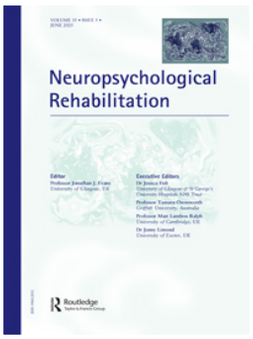

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CASE REPORT

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Use of immersive virtual reality to explore visual search behaviour in individuals with visuospatial neglect after stroke

Elissa Embrechts [a,b,c], Ivan De Boi[d], Quirine Schatteman[a,e], Tanja C. W. Nijboer[c], Steven Truijen[a] and Wim Saeys [a,e]

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ABSTRACT

Visuospatial neglect (VSN) is a common post-stroke disorder characterized by impaired attention toward the contralesional hemispace, affecting interaction with the environment. Traditional assessments (e.g., pen-and-paper tests) may not detect subtle deficits in visual search behaviour, particularly in complex, dynamic settings. This study introduces an immersive virtual reality (VR) visual search task designed to assess visual search behaviour across peri- and extra-personal spaces. By integrating eye-and-head tracking, we aimed to characterize search behaviour and evaluate group differences among individuals with stroke with VSN (VSN+, $n = 11$), those without VSN (VSN-, $n = 10$), and healthy controls (HC, $n = 11$). Additionally, we examined how task parameters (target position, spatial context, and difficulty) influenced search behaviour. Results show that VSN+ exhibited least efficient search strategies, with longer search times than VSN- and HC and more extended search paths than HC. Notably, VSN- also demonstrated visual search inefficiencies, suggesting that conventional assessments may overlook subtle visuospatial impairments. Search deficits were most pronounced in extra-personal space and under increased task demands. Despite a limited sample size, these findings highlight the potential of VR-tasks to characterize visual search behaviour. Further research on larger, more diverse samples is needed to evaluate its potential diagnostic utility.

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Introduction

Visuospatial neglect (VSN) is a common disorder of spatial cognition after stroke, leading to deficits in attention and awareness for visual targets (Heilman et al., 2000; Vallar & Calzolari, 2018). The hallmark of VSN is a lateralized attention deficit, characterized by an impaired ability to direct attention towards the contralesional hemispace. Instead, there seems to be a strong tendency to orient attention, eye fixations and (manual) exploration within the ipsilesional hemispace (Fellrath et al., 2012; Sprenger et al., 2002; Van der Stigchel & Nijboer, 2010). VSN is a heterogeneous disorder that can manifest across different regions of space, including the personal (i.e., body-related), peri-personal (i.e., within reaching distance) and/or extra-personal space (i.e., beyond reaching distance) (Rode et al., 2017; Van der Stoep et al., 2013).

Traditional neuropsychological assessments for VSN, such as cancellation tasks and line bisection tests (LBT), typically involve paper-and-pencil tasks that evaluate visual attention in the peri-personal space (Terruzzi et al., 2023). While these assessments are informative, they have been criticized for their lack of sensitivity due to their reliance on robust outcome measures, such as omissions and deviations (Bowen et al., 1999; Williams et al., 2025). Consequently, some individuals with stroke may exhibit normal scores on these tests, yet show signs of neglect in activities of daily living (Moore et al., 2021). Alternative behavioural assessments, such as the Catherine Bergego Scale or Mobility Assessment Course, offer valuable ecological insights (Azouvi, 2017; Nelemans et al., 2022), but are time-consuming and depend heavily on subjective examiner evaluations. Moreover, evaluating complex outcome measures that offer in-depth insights into the individual's task performance, such as visual search behaviour, presents challenges when using such assessments. Key performance indicators like search paths, search strategy (e.g., the ratio of eye and head movements), and search time per target demand additional tools, such as eye and head movement trackers, to gain a detailed understanding of the quality of the visual search behaviour (Sprenger et al., 2002). Eye-tracking research highlights the value of visual search analysis in VSN, demonstrating a pronounced ipsilesional bias in eye fixations and difficulty returning to the midline or contralesional hemispace (Delazer et al., 2018; Sprenger et al., 2002). However, integrating both eye and head tracking in routine VSN assessments poses logistical and resource-related challenges. Moreover, despite digitization of conventional VSN tests, they still fail to mimic real-world demands, as they are typically conducted using two-dimensional, static environments, lacking the complexity of three-dimensional, lifelike settings (Ten Brink, Van der Stigchel, et al., 2016).

Immersive VR presents a promising solution to current limitations by creating controlled, yet complex, multisensory, and interactive environments without

requiring physical modifications, patient transfers, or additional materials (Ogourtsova et al., 2017). These VR environments enable users to engage through head, eye, and body movements (Terruzzi et al., 2023), allowing for a more comprehensive interaction experience. Advanced VR technology can also track eye and head movements simultaneously, enabling the calculation of various visual search behaviour metrics, such as search strategies, search paths, and search times (Perez-Marcos et al., 2023; Ten Brink, Biesbroek, et al., 2016; Ten Brink, Van der Stigchel, et al., 2016). However, despite VR's potential, research on developing and evaluating VR tools that measure visual search behaviour for VSN remains limited. A recent study by Perez-Marcos et al. (2023) introduced a 3D immersive VR task aimed at evaluating visual search behaviour. However, this study was limited to healthy individuals and included only head tracking to evaluate visual search, omitting the crucial aspect of eye movement analysis (Perez-Marcos et al., 2023).

To address these gaps, we developed an immersive VR visual search task that extends across both peri- and extra-personal spaces, by using a head-mounted display equipped with integrated eye and head tracking (see Methods and De Boi et al. (2024) for more details on the design). This novel approach enables precise quantification of visual search behaviour, including target omissions, search times per stimulus, search paths, and search strategy – specifically, whether participants rely more on eye or head movements to locate targets.

The first objective of this study was to characterize and compare visual search behaviour metrics during the performance of our VR task across three groups: healthy individuals (HC), people with stroke with visuospatial neglect (VSN+), and people with stroke without visuospatial neglect (VSN-). We hypothesized that search efficiency would differ, with the VSN+ group expected to exhibit the least efficient search strategies of all groups, with more target omissions, longer search times per stimulus, and extended search paths. The second objective was to explore the influence of VR task settings on visual search behaviour. Specifically, we examined how target position (ipsilesional vs. contralesional), scene type (peri- vs. extra-personal space), and task difficulty (e.g., number of distractors, time constraints) affected search behaviour across and between these groups. We anticipated that contralesional targets, targets in extra-personal space, and higher task difficulty would lead to less efficient search strategies, increased omissions, longer search times, and more extensive search paths, particularly in the VSN+ group.

Methodology

Study design

This is a cross-sectional exploratory study.

Participants

Individuals who experienced a stroke were recruited in the rehabilitation hospital RevArte (Edegem, Belgium) between October 2020 and September 2021. They were considered for inclusion if they: (1) had sustained an ischemic or hemorrhagic stroke in the right hemisphere, (2) had sufficient neck rotation range of motion (i.e., $\geq 90°$ left/right), (3) were at least 16 years old, (4) had normal or corrected-to-normal visual acuity and (5) were able to provide written informed consent. Individuals were excluded if they (1) were unable to sit in a (wheel)chair, (2) were unable to understand the procedure, or (3) refused to participate. In the same period, also healthy individuals were recruited in the surrounding area of Antwerp, Belgium. These were included when: (1) being at least 16 years old; (2) having sufficient neck rotation range of motion (i.e., $\geq 90°$ left/right); (3) having no history of central neurological disorders, (4) having normal or corrected-to-normal visual acuity, (5) being able to understand the given instructions and language, and (6) being able to provide written informed consent.

Procedures

The study was approved by the Ethics Committee of the Antwerp University Hospital (BUN B30020200002) and all participants gave signed informed consent.

VR hardware and software

Hardware consisted of a Pico Neo© 2, which is a standalone head-mounted display with embedded eye and head movement tracking at a rate of 90 Hz. It monitors left-right movement on the x-axis and up–down movement on the y-axis. The device combines both eye and head movements to determine gaze, which is referred to as a gaze ray compound measure.

The software was developed in collaboration with the Department of Engineering at Karel de Grote University (Antwerp, Belgium). The virtual environment was designed to resemble a leisure park and included two scene types: a near (peri-personal) space and a far (extra-personal) space. Both scenes required participants to search for objects within the virtual environment by scanning the environment using eye and head movements after a brief presentation of the target for three seconds in the centre of their field of vision. In the extra-personal environment, the participant sits on a wooden bench within a leisure park and must look for objects presented at different locations (e.g., onto a seesaw, swing set, grass …). Within the peri-personal environment, the participant sits at a picknick table and must look for objects presented at different locations on the table. Following the identification of the correct object,

participants must maintain fixation on the object until a yellow circle fills, indicating successful detection. This procedure ensures that the object is accurately identified and allows for consistent measurement of task performance across participants. Irrelevant distractors are presented in each environment. If the target object is (not correctly) identified within the allocated time, a new target appears. During the VR task, the participant's view was cast onto a screen, allowing the researchers to track participant movements and performance in the virtual environment in real-time.

The software uses an artificial intelligence (AI) algorithm to assess the likelihood of correctly and quickly identifying a target within the virtual

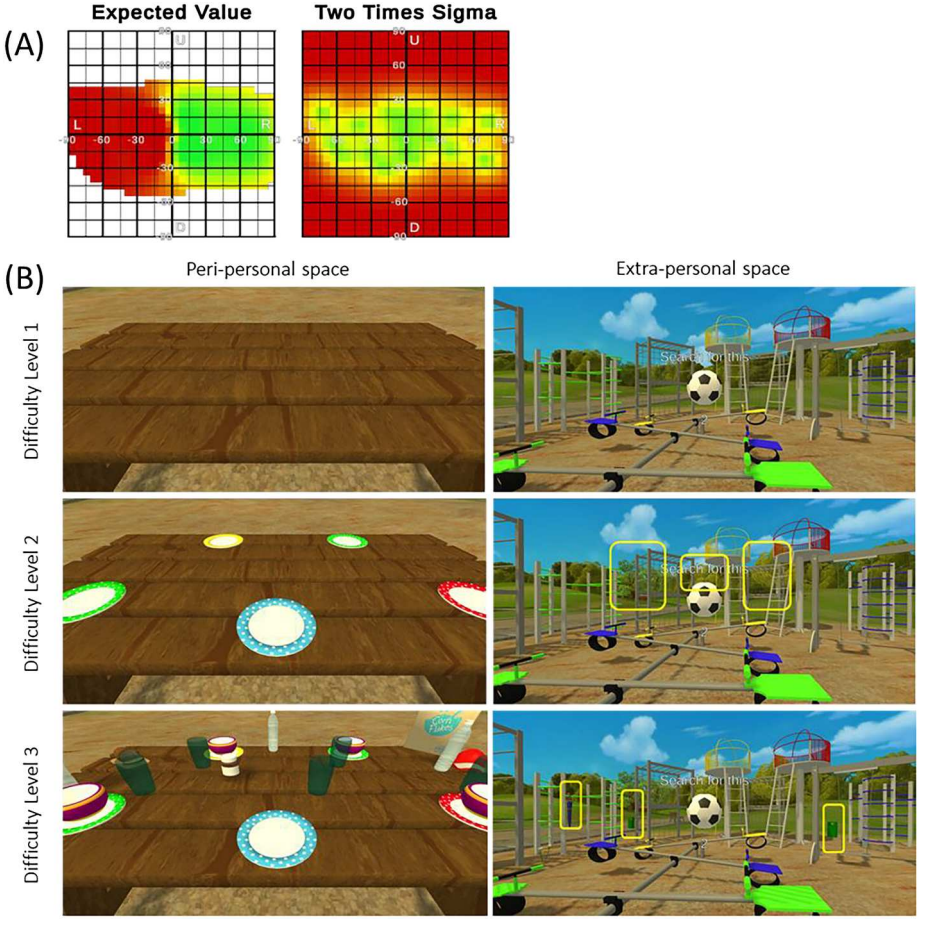

Figure 1. (A) Example of a heatmap with the expected values on the left side and two-times sigma values on the right. (B) Visual representation of the two VR environments, illustrating the distractors at each difficulty level. The peri-personal space is displayed on the left, and the extra-personal space on the right. Each row corresponds to an increasing difficulty level. In the peri-personal space, difficulty increases with the addition of non-relevant plates in level 2 and further objects like cups and bottles in level 3. In the extra-personal space, difficulty increases with extra trees in level 2 (highlighted) and additional objects such as bins and an umbrella in level 3.

environment. Based on this probability, the software strategically places subsequent targets in locations with a high uncertainty, tailoring the assessment to each participant's abilities (De Boi et al., 2024). The AI system generates heatmaps based on participant performance, visually representing areas where participants are more likely to search longer or miss the target. The heatmaps, as shown in Figure 1(A), display predictions for search times generated by the machine learning algorithm. A Gaussian process is implemented as a surrogate model, enabling active learning. Predictions for search time at specific points in a person's field of view are Gaussian distributions with a mean (expected value) and a variance, expressed as two times the sigma value. The left part of the heatmap shows the expected value: green indicates a short search time, red indicates a longer search time, and black indicates the target was not found. The right part of the heatmap shows the two times sigma values, providing information about the uncertainty of the prediction. Together, both heatmaps offer insights into the prediction and its uncertainty within the participant's field of view. Once the heatmap stabilizes, no more targets are presented, and the assessment stops, resulting in a varying number of targets presented to different participants. For more information, see De Boi et al. (2024).

There are three predetermined difficulty levels. Each level is defined by specific criteria, including the time allowed to search for a target (Level 1: 8 s, Level 2: 12 s, Level 3: 16 s), the required fixation duration on the target (Level 1: 2 s, Level 2: 3 s, Level 3: 4 s), the accuracy needed to successfully identify the target (Level 1: 95%, Level 2: 96.5%, Level 3: 98%), and with an increasing number of distractors in each level (Figure 1(B)).

Setting and participant categorization

To assess the presence of VSN in individuals with stroke, three conventional VSN tests were administered prior to the VR trials. The tests were conducted in a specific order under supervision of a researcher (QS). The categorization of having VSN was determined based on positive scores on at least two tests (i.e., falling out of norms).

Broken hearts test (BHT)

The participants had to cancel the complete hearts ($n = 50$) among distractors shaped as broken hearts, with either gaps on the right ($n = 50$) or left ($n = 50$) of the contour. The test was presented on an A4 landscape paper, whose position was central in front of the participant and standardized across participants (Demeyere et al., 2015, 2016). Participants had a maximum of three minutes to complete the test. Asymmetry was used as a measure of VSN severity. The

difference between the cancelled full outlines of the contralesional and ipsilesional sides of the paper was used as a measure of VSN severity (contralesional hits – ipsilesional hits). Asymmetry was considered present when the asymmetry would be >2 or < −2.

Computerized schenkenberg line bisection test (LBT)

The participants had to bisect 20 horizontal lines with their less-affected hand. The lines were placed central to the midline or either more left or right, with peripheral starting points at equal distances from the midline (Vaes et al., 2015). The LBT was performed using the Metrisquare DiaDiag software (www.metrisquare.com) on a Wacom® tablet (40 × 65 cm) (Vaes et al., 2015). As a measure of severity, the mean percentage of the total deviation from the centres of the ipsilesional, contralesional, and centrally placed lines was used. Normative performance in healthy individuals is a deviation of .4 ± 3.89 (Vaes et al., 2015). Positive and negative values indicate contralesional and ipsilesional deviation from the midline, respectively.

Computerized visuospatial search time test (VSTT)

The VSTT consists of 16 consecutive grids containing 20 different targets centred around one target in the middle, presented in a green square (Vaes et al., 2015). The participant had to cross out a target identical to the central target as quickly as possible. Directly afterwards, the next grid was shown with a different central target, and in this way, the task continued. This test was also performed with the Metrisquare DiaDiag software (www.metrisquare.com) using a Wacom® tablet (40 cm × 65 cm) (Vaes et al., 2015). The VSTT registers contra -and ipsilesional hemispace search times. The contralesional versus ipsilesional search time index was calculated as a measure of egocentric VSN severity (VSTT index). The normal range is 1.1 ± .39, based on data in healthy controls (Vaes et al., 2015).

During the VR trials, participants were seated with feet flat on either the ground or wheelchair footrests, and the head-mounted display was placed on their head. Eye-sight calibration was performed, and two familiarization trials were conducted, consisting of two short extra-personal space scenes, to familiarize them with the VR equipment and the task (5 min in total). Following the familiarization trials, the VR test trials began. QS was the supervising researcher during this process.

Outcome measures

Demographic information

This included information such as age, sex, and time post-stroke in days.

Spatial measures

Target ratio. The number of left or right-sided targets found vs. total targets offered. The targets offered are pre-programmed per difficulty level, however, may still depend on individual performance (cfr. heatmap stabilization). For this reason, we chose to evaluate the ratio rather than the absolute number of targets found.

Eye/head movement ratio. This metric quantifies the relative amount of eye versus head movements during target searches, providing insight into participants' scanning strategies (Godwin et al., 2014; Over et al., 2007). A higher ratio – indicating more eye movements relative to head movements – suggests a more detailed and "fine" search. Conversely, a lower ratio implies a less detailed, and thus "coarse," search strategy (Godwin et al., 2014; Over et al., 2007). This ratio is calculated individually for each successfully located target to ensure it accurately reflects active search behaviour. By focusing solely on targets found, the ratio remains precise and is not distorted by participants who may cease active searching.

Relative distance (distance travelled in relation to most direct path). Distance travelled (i.e., length of the gaze ray path) relative to the shortest direct path to find the target from starting position to the target position is calculated and referred to as "relative distance." We calculated this because the target and starting position between individuals is always different and dependent upon individual performance. This parameter is calculated individually for each successfully located target to ensure it accurately reflects active search behaviour. By focusing solely on targets found, the ratio remains precise and is not distorted by participants who may cease active searching.

Spatiotemporal (search time) measures

Relative search time (search time in relation to most direct path). Time needed to find the targets, relative to the most direct (shortest) path towards the target. We calculated this because the target position between individuals is always different and dependent upon individual performance. This parameter is calculated individually for each successfully located target to ensure it accurately reflects active search behaviour. By focusing solely on targets found, the ratio remains precise and is not distorted by participants who may cease active searching.

Statistical analysis

Descriptive statistics were performed to present mean values and variability for each outcome measure by group (Table 1).

For Objective 1, which aimed to investigate the effect of group on the outcome measures, we applied linear mixed models (LMMs) with a consistent model architecture for each dependent variable. All models included a random intercept for each participant to account for the dependency of repeated measurements within individuals. A fixed effect for Group (HC, VSN+, VSN) was added to each model (Table 2).

For Objective 2, we fitted separate LMMs to further explore the influence of additional factors on each outcome measure (Table 3). To interpret Table 3, each major column represents an outcome variable (target ratio, eye/head movement ratio, relative distance, relative search time), while sub-columns present the different models: the standard model (Group as the only predictor, similar as in Table 2), the target position model (including Group, target position, and their interaction), the scene model (including Group, scene type, and their interaction), and the difficulty level model (including Group, difficulty level, and their interaction). Each row in the table represents the predictors (group/extra covariate (VR-task setting)/interaction effect) included in the model. To analyze the results, follow a row across the columns to evaluate the effect of a predictor. Significant interactions indicate that the effect of one variable depends on another, while non-significant interactions were removed. In cases where a significant interaction was detected, post-hoc analyses were conducted using Tukey's Honestly Significant Difference (HSD) method to further investigate pairwise differences and clarify the nature of these interactions (Table 4).

For every fitted model, diagnostic plots to assess model assumptions included histograms and Q-Q plots to evaluate the normality of residuals, and a plot of conditional residuals versus predicted values to evaluate homoscedasticity. Since model assumptions were not met in three of the outcome variables (eye/head movement ratio, relative distance, relative search time), log-transformed values of these variables were entered as dependent variables. This transformation ensured that the model assumptions were met. After fitting the LMMs, log-transformed β estimates were back transformed to the original scale using the exponential function (Exp(β)).

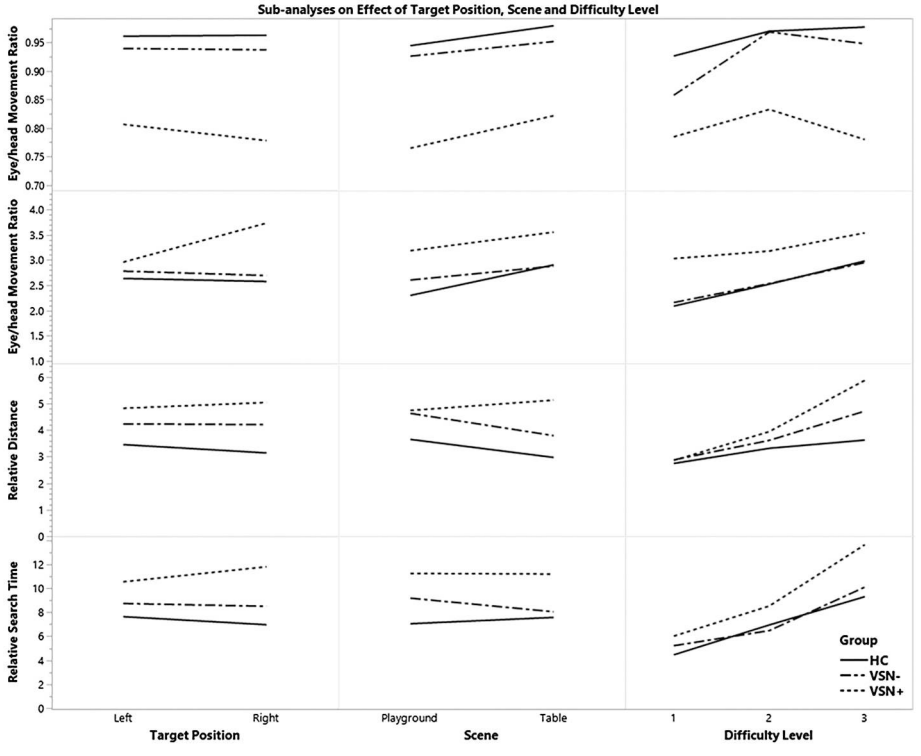

Figure 2. Graphs (mean values) that display the effect of independent variables (target position, scene, difficulty level) on outcome measures. Abbreviations: HC – Healthy controls; VSN – Individuals with stroke without visuospatial neglect; VSN+ – Individuals with stroke with visuospatial neglect.

For visual reference, we also included graphs (Figure 2) that illustrate the effects of independent variables (target position, scene, difficulty level) on the mean values of the outcome measures.

Results

Demographic data

Table 1 shows the characteristics of the participants with regards to their demographic data, clinical characteristics and outcomes on the VR visual search task.

Table 1. Demographic and clinical characteristics.

	Demographic information				Clinical VSN characteristics						VR visual search behaviour outcomes			
ID	Group	Age	Sex	Time post-stroke (days)	BHT ego asym	BHT VSN?	VSTT index L/R	VSTT VSN?	LBT deviation	LBT VSN?	Target ratio	Eye/head movement ratio	Relative distance	Relative search time
1	VSN+	67	F	28	5	Yes	3.34	Yes	52.6	Yes	.66 (.14)	4.42 (3.16)	6.55 (5.99)	15.21 (12.87)
2	VSN+	76	F	23	8	Yes	.98	No	14.68	Yes	.80 (.14)	2.07 (1.33)	3.40 (3.08)	10.50 (7.50)
3	VSN+	72	F	47	−3	Yes	3.14	Yes	9.70	Yes	.51 (.18)	10.82 (8.99)	5.00 (3.71)	14.02 (11.61)
4	VSN+	82	M	11	14	Yes	1.37	No	9.66	Yes	.81 (.14)	2.36 (1.05)	4.55 (10.89)	10.66 (17.84)
5	VSN+	82	F	20	7	Yes	1.52	Yes	13.1	Yes	.69 (.09)	5.28 (2.87)	8.89 (16.59)	15.33 (23.25)
6	VSN+	79	M	57	−4	Yes	4.35	Yes	3.80	No	.90 (.00)	2.17 (.63)	2.89 (1.51)	7.45 (6.50)
7	VSN+	73	M	14	−5	Yes	1.50	Yes	−3.68	Yes	.94 (.06)	2.76 (1.15)	4.23 (2.85)	8.36 (5.55)
8	VSN+	74	F	29	−1	No	.61	Yes	−7.57	Yes	.88 (.09)	2.24 (0.66)	4.98 (6.30)	10.25 (11.27)
9	VSN+	16	F	27	−1	No	1.71	Yes	9.68	Yes	1.00 (.00)	1.94 (1.07)	3.09 (3.22)	8.51 (11.99)
10	VSN+	46	M	65	1	No	2.05	Yes	−9.18	Yes	.98 (.03)	2.54 (.91)	4.37 (3.93)	8.38 (5.57)
11	VSN+	77	F	186	1	No	1.87	Yes	−6.8	Yes	.84 (.05)	2.19 (1.10)	4.84 (4.95)	11.86 (9.44)
12	VSN-	45	F	122	1	No	3.18	Yes	−.96	No	.92 (.10)	3.86 (2.20)	2.53 (2.26)	6.23 (5.28)
13	VSN-	85	F	21	−6	Yes	1.11	No	3.90	No	.83 (.05)	2.33 (1.19)	6.12 (7.28)	10.78 (11.12)
14	VSN-	83	M	15	0	No	1.58	Yes	−1.89	No	.95 (.08)	3.41 (1.58)	7.08 (10.83)	10.81 (15.81)
15	VSN-	50	M	5	0	No	1.26	No	−4.16	Yes	1.00 (.00)	1.55 (.48)	2.58 (1.70)	7.48 (8.31)
16	VSN-	59	F	18	0	No	1.13	No	−1.32	No	.98 (.08)	2.93 (1.46)	3.66 (2.76)	7.23 (5.80)
17	VSN-	59	M	42	1	No	1.18	No	.77	No	.99 (.02)	.73 (1.14)	2.75 (1.33)	6.74 (3.91)
18	VSN-	23	F	25	0	No	1.58	Yes	.59	No	.99 (.03)	2.94 (2.44)	2.79 (2.70)	7.38 (9.91)
19	VSN-	70	M	20	9	Yes	.91	No	−2.82	No	.83 (.11)	3.34 (2.81)	4.97 (3.94)	12.13 (13.55)
20	VSN-	75	F	29	1	No	1.92	Yes	−.78	No	.93 (.09)	3.12 (1.00)	3.86 (2.89)	7.62 (5.65)
21	VSN-	60	M	25	1	No	1.21	No	10.03	Yes	.96 (.11)	3.15 (1.74)	4.42 (5.19)	9.00 (10.37)
22	HC	18	F	/	/	/	/	/	/	/	.97 (.07)	1.97 (.40)	1.84 (1.28)	6.48 (4.79)
23	HC	74	M	/	/	/	/	/	/	/	.96 (.04)	1.94 (.95)	2.75 (2.62)	8.61 (8.94)
24	HC	75	F	/	/	/	/	/	/	/	1.00 (.00)	2.06 (.89)	2.76 (2.23)	7.75 (11.82)
25	HC	46	M	/	/	/	/	/	/	/	.99 (.03)	3.76 (4.56)	3.14 (2.42)	6.48 (5.19)
26	HC	56	M	/	/	/	/	/	/	/	.99 (.03)	2.51 (1.32)	2.81 (1.74)	6.28 (4.59)
27	HC	80	F	/	/	/	/	/	/	/	.95 (.04)	3.15 (3.41)	4.10 (2.56)	7.96 (6.32)
28	HC	83	F	/	/	/	/	/	/	/	.90 (.09)	3.25 (1.72)	6.41 (9.86)	9.10 (9.91)
29	HC	61	M	/	/	/	/	/	/	/	.98 (.04)	3.10 (.90)	2.45 (1.55)	5.94 (3.11)
30	HC	81	M	/	/	/	/	/	/	/	.86 (.12)	2.47 (.60)	3.59 (1.95)	8.12 (5.72)
31	HC	21	M	/	/	/	/	/	/	/	1.00 (.00)	1.80 (.91)	3.48 (4.43)	7.81 (11.26)

(*Continued*)

Table 1. Continued.

	Demographic information				Clinical VSN characteristics						VR visual search behaviour outcomes			
ID	Group	Age	Sex	Time post-stroke (days)	BHT ego asym	BHT VSN?	VSTT index L/R	VSTT VSN?	LBT deviation	LBT VSN?	Target ratio	Eye/head movement ratio	Relative distance	Relative search time
32	HC	82	M	/	/	/	/	/	/	/	.96 (.07)	2.54 (1.31)	3.52 (2.67)	6.43 (3.53)
Group values	*VSN+*	*67.64 (19.81)*	7F/4M		*2.00 (5.87)*	/	*2.04 (1.12)*	/	*7.82 (17.26)*	/	*.79 (.18)*	*3.37 (3.57)*	*4.94 (7.24)*	*11.23 (12.71)*
	VSN-	*60.90 (18.76)*	5F/5M		*.70 (3.59)*	/	*1.50 (.66)*	/	*.34 (4.05)*	/	*.94 (.10)*	*2.74 (1.89)*	*4.22 (5.20)*	*8.63 (10.09)*
	HC	*61.55 (23.97)*	4F/7M		/	/	/	/	/	/	*.96 (.07)*	*2.61 (2.13)*	*3.31 (3.69)*	*7.32 (7.46)*

Abbreviations: BHT: Broken Hearts Test, BHT ego asym: egocentric asymmetry on Broken Hearts Test, F: female, HC: healthy control, LBT: line bisection test, M: male, VSN-: individual with stroke without visuospatial neglect, VSN+: individual with stroke with visuospatial neglect, VSTT: visuospatial search time test. *Italicized values represent total group values (VSN+/VSN-/HC) with either mean (standard deviation) or ratio.*

Objective 1: Differences in search behavior between the three groups

There were significant group differences in target ratio, eye/head movement ratio, relative distance, and relative search time (Table 2). Post-hoc analyses revealed group differences in more detail:

Target ratio: The VSN+ group had a similar target ratio to the HC group ($P = .945$), whereas the VSN- group had a significantly lower target ratio than the HC and VSN+ groups ($P < .0001$).

Eye/head movement ratio: The eye/head movement ratio was similar between the VSN+ and HC groups ($P = .078$), whereas the VSN- group had a significantly higher eye/head movement ratio than both the VSN+ and HC groups.

Relative distance: Both the VSN- ($P = .001$) and VSN+ ($P < .0001$) groups showed a longer relative distance compared to HC, whereas there was no significant difference between VSN- and VSN+ groups ($P = .589$).

Relative search time: The VSN+ group showed significantly higher relative search times compared to VSN- ($P = .017$) and HC ($P < .0001$) groups, whereas no difference between VSN- and HC groups was found ($P = .493$).

Table 2. Difference in visual search measures between groups (HC, VSN-, VSN+).

	Fixed effect tests						Post-hoc tests					
	Term	(Exp) Estimate	(Exp) SE	*P*-value	Lower 95%	Upper 95%	Group comparison	(Exp) Estimated difference	(Exp) SE	*P*-value	Lower 95%	Upper 95%
Target ratio	Intercept	.921	.025	**<.0001***	.869	.972	HC vs. VSN-	.065	.013	**<.0001***	.036	.095
	Group (HC)	−.003	.009	.748	−.021	.015	HC vs. VSN+	−.003	.009	.945	−.024	.018
	Group (VSN-)	−.068	.015	**<.0001***	−.098	−.038	VSN – vs. VSN+	−.068	.015	**<.0001***	−.104	−.032
Log eye/head movement ratio	Intercept	2.115	1.088	**<.0001***	1.783	2.508	HC vs. VSN-	−.681	1.059	**<.0001***	.595	.780
	Group (HC)	1.094	1.042	**.031***	1.009	1.187	HC vs. VSN+	1.094	1.042	.078	.993	1.206
	Group (VSN-)	1.606	1.072	**<.0001***	1.401	1.841	VSN- vs. VSN+	1.606	1.072	**<.0001***	1.364	1.891
Log relative distance	Intercept	3.158	1.051	**<.0001***	2.856	3.479	HC vs. VSN-	−.778	1.073	**.001***	.659	.920
	Group (HC)	−.828	1.031	**<.0001***	.773	.878	HC vs. VSN+	−.718	1.058	**<.0001***	.629	.820
	Group (VSN-)	1.058	1.049	.235	.963	1.163	VSN – vs. VSN+	−.923	1.086	.589	.760	1.120
Log relative search time	Intercept	8.060	1.050	**<.0001***	7.299	8.899	HC vs. VSN-	−.932	1.064	.493	.805	1.080
	Group (HC)	−.769	1.054	**<.0001***	.692	.853	HC vs. VSN+	−.769	1.054	**<.0001***	.678	.871
	Group (VSN-)	−.825	1.072	**.007***	.718	.947	VSN – vs. VSN+	−.825	1.072	**.017***	.700	.972

Exp: exponential, HC: healthy controls, Log: logarithm, SE: standard error, VSN: visuospatial neglect. * Statistically significant difference ($P < .05$).

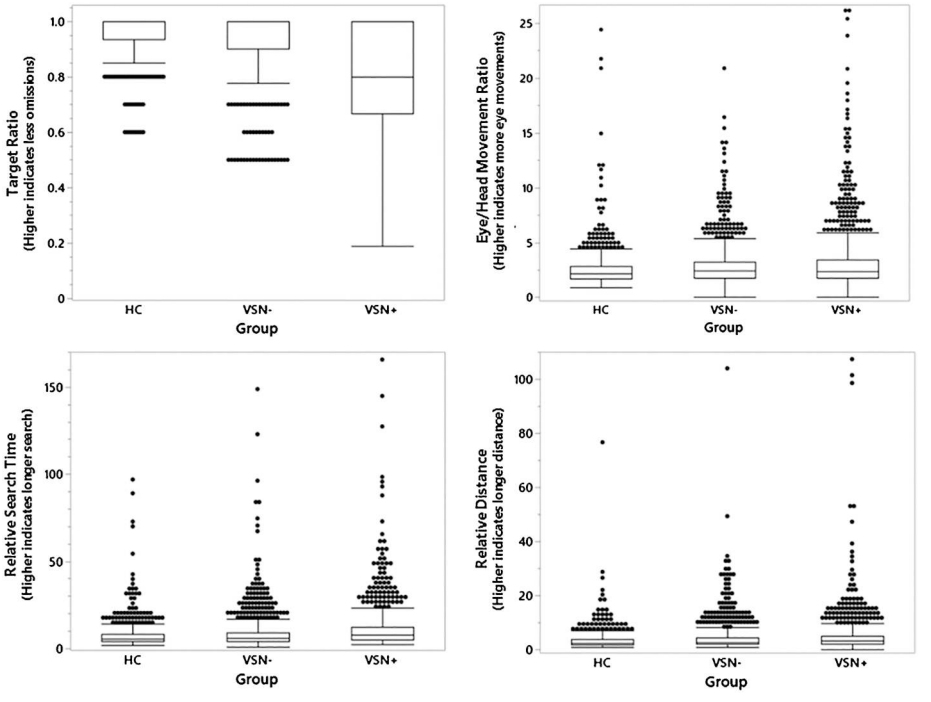

Figure 3. Boxplots displaying raw data points for four outcome measures across three groups: Healthy Controls (HC), individuals with stroke without visuospatial neglect (VSN-), and individuals with stroke with visuospatial neglect (VSN+).

Figure 3 shows boxplots of the raw data on each outcome measure as a function of group.

Objective 2: Effect of VR settings on search behavior

Given the complexity and volume of analyses, detailed statistical results – including effect sizes, confidence intervals, and *p*-values – are provided in Tables 3 and 4, rather than in the main text.

Table 3. Sub-analysis models including group and either target position, scene, or difficulty level (with interaction effects) as covariates.

	Target ratio				Log eye/head movement ratio			
	Standard model	Target position model	Scene model	Difficulty level model	Standard model	Target position model	Scene model	Difficulty level model
(Exp) β group HC (SE, p-value, 95% CI)	−.003 (.009, .748, [−.021; .015])	.002 (.010, .831, [−.017;.022])	**−.019 (.010*, .048, [−.038; −.000])**	**.013 (.010, .177, [−.006; .031])**	**1.094 (1.042, .031*, [1.009; 1.187])**	1.063 (1.047, .188, [.971;1.163])	**1.092 (1.041, .032*, [1.008; 1.184])**	**1.163 (1.046, .001*, [1.064; 1.270])**
(Exp) β group VSN- (SE, p-value, 95% CI)	**−.068 (.015, <.0001*, [−.098; −.038])**	**−.066 (.016, <.0001*, [−.097; −.035])**	**−.087 (.015, <.0001*, [−.116; −.056])**	**−.059 (.015, .0001, [−.088; −.029])**	**1.606 (1.072, <.0001*, [1.401; 1.841])**	**1.560 (1.075, <.0001*, [1.355; 1.797])**	**1.617 (1.072, <.0001*, [1.410; 1.849])**	**1.623 (1.046, <.0001, [1.064; 1.270])**
(Exp) β added covariate (SE, p-value, 95% CI)		Stimulus position[Left]: .007 (.005, .147, [−.003; .017])	**Scene [Extra-personal]: −.060 (.005, <.0001*, [−.070; −.051])**	**Level[1]: −.029 (.007, <.0001*, [−.042; −.015])** **Level[2]: .028 (.006, <.0001*, [.016; .040])**		Stimulus position[Left]: −.992 (1.008, .298, [.978; 1.007])	**Scene [Extra-personal]: −.885 (1.015, <.0001*, [.859; .991])**	**Level[1]: .860 (1.037, .<0001*, [.801; .923])** **Level[2]: .932 (1.032, .024*, [.877; .991])**
(Exp) β added covariate interactions (SE, p-value, 95% CI)		Interaction effects were not significant, and therefore deleted from model	**Group[HC]*Scene[Extra-personal]: .029 (.008, .0001*, [.014; .044])** **Group[VSN-]*Scene[Extra-personal]: .036 (.007, <.0001*, [.021; .048])**	**Level[1]*Group[HC]: −.021 (.010, .031*, −.041; [−.002])** **Level[1]*Group[VSN-]: −.060 (.010, <.0001*, [−.078; −.041])** **Level[2]*Group[HC]: −.036 (.009, <.0001*, [−.053; −.018])** **Level[2]*Group[VSN-]: −.005 (.008*, .571, [−.021; .012])**		Interaction effects were not significant, and therefore deleted from model	Interaction effects were not significant, and therefore deleted from model	**Level[1]*Group[HC]: −.884 (1.052, .015*, [.800; .976])** Level[1]*Group[VSN-]: −.929 (1.053, .152, [.840; 1.027]) **Level[2]*Group[HC-]: −.947 (1.046, .0222*, [.868; 1.034])** Level[2]*Group[VSN-]: −.968 (1.044, .448, [.889; 1.053])

	Log relative distance				Log relative search time			
	Standard model	Target position model	Scene model	Difficulty level model	Standard model	target position model	Scene model	difficulty level model
(Exp) β group HC (SE, p-value, 95% CI)	**.828 (1.031, <.0001*, [.773; .878])**	**−.703 (1.066, <.0001*, [.621; .797])**	**−.678 (1.065, <.0001*, [.599; .767])**	**−.686 (1.064, <.0001*, [.608; .775])**	**−.769 (1.054, <.0001*, [.692; .853])**	**−.726 (1.063, <.0001*, [.644; .818])**	**−.794 (1.063, .0002*; [.705; .895]**	**−.808 (1.059; .0002*; [.722; .904])**
(Exp) β group VSN- (SE, p-value, 95% CI)	1.058 (1.043; .235; [.363; 1.163])	−.897 (1.090, .211, [.756;1.064])	−.881 (1.090, .145, [.743; 1.045])	−.880 (1.087, .129, [.746; 1.038])	**−.825 (1.072, .007*, [.718; .947])**	**−.752 (1.077, .0002*, [.649; .871])**	−.807 (1.078, .005; [.649; .871])	**−.798 (1.072; .002*, [.696; .916])**
(Exp) β added covariate (SE, p-value, 95% CI)		Stimulus position[Left]: .984 (1.040, .679, [.912;1.062])	Scene [Playground]: 1.053 (1.039, .179, [.977; 1.135])	**Level [1]: −.603 (1.055, <.0001*, [.544; .669])** **Level [2]: −.777 (1.046, <.0001*, [.710; .850])**		**Stimulus position[Left]: .910 ((1.041, .020*, [.840; .985])**	Scene [Playground]: 1.057 (1.041; .160; [.833; 1.055])	**Level[1]: .523 (1.032, <.0001*, [.493; .555]** **Level[2]: .707 (1.026, <.0001*, [.671; .744])**

(Exp) β added covariate interactions (SE, p-value, 95% CI)	Interaction effects were not significant, and therefore deleted from model	**Group[HC]*Scene[Playground]: 1.127 (1.059, .036*, [1.008; 1.260])** Group[VSN-]*Scene[Playground]: 1.089 (1.054, .109, [.981; 1.208])	**Level[1]*Group[HC]: 1.266 (1.077, .0002*, [1.094; 1.465])** Level[1]*Group[VSN-]: 1.111 (1.079, .165, [.958; 1.288]) Level[2]*Group[HC]: 1.111 (1.068, .108, [.977; 1.265]) Level[2]*Group[VSN-]: 1.026 (1.066, .0683, [.906; 1.163])	Group[HC]*Stimulus position[Left]: 1.118 (1.062, .063; [.994; 1.257]à **Group[VSN-]]*target position[Left]: 1.200 (1.057, .001, [.1.076; 1.338])**	Interaction effects were not significant, and therefore deleted from model	Interaction effects were not significant, and therefore deleted from model

β: Bèta estimate, CI: confidence interval, Exp: exponential, HC: healthy controls, Log: logarithm, SE: standard error, VSN: visuospatial neglect, VSN-: individuals with stroke without visuospatial neglect, VSN+: individuals with stroke with visuospatial neglect. Statistically significant difference ($P < .05$).

Table 4. Statistical results of the post-hoc analyses on interaction effects.

Independent variable	Post-hoc tests on interaction effects (Group * Independent variable)		
	HC vs VSN+	HC vs VSN-	VSN + vs VSN-
Effect of Target Position (Left/Right) with Group			
Relative search time	• Higher relative search time for left-sided (ED (Exp)β = −.811, SE 1.062, $P < .007$, 95%CI [−.381; −.038]) and right-sided targets (ED (Exp)β = −.7381, SE 1.062, $P < .0001$, 95%CI [−.476; −.132]) in VSN + as compared to left-sided targets in HC. • Higher relative search time for left-sided targets in VSN + compared to right-sided targets in HC (ED (Exp)β = −.726, SE 1.063, $P < .0001$, 95%CI [−.494; −.148])	• NS	• Relative search time was significantly higher for right-sided targets in VSN + compared to VSN- (ED (Exp)β = −.752, SE 1.077, $P = .002$, 95%CI [−.496; −.075]).
Effect of Scene Type (Peri-Personal/Extra-Personal) with Group			
Target Ratio	• NS	• In extra-personal space, VSN- had a significantly lower target ratio compared to HC (ED β = .061, SE = .013, $P < .0001$*, 95%CI [.024; .097] • In peri-personal space, VSN- group had a significantly lower target ratio as compared to HC (Estimated difference β = .068, SE .013, $P < .0001$*, 95%CI [.031; .104])	• In peri-personal space, VSN- group had a significantly lower target ratio as compared to VSN + (Estimated difference β = .086, SE .015, $P = <.0001$, 95%CI [−.131; −.043])
Relative distance	• HC had significantly lower relative distance values in both peri-and extra-personal space as compared to VSN + (Extra-personal: ED β = .76, SE 1.065, $P = .0003$, 95%CI [.639; .913]; peri-personal: ED β = .678, SE 1.065, $P < .0001$, 95%CI [.566; .811]	• HC had significantly lower relative distance values in both peri-and extra-personal space as compared to VSN- (extra-personal: ED (Exp)β = .796, SE 1.079, $P = .032$, 95%CI [.641; .988]; peri-personal: ED (Exp)β = .769, SE 1.079, $P = .007$, 95%CI [.620; .955])	• NS
Effect of difficulty levels on Different Outcomes Across groups			
Target Ratio	• NS	• In levels 1 and 3, the target ratio for VSN- was significantly lower than those for HC (level 1: ED β = 1.116, SE 1.014, $P < .0001$, 95%CI [1.068; 1.166], level 3: ED β = 1.074, SE 1.013, $P < .0001$, 95%CI [1.032; 1.117]).	• VSN- had a significantly lower target ratio across all levels compared to VSN + group (level 1: ED β = .889, SE 1.017, $P < .0001$, 95%CI [.844; 1.117], level 2: ED β = .939, SE 1.016, $P = .002$, 95%CI [.894; .986], level 3: ED β = .943, SE 1.015, $P < .003$, 95%CI [.900; .988]).

(*Continued*)

Table 4. Continued.

Independent variable	Post-hoc tests on interaction effects (Group * Independent variable)		
	HC vs VSN+	HC vs VSN-	VSN + vs VSN-
Eye/head movement ratio	• HC had a significantly larger eye/head movement ratio compared to VSN + in level 3 (ED (Exp)β = 1.163, SE 1.046, *P* = .024, 95%CI [1.011; 1.337]).	• HC had a significantly lower eye/head movement ratio in levels 1 (ED (Exp)β = .681, SE 1.071, *P* < .0001, 95%CI [.550; .843]) and 3 (ED (Exp)β = .715, SE 1.062, *P* < .0001, 95%CI [.584; .862]) compared to VSN-.	• NS
Relative distance	• Relative distance was significantly higher in VSN + compared to HC in level 3 (Estimated difference (Exp)β = .808, SE 1.089, *P* = .006, 95%CI [.677; .965]).	NS	• Relative distance was significantly higher in VSN + compared to VSN- in level 2 (ED (Exp)β = .749, SE 1.084, *P* = .010, 95%CI [.583; .962]), and in level 3 (ED (Exp)β = .798, SE 1.072, *P* = .031, 95%CI [.644, .989])

Only significant interaction effects were analyzed and thus presented. CI: confidence interval, ED: estimated difference, Exp: exponential function, HC: healthy controls, *P*: *p*-value, SE: standard error, Vs: versus, VSN: visuospatial neglect, VSN-: individuals after stroke without visuospatial neglect, VSN+: individuals after stroke with visuospatial neglect.

Effect of target position (left vs. right side of space)

Target position did not significantly affect target ratio, eye/head movement ratio, or relative distance. However, there was a significant interaction between target position and group for relative search time (Table 3).

Relative search time. Post-hoc analysis revealed that the VSN+ group took significantly longer to find both left-sided and right-sided targets compared to left-sided or right-sided targets in the HC group. Additionally, the VSN+ group required more time to find right-sided targets than the VSN- group (Table 4).

Effect of scene type (extra-personal vs. peri-personal)

Target ratio. There was a significant interaction between scene type and group. The target ratio was lower in extra-personal space compared to peri-personal space across all groups (Table 3). In extra-personal space, the VSN- group had a lower target ratio than the HC group. In peri-personal space, the VSN- group also had a lower target ratio than both the VSN+ and HC groups (Table 4 for post-hoc Group*Scene analysis).

Eye/head movement ratio. Participants had a significantly lower eye/head movement ratio in the extra-personal space compared to the peri-personal space. There was no significant interaction between scene type and group for this measure (Table 3).

Relative distance. A significant interaction was found between scene type and group. Relative distances were shorter in peri-personal space across all groups. HCs had shorter distances in both spaces compared to the VSN- and VSN+ groups. However, no significant differences were found between the VSN- and VSN+ groups (Table 4).

Relative search time. No significant interaction effects or main effects of scene type were observed (Table 3).

Effect of difficulty levels

Target ratio. There was a significant interaction between difficulty level and group (Table 3). Across all groups, participants missed more targets at level 1 compared to levels 2 and 3. In the VSN+ and VSN- groups, performance was better at level 2 than level 3, with fewer omissions at this intermediate level.

When comparing groups, the VSN- group consistently had lower target ratios across all levels, particularly at levels 1 and 3, where they performed worse than both the VSN+ and HC groups (Table 4).

Eye/head movement ratio. A significant interaction was found between difficulty level and group (Table 3). The VSN+ group had a lower eye/head movement ratio than the VSN- group across all difficulty levels. At level 3, the HC group had a higher eye/head movement ratio than the VSN+ group, showing more detailed eye movements. However, at levels 1 and 3, the HC group had a lower ratio than the VSN- group, suggesting that VSN- participants used finer scanning strategies (Table 4).

Within the HC group, the ratio increased with difficulty. The same trend was observed in the VSN- and VSN+ group from levels 1 to 3.

Relative distance. Relative distance increased from level 2 to 3 across all groups. In the HC and VSN+ groups, it also increased from level 1 to 2 and from level 1 to 3. When comparing groups, the VSN+ group had significantly higher relative distances than the VSN- group at level 2 and higher distances than both the VSN- and HC groups at level 3, indicating longer search paths as difficulty increased (Table 4).

Relative search time. Search time increased from level 1 to 2 and from level 2 to 3 across all groups. However, no significant interaction with group was found (Table 3).

Discussion

This study aimed to characterize and compare visual search behaviour metrics during a newly developed VR task across VSN+, VSN- and HC groups, while also examining the influence of target position, scene type, and task difficulty on search performance. We hypothesized that the VSN+ group would demonstrate the least efficient search strategies, exhibiting more target omissions, longer search times per stimulus, and extended search paths compared to other groups. Additionally, we expected contralesional (leftward) targets, targets in extra-personal space, and higher task difficulty to exacerbate search inefficiency, particularly in the VSN+ group.

Regarding objective one, our hypothesis was partially supported. Results revealed significant group effects across all outcome measures. Specifically, the VSN+ group took longer to locate targets compared to both the VSN- and HC groups, with search paths that were longer in distance than those of the HC group. However, their target detection ratio and eye/head movement ratio were comparable to the HC group. This suggests that while their search was less efficient – characterized by prolonged search times and longer paths, despite using a similar eye/head movement strategy – it was ultimately effective. In contrast, the VSN- group, though faster than VSN+ and with search path distances similar to VSN+, was less effective in detecting targets compared to both the HC and VSN+ groups. The VSN- group also relied

significantly more on eye movements relative to head movements than the HC and VSN+ groups, indicating a more detailed, localized search strategy. However, this increased reliance on eye movements did not improve target detection, suggesting their search may have been fragmented or lacked global exploration.

Regarding objective two, our hypothesis was partially met. Target position significantly influenced search time, with the VSN+ group requiring more time to locate both left- and right-sided targets compared to the HC group. However, target position did not significantly affect other outcome measures, nor did it show a specific lateralized effect on search time. Given that VSN is typically characterized by a lateralized deficit, this finding was unexpected. One possible explanation for this observation could be the presence of a generalized attentional deficit that is more pronounced in individuals with VSN (Husain & Rorden, 2003; Rorden et al., 2006), which could reduce overall search efficiency regardless of target location. This generalized deficit might overshadow the expected lateralized impairments, leading to uniformly prolonged search times across both hemispaces. Additionally, learned compensatory strategies or variability in VSN severity within this small sample ($n = 11$) may have limited the detection of strong lateralized effects.

The absence of a significant difference between the VSN- and VSN+ groups in search time relative to target position suggests that some individuals in the VSN- group may also exhibit a generalized, non-lateralized attentional deficit following stroke. This possibility is particularly relevant given that only right-sided strokes were included, as the right hemisphere plays a dominant role in visual search organization (Loetscher & Lincoln, 2013; Ten Brink, Biesbroek, et al., 2016). Although these deficits may be less pronounced than in VSN+, they could still impair efficient target search, potentially explaining the VSN- group's lower target detection rate and similar search path distances to VSN+.

Regarding the effect of scene, our hypothesis was supported. Results show more frequent target omissions and longer search paths in extra-personal space, particularly in the VSN+ and VSN- groups. Interestingly, across all groups, participants adopted a more head-dominant approach in extra-personal space and relied more on eye movements in peri-personal space. This likely reflects the need for spatial orientation and larger head movements to cover greater distances in extra-personal space, whereas finer eye movements are more suited for detailed searches in peri-personal space. These findings align with Perez-Marcos et al. (2023), who identified head movements as a reliable indicator of search behaviour, particularly in extra-personal space. In contrast, more detailed searches, which typically occur in peri-personal space, tend to rely on finer eye movements (Godwin et al., 2014; Over et al., 2007).

Concerning the difficulty level, our results partially aligned with our hypothesis, indicating that higher difficulty levels corresponded to a genuine increase

in task complexity. As difficulty increased, participants relied more on eye movements for detailed scanning (coarse-to-fine search), as reflected in an increasing eye/head movement ratio (Godwin et al., 2014; Over et al., 2007). This shift likely results from the greater number of distractors in harder levels, requiring a more thorough search. Consequently, search time and path length also increased, further confirming the genuine increase in difficulty. This effect was particularly pronounced in the VSN+ group, indicating greater task demands for this group. These findings align with prior research showing that, on conventional VSN tests, a higher number of distractors led to a slower search and fewer targets found (Eglin et al., 1989; Husain & Kennard, 1997). Contrary to this research, in our study, target omissions were higher at the easiest level (level 1) than in the more difficult levels across all groups. This may be due to the smaller number of pre-programmed targets at level 1 ($n = 10$), where missing even one significantly impacts the target ratio. Additionally, participants may not have had sufficient familiarization time with the VR game before the test session, leading to a lack of understanding and a higher target omission rate in level 1. Another possibility is that increased task difficulty heightened alertness or arousal, leading to improved performance. This suggests that search efficiency may fluctuate depending on task complexity – some individuals may struggle more under higher task demands, while others may perform better with added complexity. This aligns with the concept of stochastic resonance (Moss et al., 2004; Söderlund et al., 2007), which posits that an optimal level of difficulty enhances performance, whereas too few or too many challenges may impair it. These findings highlight the importance of using both traditional pen-and-paper tests and interactive VR-based assessments to capture these nuanced effects in VSN behaviour.

Overall, the VR search task appears to offer detailed insights into visual search behaviour. Specifically, the ability to assess in-depth visual search measures in both peri-personal and extra-personal spaces marks a significant, necessary advancement compared to conventional and behavioural VSN tests. Our results highlight notable differences in search strategies between these spatial sectors, with extra-personal space seemingly presenting greater challenges for target detection compared to peri-personal space, especially in those with VSN. This distinction is crucial as this space reflects real-world scenarios more accurately, considering that everyday navigation and interaction with the environment predominantly rely on extra-personal spatial cues. For instance, tasks such as walking, driving, or even simply locating items in a room depend heavily on the ability to efficiently scan and process visual information in the extra-personal space. The difficulties observed in extra-personal space during our VR assessments suggest that individuals with VSN may face substantial challenges in daily activities that are not fully captured by conventional two-dimensional, paper-and-pencil tests (Azouvi, 2017; Williams et al., 2025).

Limitations

The differences in visual search behaviour between individuals with and without VSN were often subtle and, in some cases, non-significant. This may reflect a true absence of group differences or could be attributed to methodological constraints, including the relatively small sample size, variability in participant characteristics (e.g., age, time post-stroke), and the classification of VSN based on a limited set of conventional assessments. These factors may restrict the generalizability of our findings.

The modest sample size likely reduced statistical power, particularly for detecting subtle group differences. To provide a more comprehensive perspective, we reported effect sizes and confidence intervals (Tables 3 and 4), which offer insights into the magnitude, direction, and precision of the observed effects. While some comparisons did not reach conventional significance thresholds, the confidence intervals help contextualize these findings by providing the range of plausible effects.

There was considerable heterogeneity both within and between groups, particularly regarding age and time post-stroke. The wide age range – from adolescents to older adults – introduces variability, as aging is known to influence spatial processing. Older adults, for instance, often adopt a more conservative target selection strategy and utilize different target encoding processes compared to younger individuals (Segen et al., 2021). Additionally, our post-stroke participants spanned the acute to chronic phases of recovery – an important consideration since VSN is most pronounced shortly after stroke, with substantial recovery occurring within the first 5–8 weeks (Embrechts, 2024; Nijboer et al., 2013). Moreover, VSN severity also varied widely within the groups, further complicating comparisons. While these variables may thus influence the results, they were not included as covariates to minimize the risk of overfitting the models.

Post-stroke individuals were classified as VSN+ or VSN- based on conventional tests, which may fail to capture the full complexity of VSN (Moore et al., 2021). As a result, these assessments could have overlooked subtle visuospatial deficits that our VR-based task might have been able to detect. Indeed, some participants (ID 12, 13, 19) exhibited search behaviours that deviated from their group norms, suggesting possible lingering presence of VSN. While this could provide (very) preliminary evidence that our VR-based search behaviour assessment could identify residual deficits missed by conventional tests, the limitations of our study prevent any strong conclusions or validation of the VR task.

Finally, the possibility of ceiling effects in the target ratio measure may have reduced sensitivity to group differences, particularly for individuals with relatively intact visual search abilities. However, complementary measures – such as the eye/head movement ratio, relative search distance, and relative search time – offered additional insights into search behaviour. Nevertheless, this

also underscores the need to use multiple outcome measures rather than relying solely on target detection rates to assess VSN.

Suggestions for future research

Future research should further explore the potential of VR-based visual search tasks to characterize visual search behaviour and more deeply evaluate its value for assessment of individuals with VSN after stroke. Expanding sample sizes and diversity – by including individuals with both left- and right-sided brain lesions across different post-stroke stages (acute, subacute, and chronic) and controlling for confounding factors such as age – would enhance generalizability and provide insights into the time-dependency of visual search deficits.

Given the possibility that our VR-based task detected residual VSN deficits undetected by conventional tests, future studies should validate this approach using a larger sample and a more comprehensive test battery incorporating both conventional and behavioural VSN assessments. This would help determine its diagnostic utility.

Future research should also explore how the differences in search strategy between peri-personal and extra-personal space, as observed in this study, might extend to other conditions affecting spatial perception, such as simultanagnosia. Individuals with simultanagnosia struggle to process multiple objects simultaneously within a visual scene and could exhibit a task-dependent reduction in attentional field size (Khan et al., 2016). VR-based visual search tasks that capture detailed search strategies could provide valuable insights into how their search behaviour would differ across spatial sectors. Additionally, examining whether simultanagnosia leads to similarly inefficient searches as seen in VSN could enhance our understanding of the mechanisms underlying spatial attention deficits.

Conclusion

This study highlights the potential of VR-based visual search tasks to provide insight into an individual's visual search behaviour after stroke. Our findings indicate that individuals with VSN+ demonstrated the least efficient search strategies, characterized by longer search paths and slower target detection. These deficits varied depending on the scene and were particularly pronounced in extra-personal space, emphasizing the importance of assessing VSN across both peri-personal and extra-personal spaces – an aspect often overlooked in conventional VSN assessments.

Additionally, search inefficiencies observed in the VSN- group suggest that individuals without overt neglect on standard tests may still exhibit subtle impairments in visual search behaviour. While these results provide (very) preliminary evidence that VR-based tasks may detect visuospatial deficits beyond

conventional assessments, further research is needed to validate this approach. Future studies should expand participant diversity, integrate a broader battery of VSN assessments, and investigate search behaviour across different post-stroke recovery stages to determine its diagnostic value.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Patent and data sharing

The VR software package used in this study is a proprietary system and is, at time of publication of this study, patented (PCT/EP2021/084817). As such, it is not freely available for unrestricted use. However, we are open to collaborations with researchers and institutions interested in reproducing or further developing this approach. For inquiries regarding potential collaborations, please contact the Prof. Dr. Wim Saeys (wim.saeys@uantwerpen.be).

The data supporting the findings of this study are available from the corresponding author, EE, upon reasonable request.

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