemiparesis with or without distractor inhibition difficulties, individuals with hemiparesis with or without lateralised spatial deficits, and individuals with hemiparesis and lateralised spatial deficits (neglect) with or without distractor inhibition difficulties. This novelty in diagnosis test allows a better understanding of patient profiles and may lead to predictions in the efficacy of treatment success (i.e., with profiles of attention impairments predicting compromising efficacy).

Previous research on cognitive assessment in aged participants has demonstrated better response to non-immersive VR (niVR) relative to iVR with the iVR sometimes causing participant stress (Plechatá et al., 2019). Stress can be further increased by the shorter proximity to stroke onset (i.e., time since stroke) (Plechatá et al., 2019). Nevertheless, recent studies involving immersive VR in older adults with cognitive decline have reported high levels of acceptance (Arlati et al., 2021). This may be related to advancements in head-mounted displays, which reduce cyber sickness and provide immersive experiences that closely mimic real-world environments, reducing stress and anxiety (Arlati et al., 2021). Therefore, the debate in the literature remains active, with findings highlighting both challenging and promising outcomes.

We decided to recreate the REAsmash in a non-immersive environment (i.e., REAsmash-niVR). Non-immersive VR is typically defined as interaction with digital content through input peripherals (e.g., keyboard, touchscreen or hand tracker) and an output device (e.g., screen or tablet) (Ventura et al., 2019). The REAsmash-niVR adheres to this format by offering an interactive virtual environment on a large touch-sensitive screen (i.e., the REAtouch®), without the use of immersive head-mounted displays. This technology brings the advantages of VR, without increasing stress to individuals, thereby providing test quality suitable for acute and sub-acute patients (Rafsten et al., 2018; Rmadi et al., 2023). REAsmash can be used as an assessment tool in both clinical and research settings for cognitive impairments, supporting both diagnosis and future stratification of post-stroke patients thanks to its accessibility and user-friendly interface for both patients and clinicians.

Given the increasing clinical integration of VR technologies in neurorehabilitation, demonstrating standard cognitive effects in VR environments represents an essential step toward supporting their use in evidence-based assessment. In this context, we describe the technical implementation of the REAsmash-niVR and present a proof-of-concept investigation aimed at demonstrating its feasibility and sensitivity in detecting group-level attentional deficits. While the establishment of criterion validity against traditional neuropsychological measures remains a critical objective, it falls beyond the scope of this initial study.

We contrasted a group of 15 post-stroke participants with a control group of 15 mean age-matched healthy volunteers. Based on previous literature, we hypothesised an overall general FIT effect for all participants: (i) longer mean response time to accomplish the task in low compared to high salience conditions; and (ii) 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. Furthermore, we predicted (iii) an interaction between group and salience, with post-stroke participants exhibiting a specific difficulty in inhibiting distractors, characterised by slower responses, in the low salience condition, but with no significant group differences in the high salience condition.

In addition to the FIT effect and group differences, the REAsmash measures peripersonal space reaching responses, offering the possibility to investigate differences in the position of the target stimulus relative to the response hand. In this study we contrasted target position relative to response hand (congruent vs incongruent hemi-field), making (iv) the hypothesis of a target-response hand congruency effect showing faster responses for congruent relative to incongruent (i.e., showing a Simon effect (Simon, 1990)), and no interactions with distractor salience, distractor number and group.

2. Materials and methods

2.1. Study design

The protocol was approved by the Saint Luc-UCLouvain Hospital-Faculty Ethics Committee (Belgium) (2015/10FEV/053) and registered on clinicaltrial.gov (NCT04694833).

2.2. Participants

Sample size estimation was guided by a power analysis performed using G*Power® (version 3.1.9.7), and data from a previous study that investigated the REAsmash interaction between target-distractor saliency and distractor number (FIT) (Ajana, Everard, Lejeune, & Edwards, 2023). This interaction effect underlies the task objective to measure distractor inhibition. From these data (healthy participants) a significant interaction effect was reported ($F(2,114) = 117.58$, $p < 0.001$, $\eta^2 = 0.67$), with an associated effect size (Cohen's f) of 1.425. Based on these parameters, the power analysis indicated that a sample of 4 participants would be sufficient to detect this interaction with 80 % power at an alpha level of 0.05. Since our study involved a between-group design comparing post-stroke participants with healthy controls, we opted for a more conservative sample size of 15 participants per group. A post-hoc power check confirmed this sample was sufficient to detect the observed between-group effect ($\eta^2 = 0.391$).

Post-stroke participants were recruited from the physical medicine and rehabilitation department of the Cliniques universitaires Saint-Luc in Brussels, and all were hospitalised or discharged patients. The inclusion criteria were: (1) presence of an ischemic or haemorrhagic first cortical and/or sub-cortical stroke, diagnosed by CT (computed tomography) or MRI (magnetic resonance imaging) and (2) a good understanding of the task instructions. The latter was assessed through a verbal walkthrough of the task with verbal confirmation followed by a simulated brief trial practice session. Participants were included only if they successfully completed the practice. The exclusion criteria were: (1) uncorrected vision deficiencies (e.g., hemianopia, peripheral vision loss, amblyopia, color blindness or uncorrectable visual acuity deficits) (2) the presence of other neurological conditions (e.g., dementia or extrapyramidal disorders); or orthopaedic dysfunction that could influence upper extremity function; (3) cognitive impairment (indicated either by MoCA scores (Nasreddine et al., 2005) below 20 out of 30, administered no more than 7 days prior to the trial, or by an inability to complete the practice task) and (4) too poor trunk control to sustain the trial. Recruitment started in February 2023 and ended in June 2024. The post-stroke participants group consisted of 15 participants (1 female, all right-handed) with an average age of 59.6 years (SD = 13.0), 1 non-naïve for VR. Average time from the stroke was of 13 months (SD = 13) with 9 participants in sub-acute phase and 6 in chronic phase at the time of the trial, average MoCA score was of 26.2 (SD = 2) (See Table 1).

From the 15 participants, 8 had a history of visual spatial attention deficits reported in the medical records. We therefore tested all post-stroke participants with gold standard tests for spatial attention at the time of testing. Further, we conducted a post-hoc analysis (first post-hoc analysis) on participants without signs of visual USN at the time of testing relative to healthy controls. The post-hoc sample was composed of 12 participants (1 female, all right-handed, average age 59.5 years, SD 14.3). See the Procedure section for details of the gold standard tests.

The group of 15 healthy adults (7 females, 4 left-handed), with an average age of 57.9 years (SD = 14.0), were recruited between

Table 1
The demographic characteristics of the post-stroke participants.

ID	Sex	Age (years)	Height (cm)	VR naive	The response hand was the dominant one?	Months from the stroke	Stroke type	Brain lesion side	Brain lesion location	MoCA score	History of spatial attention impairment	Current spatial attention impairment	Current Rehabilitation
P1	M	69	172	Yes	Yes	6	Hem	Right	Sylv + Deep	26	Yes	No	Nps + OT + PT
P2	M	65	176	Yes	No	2	Isch	Left	MCA	25	No	No	Nps + OT + PT
P3	M	62	183	Yes	Yes	5	Isch	Right	MCA	27	Yes	Yes	Nps + OT + PT
P4	M	53	173	Yes	No	4	Isch + Hem	Left	Sylv	20	No	No	Nps
P5	M	65	180	Yes	No	38	Isch	Left	MCA	26	No	No	No more
P6	F	52	166	Yes	No	20	Isch	Left	Sylv	26	No	No	PT
P7	M	52	178	Yes	Yes	23	Isch	Right	Sylv	28	Yes	Yes	No more
P8	M	62	164	Yes	No	16	Hem	Left	MCA	25	No	No	No more
P9	M	64	181	Yes	Yes	41	Isch	Right	Sylv	27	No	No	PT
P10	M	54	180	Yes	Yes	23	Isch + Hem	Right	Sylv	28	Yes	No	No more
P11	M	21	172	No	Yes	2	Hem	Right	Sylv	26	Yes	No	Nps + OT + PT
P12	M	60	182	Yes	Yes	3	Isch	Right	Sylv	26	Yes	No	Nps + OT + PT
P13	M	71	173	Yes	No	5	Isch	Left	MCA	28	No	No	Phys
P14	M	66	178	Yes	Yes	4	Isch	Right	MCA	28	Yes	Yes	Nps + OT + PT
P15	M	78	178	Yes	Yes	4	Isch	Right	Sylv	27	Yes	No	Nps + OT + PT

F = Female, M = Male; Isch = Ischemic, Herm = Hemorragic; MCA = Middle cerebral artery, Sylv = Sylvian Segment of MCA; Nps = neuropsychological therapy, OT= Occupational Therapy, PT = Physio therapy.

November 2021 and March 2024 through the University of Louvain participation panel and social media groups (See Table 2). The participants had normal or corrected to normal vision and no neurological, psychiatric or orthopaedic disorders potentially affecting compliance or limiting cognition and/or upper limb functionality. Difficulty in understanding French (the language of the task instructions) was an exclusion criterion. Two healthy volunteers were non-naïve for VR.

The post-stroke and control groups were mean age matched (59.6 years vs 57.9 years respectively, with a *t*-test showing no significant difference in age between the two groups ($t(28) = 0.351$, $p = 0.726$). All the participants volunteered to participate in the study, providing written informed consent before participation.

2.3. Materials

The REAsmash-niVR was developed to run on the REAtouch® (Axinesis®) interactive medical device. This was composed of a touch-sensitive screen (43", 95 × 53 cm) incorporated in a motorised structure that allowed customised screen lifting and inclination tilting (Fig. 1). 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 REAsmash was developed using Unity 2019.3 software (C#). It displayed a cartoon-like garden containing 24 molehills (6 columns and 4 rows), placed on an active playing surface of 95x42cm. The stimuli consisted of moles emerging from the molehills, with each mole and molehill covering a surface of 8x8cm. The stimuli were presented in 7 trial blocks, with the target mole (wearing a red miner's helmet) pseudo-randomly appearing one time from each of the 24 molehills for each trial block, making 24 trials. In the baseline (level 1), no distractors were presented with the target mole, allowing a baseline measure of participants response time without distractor inhibition demands. In the high saliency target-distractor contrast conditions, the target was presented with distractor moles wearing blue helmets (miner's or horned) (levels 2, 3 and 4). In the low saliency target-distractor contrast conditions, the target was presented with distractor moles wearing blue miner's or red horned helmets (levels 5, 6 and 7), with the distractors sharing a conjunction of features with the target. In each of the two target-distractor salience conditions, 11, 17 or 23 distractors accompanied the target (respectively), making randomised stimuli sets of 12, 18 and 24 stimuli (Fig. 2).

2.4. Procedure

The study was run in a controlled laboratory at the Cliniques universitaires Saint-Luc of Brussels (Belgium). Participants were asked to sit on a chair, with their feet on the ground, positioned in front of the REAtouch® and aligned with the central sagittal axis of the interactive touch-sensitive screen. For participants in wheelchairs, the wheelchair was appropriately positioned to align the participant in the same playing conditions as the other participants, with their feet placed on the footrest of the wheelchair. The screen was adjusted to a suitable height to make the reaching span of the participant comfortable and safe. The touch-sensitive screen was presented at a horizontal angle of zero degrees relative to the ground. The participants were instructed to begin each trial by touching a "X" with their playing hand that appeared in the central 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 began, and the participant was instructed to touch the target as quickly as possible using their dominant hand in the case of healthy control participants and the less-impaired hand in the case of post-stroke participants. This approach helped to minimise the impact of motor impairments, ensuring a clearer assessment of cognitive function. The instructions were given orally by the examiner before the start of the session and displayed on the touchscreen immediately before the session began. Prior to the main experiment, a 10-trial practice session was used to familiarise participants with the test and device. A 20-s rest period was provided between each of the 7 trial blocks (24 trials in each block; 168 total trials). The trial blocks were run from easy to difficult levels (1–7). Each target stimulus was presented for a maximum duration of 7 s. Correctly responding to the target within 7 s was designated as a correct response time (i.e., the time between the beginning of the stimuli

Table 2
The demographic characteristics of the heathy participants.

	Sex	Age	Height (cm)	VR naive	Dominant hand
HS1	M	48	180	No	Right
HS2	F	21	168	Yes	Right
HS3	M	45	178	Yes	Left
HS4	F	54	166	Yes	Left
HS5	F	67	174	Yes	Right
HS6	M	55	182	Yes	Right
HS7	M	61	181	Yes	Left
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.

Fig. 1. The non-immersiveVR device. REAtouch® (Axinesis®) touch-sensitive 43″ screen tablet with multisensory and real-time performance feedback. The height and inclination of the screen can be adjusted. In the present study, the inclination was the same as that presented here (i.e., 0°).

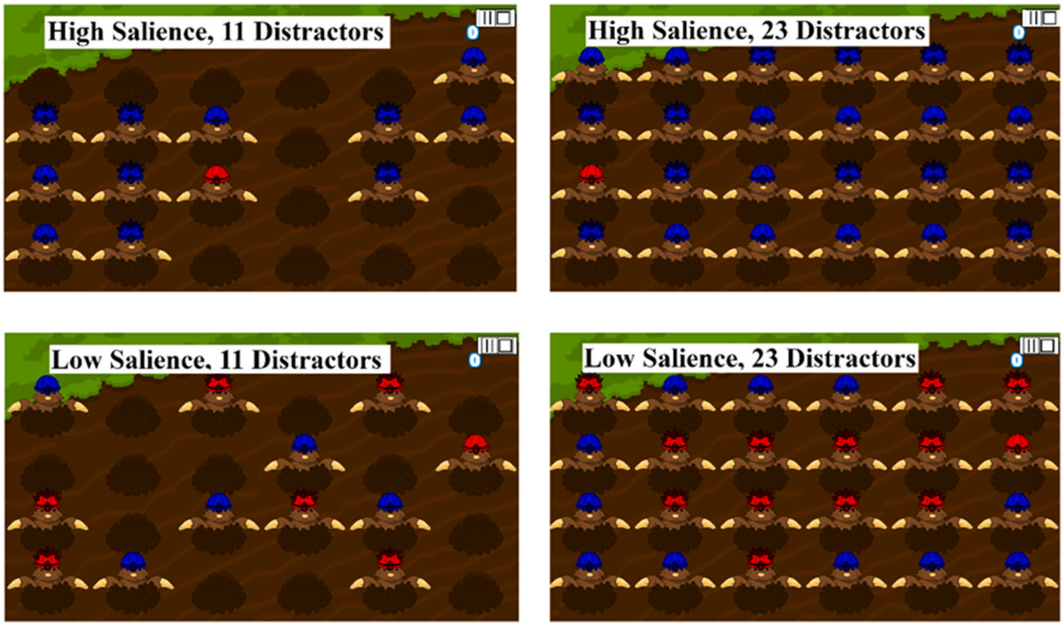

Fig. 2. Target-distractor search stimuli. Examples of stimulus settings in (i) Levels 2 and 4 (i.e., high salience): with 11 and 23 distractors wearing horned or miner's blue helmets and (ii) levels 5 and 7 (i.e., low salience) with 11 and 23 distractors wearing red helmets with horns or blue miner's helmets. For both high and low saliency conditions, there were two intermediate levels (i.e. levels 3 and 6) with 17 distractors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

presentation and the manual response). Omissions were defined as the target not being found within the 7 s, and errors responses were defined by the participant responding to a distractor instead of the target. For all manual response (irrespective of correct or incorrect), the position of final response on the stimulus playing field was recorded, along with the position of the target stimulus for that trial. Participants, including those with cognitive deficits, completed the full assessment in under 10 min (average time approximately 8 min).

All post-stroke participants underwent a battery of neuropsychological tests to explore spatial attention within 7 days of the niVR session. This assessment included the Bells Test (Gauthier et al., 1989), a paper-and-pencil cancellation task in which participants are asked to circle bell figures scattered among various distractor figures. This test evaluates egocentric neglect by examining the number and spatial distribution of target omissions across the visual field. In addition, participants completed the Apple Cancellation Test (Bickerton et al., 2011), which is specifically designed to distinguish between egocentric and allocentric neglect. In this task, participants must identify and cancel only complete apple figures while ignoring distractor apples that are incomplete on either the left or right side. As for the Bells Test, egocentric neglect is defined by a difference in target omissions for contralesional relative to ipsilesional targets. Allocentric neglect is defined by error responses to the incomplete distractors, and more errors when the incomplete side is contralesional relative to ipsilesional. Finally, participants were assessed using the Visual Field and Visual Scanning subtests from the computerised Test for Attentional Performance (TAP) battery (Zimmermann & Fimm, 2002). The Visual Field subtest assesses the presence of visual field deficits by measuring detection speed across various spatial locations, while the Visual Scanning subtest evaluates the participant's ability to systematically explore and search for targets within a structured visual array. Participants were considered to have visual USN if they had pathological results in any of the tests. Results showed that participants either showed peri-personal egocentric USN on all tests or showed no evidence of USN. There are no validated gold standard tests that systematically assess distractor inhibition impairments when searching for a target.

2.5. Data analyses

Data analyses were performed using SPSS 27.0 (IBM®). Omissions and error percentage responses were analysed using chi-square analysis (relative to correct responses). Mean correct response time analyses were first verified for data normality using the Shapiro-Wilk test, and then analyses were made using repeated measures ANOVAs. Post-hoc analyses were performed with Bonferroni with corrections for multiple comparisons.

The independent within-participant variables were target-distractor saliency (high vs low), distractor number (11, 17 and 23), and target-response hand congruency (congruent vs incongruent). For example, when participants played with their right hand, targets presented in columns 1–3 (i.e., left hemifield) were defined as incongruent targets, and targets presented in columns 4–6 (i.e., right hemifield) were defined as congruent targets. This definition was used to align the Simon effect relative to spatial targets, whereby incongruent trial corresponds to targets positioned in contralesional space. For the within-participant manipulations (2x3x2; 144 trials across 6 levels), a mean derived from 12 trials (collapsing target position) were used. We also tested the between-participants variable of group (post-stroke vs healthy). The dependant variables were omissions, error responses and correct target response time. Mean response time refers to the time between the appearance of the target mole stimulus and the response to correctly touch the target. Mixed measures ANOVA were used to test within-participant variability across task conditions (i.e., salience, distractor number, and target-hand congruency), and between participant groups.

3. Results

All participants completed the experiment without adverse event. In a general feedback discussion session with the participants after the study, they all described the experimental tasks as non-stressful and engaging. No participants asked to stop the experiment prematurely or to extend the rest periods.

For the post-stroke participant group, from the total dataset of 2520 trials (i.e., 7 levels x 24 trials x 15 participants), 51 trials were excluded due to technical issues in data collection. From the remaining 2469 trials, there were 76 omissions (3.1 %), 37 error responses (1.5 %) and 0 anticipatory responses (i.e., responses executed in less than 250ms). For healthy controls, from the total dataset of 2520 trials, there was one trial excluded due to technical issues. From the remaining 2519 trials, there were 9 omissions (0.3 %), 8 error

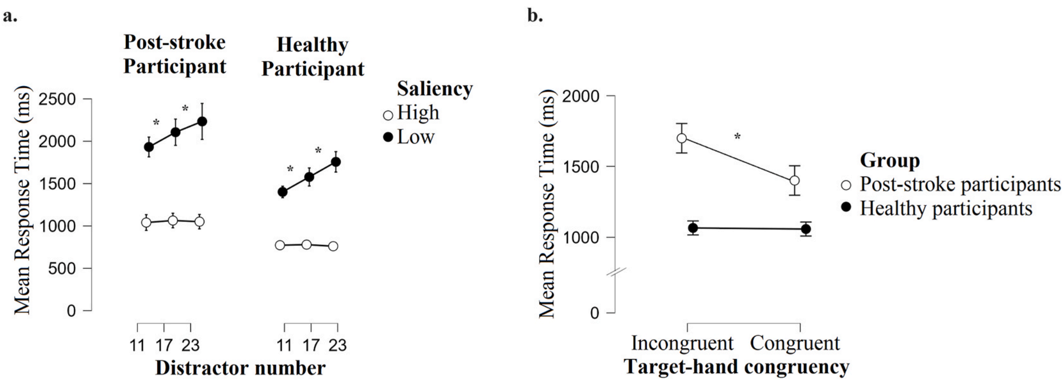

Fig. 3. a Number of distractors and target-distractor saliency interaction for mean response. Presentation of the mean response time (in milliseconds) as a function of distractor number and target-distractor saliency contrast. On the Y-axis the response time. On the X-axis the three possible distractor number conditions (11, 17 and 23). Outlined circles represent high salience conditions; black-filled circles represent low salience conditions. On the left, the group of post-stroke participants and on the right, the healthy controls. The error bars show the 95 % confidence interval. "*" represent significant main effect for distractor number.

Fig. 3b. Mean response times levels from 2 to 7 organised according to target-hand congruency, in post-stroke with sequelae vs healthy controls groups. Presentation of the mean response times (in milliseconds) in successful trials with target emerging in the two alternative positions. On the Y-axis the mean response time. On the X-axis the two possible target position (i.e., hemifield contralateral vs. ipsilateral to the playing hand). The error bars show the 95 % confidence interval. Outlined circles represent post-stroke participants; black-filled circles represent healthy controls. "*" represent significant main effect of target-hand congruency.

responses (0.4 %) and 1 anticipatory response (0.04 %). We used a standard practice three standard deviation confidence interval filter for response time to remove 36 outliers (1.4 %) from the control data. No outlier filter was applied to the patient data.

Chi-square analyses for error and omission rates relative to correct responses, showed a significant group effect. The post-stroke participants committed significantly more errors and omissions than healthy participants ($X^2(1) = 19.452$, $p < 0.001$ and $X^2(1) = 55.108$, $p < 0.001$ for errors and omissions respectively, on a dataset of N = 4988). Because of the low number of omissions and error responses, no further analyses could be conducted.

The ANOVA for mean response time showed a significant between-participants group effect, ($F(1,28) = 17.957$, $p < 0.001$, $\eta 2 = 0.391$), with slower mean response times for the post-stroke relative to healthy participant group (mean 1571ms, SD 69.905 and 1152ms, SD 69.905 for post-stroke and healthy participants respectively). The ANOVA supported the FIT effect, showing within-participants main effects of saliency, ($F(1,28) = 497.626$, $p < 0.001$, $\eta 2 = 0.947$) and number of distractors ($F(2,56) = 24.968$, $p < 0.001$, $\eta 2 = 0.471$). As predicted, the results showed faster responses in high (mean 900ms, SD 45.531) compared to low (mean 1824, SD 60.584) target-distractor salience conditions and increased response time with increased numbers of distractors (mean 1276ms, SD 52.310; mean 1371ms, SD 52.726 and mean 1439ms, SD 48.533 for 11, 17 and 23 distractors respectively) (Fig. 3a). There was also a significant main effect of target-hand congruency ($F(1,28) = 10.414$, $p = 0.003$, $\eta 2 = 0.271$), with slower mean response times when target position was incongruent to the response hand (mean 1440ms, SD 65.249) compared to congruent (mean 1284ms, SD 42.279). Significant interactions were found between saliency and number of distractors ($F(2,56) = 26.616$, $p < 0.001$, $\eta 2 = 0.487$) (replicating the FIT effect) and between saliency and group ($F(1,28) = 7.794$, $p = 0.009$, $\eta 2 = 0.218$) (Fig. 3). Target-hand congruency and group was also significant ($F(1,28) = 4.499$, $p = 0.043$, $\eta 2 = 0.138$). No other interactions were significant.

To analyse the interactions, separate ANOVAs were run for each saliency condition and group. Concerning the interactions with the saliency condition, the high saliency target-distractor condition showed no significant differences for number of distractors or group. However, for the low saliency target-distractor condition, there was a significant effect for distractor number ($F(2,56) = 30.005$, $p < 0.001$, $\eta 2 = 0.517$) (as predicted by the FIT effect) and group ($F(1,28) = 19.459$, $p < 0.001$, $\eta 2 = 0.970$). Analysis of distractor number showed increased mean response time increased with increased numbers of distractors (mean 1656ms, SD 65.587; mean 1831ms, SD 67.865 and mean 1984ms, SD 62.464 with 11, 17 and 23 distractors respectively). Analysis of group showed slower mean response times for the post-stroke relative to healthy participant group (mean 2091ms, SD 85.678 and mean 1556ms, SD 85.678 respectively).

Concerning target-hand congruency interaction with group, healthy participants showed no target-hand congruency effect ($F(1,14) = 1.754$, $p = 0.207$, $\eta 2 = 0.111$). However, post-stroke participants showed a significant main target-hand congruency effect ($F(1,28) = 8.661$, $p = 0.011$, $\eta 2 = 0.382$) with mean response times slower for incongruent (mean 1700ms, SD 122.849) relative congruent (mean 1443ms, SD 68.548) condition (Fig. 3b).

For the first post-hoc analysis, we removed three participants diagnosed with visual USN within 7 days prior to niVR session. The objective of this analysis was to test if the significant interactions between saliency and group, and target-hand congruency and group mean response time was caused by the inclusion of these three participants with spatial attention impairments. The ANOVA of the mean response times confirmed the same significant effects. There was a significant effect of group ($F(1,25) = 12.695$, $p = 0.002$, $\eta 2 = 0.337$), target-distractor saliency ($F(1,25) = 559.773$, $p < 0.001$, $\eta 2 = 0.957$) and distractor number ($F(1,25) = 27.365$, $p < 0.001$, $\eta 2 = 0.523$). Significant interactions were found between saliency and group ($F(1,25) = 13.478$, $p = 0.001$, $\eta 2 = 0.350$) and saliency and distractor number ($F(2,50) = 27.097$, $p < 0.001$, $\eta 2 = 0.520$). Target-hand congruency also remained significant ($F(1,25) = 6.780$, $p = 0.015$, $\eta 2 = 0.213$), but now with no interaction between target-hand congruency and group ($F(1,25) = 2.363$, $p = 0.137$, $\eta 2 = 0.086$).

The second post-hoc analysis focused on the baseline level, contrasting the 15 post-stroke participants with the 15 healthy controls. The aim of this analysis was to explore the effect of target position (congruent vs incongruent hemi-field) relative to the response hand on mean response time in a search task without distractor inhibition demands. The ANOVA on mean response times showed a main target-hand congruency effect ($F(1,28) = 8.982$, $p = 0.006$, $\eta 2 = 0.243$) and a significant interaction between target-hand congruency

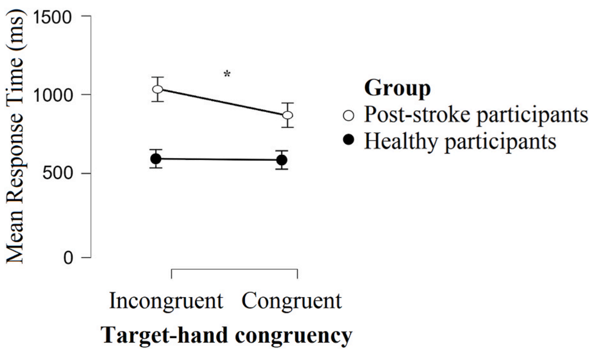

Fig. 4. Mean response times in baseline level organised according to target-hand congruency, in post-stroke with sequelae vs healthy controls groups. Presentation of the mean response times (in milliseconds) in successful trials of level 1 with target emerging in the two alternative positions. On the Y-axis the mean response time. On the X-axis the two possible target position (i.e., hemifield contralateral vs. ipsilateral to the playing hand). The error bars show the 95 % confidence interval. Outlined circles represent post-stroke participants; black-filled circles represent healthy controls. “*” represent significant main effect of target-hand congruency.

and group ($F(1,28) = 7.801$, $p = 0.009$, $\eta 2 = 0.218$). Separate ANOVAs per group showed a target-hand congruency effect only in the post-stroke participants group ($F(1,14) = 10.271$, $p = 0.006$, $\eta 2 = 0.423$), with longer response times in the incongruent target-hand condition (mean 1026.593ms, SD 126.509 and mean 801.288ms, SD 76.463 respectively) (Fig. 4).

Combining the two planned post-hoc analyses, a further ANOVA contrasting the healthy controls with the 12 post-stroke participants without signs of visual USN showed a main target-hand congruency effect ($F(1,25) = 6.904$, $p = 0.014$, $\eta 2 = 0.216$) and a significant interaction between group and target-hand congruency ($F(1,25) = 5.052$, $p = 0.034$, $\eta 2 = 0.168$). Separate ANOVAs per group showed a target-hand congruency effect only in the post-stroke participants group ($F(1,11) = 24.043$, $p < 0.001$, $\eta 2 = 0.686$).

4. Discussion

Compared to currently available gold standard diagnosis tests, the REAsmash SG, based on Feature Integration Theory (FIT) (Treisman & Gelade, 1980), provides a novel systematic evaluation of distractor inhibition attention. Further, the REAsmash SG involves direct reaching responses to the target stimuli in peripersonal space, providing interesting target-hand congruency response time measures that depend on the spatial position of the target relative to the response hand. This present study aimed to provide a preliminary investigation into the potential of the niVR version of REAsmash as a diagnostic tool for distractor inhibition. We contrasted, for the first time, the mean response times of post-stroke participants and healthy controls. Our results replicated Ajana et al.[29] who presented the iVR version of REAsmash SG on healthy aged adults, further demonstrating a replication of the FIT effect using gamified stimuli. Post-stroke participant outcomes probed the presence of specific attentional and motor response selection deficits that might remain undetected by conventional clinical assessments. The observed group differences, including the Simon effects, underscore the value of a task sensitive to both spatial and non-spatial aspects of attention.

The analyses of mean response time supported the FIT effect, characterised by longer mean response times to find and point to the target in low compared to high salience conditions (hypothesis 1), and an interaction effect (hypothesis 2), with no effect of distractor number for the high salience condition, but increased time to find the target with increased distractor numbers in the low salience condition.

For mean response time, we also reported a main effect of group, with the post-stroke group responding slower than the healthy control group. The third hypothesis predicted an interaction between saliency and group, which was supported. In the high salience condition with low distractor inhibition demands, there were no differences in mean response times. However, for the low salience condition with high distractor inhibition demands, the post-stroke participants were significantly slower than the control group. This finding suggests potential inhibition difficulties in the post-stroke participants. This interaction remained consistent in the first post-hoc analysis, were participants with visual USN were excluded, suggesting that the effect was not simply driven by the presence of USN in some individuals.

The fourth hypothesis, which predicted a target-hand congruency (Simon effect) effect, was confirmed in the principal analyses. Mean response time analyses showed an interaction between target-hand congruency and group, demonstrating significant differences in mean response times only for the post stroke group. Interestingly, we found this same effect in the baseline post-hoc analysis. In the present version of the REAsmash SG, we introduced a baseline level (level 1), making it possible to benchmark response times to targets presented without distractor inhibition demands. As for the principal analysis of data, this analysis of baseline demonstrated a significant interaction between target-hand congruency and group, with a target-hand congruency effect only in the post-stroke participants group, and longer response times in the incongruent than congruent target-hand condition. This suggests that the interaction effect is unrelated to distractor inhibition cognition, and more related to hand response after target attention selection. The interaction between target-hand congruency and group disappeared in the post-hoc ANOVA on the selected group of 12 post-stroke participants without signs of visual USN. However, the interaction between target-hand congruency and group for the baseline post-hoc ANOVA on the selected group of 12 post-stroke participants again showed the same interaction effect as the principal results. This variance in consistency of results would merit further investigation with a larger sample of participants with and without signs of spatial attention deficit in order to understand whether the target-hand congruency and group interaction is caused by spatial attention impairments.

The results of the present paper, and the paper by Ajana et al. (Ajana, Everard, Sorrentino, et al., 2023) demonstrate that the REAsmash (iVR and niVR versions) provides a new assessment of distractor inhibition demands on spatial target search performance. The SG was well received by participants, demonstrating the potential value that the test brings to testing participants, and maintaining their motivation. In line with the observed attentional patterns, we plan to conduct dedicated analyses on participants diagnosed with visual USN. Future investigations will explore the reliability of REAsmash in detecting spatial lateral biases (i.e., slower response times to contralesional versus ipsilesional targets) in individuals with USN. These analyses will help disentangle spatial attentional impairments from motor planning or execution difficulties. A preliminary version of these analyses, based on the participants identified with USN in the present data using gold-standard tests is provided as Supplementary Materials. Embedding both spatial target selection and distractor inhibition into a single SG framework offers a promising avenue for stratifying stroke survivors, for instance by differentiating patients with hemiparesis with or without co-occurring inhibitory deficits, distinguishing patients with hemiparesis with or without spatial attention impairments and distinguishing patients with hemiparesis and spatial attention impairments with or without co-occurring inhibitory deficits.

The target-hand congruency effect and group interaction results are interesting as they highlight a potential difference for post-stroke participants. The results suggests that this difference is not caused by distractor inhibition, but rather is more likely linked to problems in motor processes related to the cortical or subcortical lesion. Particularly when the task requires reaching movements across the midline, the increased demand for postural control and coordination of the trunk and upper limb may expose impairments in motor planning or execution in post-stroke individuals. It is well known that individuals post-stroke often face impairments in trunk control (Bohannon, 2022; Massie et al., 2012). The trunk plays a crucial role in stabilising the pelvis and supporting upper limb movements, enabling coordinated reaching tasks and maintaining overall core stability during functional activities (Verheyden et al., 2006). Furthermore, previous research has demonstrated that even the less-affected upper limb may exhibit subtle yet functionally relevant motor deficits in post-stroke individuals, particularly during reaching movements that require proximal arm control and precision (Schaefer et al., 2007; Semrau et al., 2017). Although cognitive causes cannot be ruled out, such ipsilesional impairments can influence motor response strategies, contributing to prolonged response times and increased variability in movement trajectories, even in the absence of overt functional limitations in the post-stroke population. Lateral and diagonal reaching, especially to distant, such as those needed in the target-hand incongruent condition of our SG, required greater trunk control than the congruent condition (Sommer et al., 2023). The incongruent target-hand condition could therefore constitute a further motor challenge for stroke survivors. Future studies on REAsmash could benefit from the introduction of a trunk control rating scale (as the Trunk Impairment Scale (Sorrentino et al., 2018; Verheyden et al., 2004)) in the assessment battery.

The present study has nevertheless some limitations. We chose not to divide participants based on their stage of post-stroke recovery, principally due to the participants sample size. However, the stage of recovery (subacute vs chronic) could impact outcomes in complex task such as REAsmash. Controlling for gender was not prioritised, as the FIT processes under investigation generally believed to operate independently of gender-related differences (Treisman & Gelade, 1980). Nevertheless, gender-based differences may provide meaningful insights into other factors, such as differences in engagement of the SG. Another limitation is that our sample included both participants with prior VR experience and VR naïve. Given the cross-sectional clinical design of this study, lack of familiarity with VR may have influenced the findings. Future research, aiming to establish REAsmash as a diagnostic tool, should explore how recovery phases, gender and familiarity with VR may influence outcomes in both iVR and niVR versions.

We plan to include 3 populations (i.e., (i) post-stroke participants with signs of visual USN on gold standard tests, (ii) post-stroke participants without signs of visual USN on gold standard tests and (iii) healthy controls). This will allow for further understanding of the interactions between distractor inhibition attention, spatial attention and target-response hand congruency effects post stroke. Furthermore, contrasting results between the REAsmash iVR and niVR versions on the same participants, we hypothesise that the two tests will show the same results (i.e., equivalence). These data will be important for developing tests to be used with post-stroke individuals in the acute to sub-acute stages, starting with niVR, and transferring to iVR versions that can be used by post-stroke individuals in the sub-acute to chronic stages, particularly for outpatient diagnosis measures.

Beyond diagnostic potential, the REAsmash offers practical advantages in rehabilitation. The motivational affordances of serious gaming are known to enhance engagement and reduce performance variability across sessions, thereby enabling more consistent longitudinal tracking of patient progress (Gómez Bergin & Craven, 2023). We are currently conducting studies aimed at validating rehabilitation-oriented versions of REAsmash that specifically challenges difficulties experienced by the post-stroke individual (i.e., distractor inhibition attention vs spatial target-hand congruency and motor impairment). Future publications will report on their effectiveness, allowing clinicians and researchers to follow the evolution of this tool for neurorehabilitation purposes.

5. Conclusions

In conclusion, we have shown that REAsmash niVR test provides measures of non-spatial distractor inhibition attention, replicating the results of the iVR version, and the FIT paradigm. The REAsmash provides an ideal candidate to study whether and how distractor inhibition demand influences attention performance. Future studies will explore the effects of different degrees of immersion (iVR vs niVR) for the REAsmash and will contrast groups of participants with and without signs of visual USN to better understand distractor inhibition, spatial attention and target-response hand congruency effect in stroke survivors.

6. Glossary

- **Non-immersive Virtual Reality (niVR)**: A type of virtual reality that provides an interactive experience without the use of immersive devices like head-mounted displays, typically using large screens or projectors.
- **Target-Distractor Salience**: The degree to which a target stands out relative to surrounding distractors, influenced by factors like color, shape, and spatial positioning.
- **Distractor Inhibition**: The cognitive ability to suppress irrelevant stimuli or distractions while focusing on a specific task or target.
- **Peripersonal Space**: The immediate space surrounding a person's body, within which objects can be easily reached and interacted with, critical for motor control and spatial awareness.
- **Simon Effect**: A phenomenon where response times are faster and more accurate when the stimulus location matches the response hand laterality.

CRediT authorship contribution statement

Gregorio Sorrentino: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gauthier Everard:** Writing – review & editing, Data curation, Conceptualization. **Florence Vanhoof:** Writing – review & editing, Data curation, Conceptualization. **Thierry Lejeune:** Writing – review & editing, Supervision, Resources, Formal analysis, Conceptualization. **Martin Gareth Edwards:** Writing – review & editing, Supervision, Resources, Formal analysis, Conceptualization.

Ethics approval and consent to participate

All participants signed a written informed consent form according to the Helsinki Declaration. The Hospital Ethics Committee of the Cliniques universitaires Saint-Luc (Brussels, Belgium) authorised the current analysis procedure. The protocol identification number is NCT04694833.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smhl.2025.100595.

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.

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