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Application of immersive virtual reality for assessing chronic neglect in individuals with stroke: the immersive virtual road-crossing task

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ABSTRACT

Background: Neglect can be a long-term consequence of chronic stroke that can impede an individual's ability to perform daily activities, but chronic and discrete forms can be difficult to detect. We developed and evaluated the "immersive virtual road-crossing task" (iVRoad) to identify and quantify discrete neglect symptoms in chronic stroke patients.

Method: The iVRoad task requires crossing virtual intersections and placing a letter in a mailbox placed either on the left or right. We tested three groups using the HTC Vive Pro Eye: (1) chronic right hemisphere stroke patients with ($N = 20$) and (2) without ($N = 20$) chronic left-sided neglect, and (3) age and gender-matched healthy controls ($N = 20$). We analyzed temporal parameters, errors, and head rotation to identify group-specific patterns, and applied questionnaires to measure self-assessed pedestrian behavior and usability.

Results: Overall, the task was well-tolerated by all participants with fewer cybersickness-induced symptoms *after* the VR exposure than before. Reaction time, left-sided errors, and lateral head movements for traffic from left most clearly distinguished between groups. Neglect patients committed more dangerous crossings, but their self-rated pedestrian behavior did not differ from that of stroke patients without neglect. This demonstrates their reduced awareness of the risks in everyday life and highlights the clinical relevance of the task.

Conclusions: Our findings suggest that a virtual road crossing task, such as iVRoad, has the potential to identify subtle symptoms of neglect by providing virtual scenarios that more closely resemble the demands and challenges of everyday life. iVRoad is an immersive, naturalistic virtual reality task that can measure clinically relevant behavioral variance and identify discrete neglect symptoms.

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Neglect; neuropsychological assessment; virtual reality; stroke; road crossing

Introduction

Selectively focusing and dividing our attention are fundamental cognitive processes that are crucial for everyday tasks. For instance, pedestrians must be able to process unexpected and rapidly changing situations when crossing the road. When relevant information is not processed accurately, for example due to distractions, crossing roads can become challenging and potentially dangerous, as seen in individuals with neglect (Corbetta & Shulman, 2011; Heilman et al., 2000; Vallar, 2001).

Neglect is a disabling neurocognitive disorder that frequently occurs after stroke and is characterized by a lack of attention to the contralesional side (Husain, 2008; Karnath, 2015). This systematic shift in the perceived visual horizontal axis toward the unaffected side occurs more frequently and severely after right-hemispheric lesions, thereby affecting the left hemifield (Karnath & Rorden, 2012; Ringman et al., 2004). The lateral orientation bias associated with neglect is not due to deficits in the primary sensory or motor systems (Heilman et al., 1994), but the result of dysfunction in higher level cognitive and attentional processes (Bartolomeo & Chokron, 2002; Karnath, 2015). Furthermore, neglect adversely has been associated with prolonged hospitalization, increased care needs, and reduced functional outcomes (Jehkonen et al., 2006; Kerkhoff & Schenk, 2012). While spontaneous remission can occur in the first post-stroke weeks (Farnè et al., 2004), later recovery is more rare (Nijboer et al., 2013). Given the distinct subtypes and temporal variations (Azouvi et al., 2002; Bowen et al., 1999), neglect is a complex supramodal syndrome (Parton et al., 2004).

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Clinical neglect assessment tools typically consist of multiple, varying bedside paper-and-pencil tests, such as cancellation, drawing, and line bisection tasks (Azouvi et al., 2002; Moore et al., 2022). However, existing instruments have low sensitivity, particularly for subtle but clinically relevant neglect symptoms in chronic stroke (Barrett et al., 2006; Bonato, 2012; Buxbaum et al., 2012). As a result, discrete forms of neglect often go unrecognized and untreated, even though they may severely affect patients' everyday lives (Chen et al., 2012). Despite their extensive use in clinical practice, conventional tests do not resemble relevant everyday life tasks (*verisimilitude*) and have limited predictive power for the performance of daily tasks (*veridicality*) (Kaiser et al., 2022). The discrepancy between test scores and functional performance (Bonato, 2012) can be attributed to various clinical neglect manifestations (Aimola et al., 2012). Reasons for this discrepancy include repeated test administration, (partial) recovery, increased "on-the-spot alertness" (i.e., improvement of sustained attention by situational awareness of the environment and testing situations to respond appropriately) (Bonato, 2012, p. 3), and acquired compensatory strategies (Andres et al., 2019).

The prevalence of neglect following stroke is highly variable, with reported frequencies ranging from 20% to 80% (Esposito et al., 2021). However, neglect symptoms are often under-reported, as demonstrated by test sensitivities from as low as 13% to 82% (Bowen et al., 1999). Therefore, it is hardly surprising that the severity and frequency of neglect in clinical practice and daily life are higher than currently recognized (Buxbaum et al., 2004; Edwards et al., 2006).

While paper-and-pencil tests are two-dimensional, static, and possess low verisimilitude, everyday tasks are typically three-dimensional, dynamic, and interactive. Overcoming the inherent limitations of traditional neglect tests therefore requires tasks that resemble real-life demands and involve a synergy of motor, postural, visual, and cognitive-perceptual skills (Azouvi et al., 2002; Brink et al., 2017; Simpson et al., 2003). Yet, assessing spatial deficits in neglect can be challenging, as an adequate assessment must preclude the possibility of implementing compensatory strategies for the deficits (Bonato, 2012) and elicit lateralized sustained attention and fatigue (Kerkhoff et al., 2020). Other task-related factors like complexity (Aravind & Lamontagne, 2017; Villarreal et al., 2020), varying levels of cognitive demand (Bonato, 2012; Spreij et al., 2020), divided attention (Buxbaum et al., 2008), and stimulus density (Brink et al., 2020; Nijboer & van der Stigchel, 2019) need to be considered to sensitively assess chronic neglect. For a more precise assessment of neglect, it is relevant to incorporate behavioral parameters reflecting everyday behavioral and functional performance. These may include measures of eye and head movements (Karnath et al., 1998) and temporal parameters such as reaction times (Deouell et al., 2005; Rengachary et al., 2009), total time (Jannink et al., 2009), and time constraints (Kwon et al., 2020).

The application of immersive Virtual Reality (VR) has great potential to effectively detect discrete neglect symptoms by presenting tasks that closely resemble real-life scenarios and better target functional performance. In VR, realistic and interactive virtual content with high ecological validity can be presented three-dimensionally and dynamically. The vast majority of VR research on neglect has involved either: (1) conventional paper-and-pencil tests converted into immersive tasks (Gupta et al., 2000; Knobel et al., 2020; Tanaka et al., 2005) or non-immersive tasks (Broeren et al., 2007; Fordell et al., 2011) or (2) immersive applications with relevance to everyday life activities. The latter included tasks for navigation (Ogourtsova et al., 2018; Peskine et al., 2011), or detection and searching (Jannink et al., 2009; Kim et al., 2010; Knobel et al., 2021; Ogourtsova et al., 2018; Yasuda et al., 2018). However, previous studies have been limited by small sample sizes and have not included post-stroke patients with subtle neglect symptoms or a clinical control group (Pedroli et al., 2015). The use of head-mounted displays (HMDs) may induce motion sickness, known as cybersickness, manifested as symptoms of nausea, headache, and general discomfort. It is therefore important to have valid self-assessment tools and symptom insights to understand and mitigate the adverse effects of virtual experiences.

Pedestrian accidents at road crossings are a significant global issue, particularly affecting older adults and vulnerable populations with cognitive impairment due to stroke or other neurological disorders (Oxley et al., 2005; Wilmut & Purcell, 2022). Road-crossing scenarios impose high demands on multiple cognitive functions (e.g., attention), visual perceptual processing (e.g., speed, distance perception), and physical abilities (Oxley et al., 2005). This is especially relevant as subjects with neglect are at high risk of falls (Ugur et al., 2000) and frequently collide with contralateral obstacles (Aravind & Lamontagne, 2017). In addition, extensive evidence suggests that healthy elderly pedestrians exhibit riskier crossings, in higher speed traffic, due to poorer distance and speed estimation (Papić et al., 2020; Petzoldt, 2014), longer decision times (Lobjois et al., 2013; Oxley et al., 1999), and longer road-crossing times than younger individuals (Dommes et al., 2014; Holland & Hill, 2010). Taken together, a virtual road-crossing task is highly relevant as the risks of elderly pedestrians with neglect accumulate, resulting in a higher risk of traffic injury. Thus, such a road-crossing task would be highly appropriate for clinical assessment. A virtual road-crossing task, as a diagnostic tool for neglect, has the potential to bridge the gap between neglect task demands and clinical experience. This would allow patient behavior to be examined and quantified in a highly controlled and ecologically valid, yet safe, way. Compensatory strategies, as observed in paper-and-pencil tests, can be overcome given the high relevance of road crossing to everyday life, as well as high cognitive demand, and multimodal, dynamic nature (Kim et al., 2010; Peskine et al., 2011; Wu et al., 2018).

There are various virtual road-crossing tasks documented in the literature. Non-immersive (Broeren et al., 2007; Fordell et al., 2011) and immersive road-crossing tasks have either examined the behavior of children (Morrongiello et al., 2015; Ridene et al., 2015; Simpson et al., 2003), adolescents (Cherix et al., 2020; Clancy et al., 2006; Kaimara et al., 2021) or healthy adults (Anthes et al., 2016; Deb et al., 2017; Feldstein & Dyszak, 2020). However, this leaves a gap in the evaluation of these tasks for neurological patients, particularly those with neglect. Only a few studies have applied virtual road-crossing tasks for the assessment of neglect. For instance, Mesa-Gresa et al. (2011) used the non-immersive VR Street Crossing Test with five subjects with neglect following acquired brain injury. They showed that neglect patients had a higher number of accidents compared to no neglect patients while the total time taken for the VR task did not differentiate the two groups. In addition, Kim et al. (2010) employed an immersive virtual street scenario with four levels of car speed and one lane to assess neglect in far space. For traffic from the left, neglect patients exhibited significantly higher reaction times and failure rates, and an increased deviation angle to the left compared to no neglect patients. These studies indicate the potential of virtual tasks for neglect detection but suffer from considerable limitations. Specifically, studies in this domain often exhibit issues such as artificial graphics, insufficient validation, and low verisimilitude (Kim et al., 2010), or are restricted by small sample sizes without clinical control groups (Peskine et al., 2011). Although they provide promising results, a more sensitive and virtual road-crossing task with an appropriate study design is needed to assess neglect.

The primary objective of this study was to develop a clinically relevant paradigm involving a virtual road-crossing task and evaluate its sensitivity for subtle neglect symptoms in a sample of right-hemisphere post-stroke patients with and without neglect, and healthy controls. This is the first step toward the systematic evaluation of novel VR measures to improve neuropsychological assessment of spatial neglect. We aimed to identify relevant behavioral patterns and movement parameters to distinguish between neglect-typical and other behavior. Given the lateral bias in neglect, we examined the performance for different traffic directions. Our secondary objective was to demonstrate feasibility and usability from patients' perspective and acceptability as we applied the VR task to a clinical population. Finally, a typical characteristic of neglect is poor self-assessment and a lack of insight into the syndrome (Grattan et al., 2018). Therefore, we expected that the self-rated behavior in patients with neglect to be less related to performance in iVRoad compared to those without neglect.

Materials and methods

Participants

A total of $N = 60$ participants, all of whom identified as White, divided into three groups of $n = 20$ each, took part in this study (cf. Table 1): (1) Chronic right-hemisphere post-stroke patients with chronic left-sided spatial neglect as the experimental sample (USN+), (2) chronic right-hemisphere post-stroke patients without neglect as the clinical control group (USN-), and (3) healthy participants as the healthy control group (HC). We used a matched-pair case-control design as cases and controls were selected based on matching medical history (stroke/no stroke, neglect/no neglect), age, and gender.

Participants in the clinical groups were recruited between September 2020 and March 2022 via the databases of the Clinic for Cognitive Neurology, University Hospital Leipzig, Germany, and the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany (MPI-CBS). Eligible participants received an invitation letter and were contacted by telephone, while current patients were recruited during their hospital stay. We classified clinically eligible participants as members of the USN+ group based on three criteria: (1) a history of right-hemisphere stroke and left hemispatial neglect in the acute phase, (2) a confirmed diagnosis of neglect in the most recent medical report. Additionally, (3) neglect typical patterns, clinical assessments, or clinical observations had to be confirmed by neurologists, neuropsychologists, or orthoptists. Neglect symptoms were classified as discrete if the majority of test results in the paper-and-pencil tests were inconspicuous, but isolated tests and behavioral observations

Table 1. Participant demographic and clinical data.

Variables	USN+ ($N = 20$)	USN- ($N = 20$)	HC ($N = 20$)
Age (years)	60.00 ± 6.93	57.34 ± 9.34	59.05 ± 9.52
Sex (female/male)	5/15	8/12	7/13
Handedness (left-/right-handed/ambidexter)	1/19/0	1/17/2	0/20/0
Years of education (low/mid/high)	1/10/9	0/14/6	0/3/17
MoCA (/30) ***[b]	22.75 ± 3.34	23.65 ± 2.46	28.00 ± 1.56
Self-reported CBS score (/30) **[a], ***[b]	7.10 ± 5.44	2.50 ± 3.19	-
Post-stroke time (months)	37.80 ± 32.98	45.35 ± 49.53	-
Transportation per week (/5)			
Car (driver/passenger)	3.75 ± 0.91	3.55 ± 1.31	3.50 ± 1.05
Pedestrian	3.65 ± 1.66	4.55 ± 0.83	4.50 ± 0.83
Public transportation	2.30 ± 1.52	2.40 ± 1.43	2.00 ± 0.72
First-time use of VR (*n*, %)	18 (90)	17 (85)	11(55)
Technology use (/5)			
Laptop/computer	3.70 ± 1.78	3.20 ± 2.09	4.60 ± 0.96
Smartphone/tablet	4.55 ± 1.91	4.50 ± 1.54	4.90 ± 0.31
Stroke type (*n*, %)			
Ischemic	13 (65)	16 (60)	-
Hemorrhagic	7 (35)	4 (20)	-
Transient ischemic attack	-	-	-
Additional neurological deficits (*n*, %)			
Hemianopia	6 (30)	6 (30)	-
Sensitivity disorder	8 (40)	5 (25)	
Paresis	14 (40)	14 (40)	-
Ataxia	0 (0.0)	3 (15)	-

Significant group differences are asterisked: *indicates $p < 0.05$, **indicates $p < 0.01$, ***indicates $p < 0.001$. [a]Marks significant differences between USN+ and USN-, [b]marks significant differences between USN+ and HC. USN+ = Left-sided neglect after right-hemisphere stroke; USN- = No left-sided neglect after right-hemisphere stroke; HC = Healthy controls; CBS = Catherine Bergego Scale (Azouvi, 1996); MoCA = Montreal Cognitive Assessment Test (Nasreddine et al., 2005); VR = Virtual Reality; Years of education: "Low" corresponds to fewer than 10 years of education, including both school and higher education; "Mid" corresponds to 11–14 years; and "High" corresponds to 15 years or more; transportation per week scale: 1 ("never") to 5 ("daily"). Technology use scale: 1 ("daily") to 5 ("rarely").

indicate the presence of neglect. Participants were classified as belonging to the USN- group if they had a right-hemisphere stroke and showed no evidence of neglect, as determined by both the latest medical records and observations made during the administration of the study.

Healthy controls were recruited through the MPI-CBS and were included if they had normal or corrected-to-normal vision, and no history of neurological or psychiatric disease. The experiment lasted approximately three hours and all participants received reimbursement for their participation. The study followed the Declaration of Helsinki and was approved by the Ethical Committee at the Medical Faculty of Leipzig University (Ethics code: 117/18-lk, March 5th, 2020) and was preregistered (DOI: 10.17605/OSF.IO/M9CHU).

Materials and procedure

We used questionnaires, a conventional neuropsychological test battery with various neglect and attention tests, and behavior recorded in the VR task. The quality of the measurements was ensured by training of the experimenters to collect the VR data reliably. Certified neuropsychologists and orthoptists trained the staff in the administration of the neuropsychological tests.

Clinical assessment

The administered neuropsychological test battery evaluated a range of cognitive functions, including global cognition, visuospatial memory, and attention. Neglect assessment tools included the Neglect-Test (NET; Fels & Geissner, i.e., the German version of the Behavioural Inattention Test (BIT; Wilson et al., 1987), the Sensitive Neglect Test (SNT; Reinhart et al., 2016) in both single and dual-task versions, and the Catherine Bergego Scale as self-reported test (CBS; Azouvi, 1996) (Table 2).

Questionnaires

Custom questionnaires were used with regards to the feasibility and usability, using a combination of existing and newly created or adapted items. We assessed cybersickness, user experience, level of presence, motivation, and overall impression of the VR task, as well as the self-assessed pedestrian behavior in real-life situations. These questionnaires were administered on a computer to the examiner and the participants via a study website, both before and after the VR task.

Immersive virtual road crossing task (iVRoad)

A summary of the procedure for the virtual road crossing task is shown in Figure 1. All subjects participated in the study in a seated position. After setting up the HMD and adjusting for the height in the virtual environment,

Table 2. Results of neglect paper-and-pencil tests for each of the three study groups.

Variables	USN+ ($N = 20$)	USN- ($N = 19$)	HC ($N = 20$)
Self-reported CBS score**[a]	7.10 ± 5.44	2.50 ± 3.18	-
NET: Line crossing	35.60 ± 1.09	36.00 ± 0.00	36.00 ± 0.00
NET: Figure and shape copying **[a], ***[b]	7.65 ± 1.14	8.65 ± 0.49	8.70 ± 0.57
NET: Line bisection **[a], **[b]	7.00 ± 2.51	8.85 ± 0.37	8.80 ± 0.70
NET: Picture scanning *[a]	29.30 ± 2.43	30.75 ± 1.41	-
SNT-S (CoC)	0.05 ± 0.22	−0.01 ± 0.05	−0.01 ± 0.02
SNT-D (CoC) *[a], *[b]	0.07 ± 0.15	−0.00 ± 0.06	−0.01 ± 0.03

Group-specific mean ± standard deviation are shown. Significant group differences are asterisked: *indicates $p < 0.05$, ** indicates $p < 0.01$, ***indicates $p < 0.001$. USN+: Left-sided neglect after right-hemisphere stroke; USN-: No neglect after right-hemisphere stroke; HC: Healthy controls; [a]Marks significant differences between USN + and USN-, [b]marks significant differences between USN+ and HC. CBS: Catherine Bergego Scale (Azouvi, 1996) NET: Neglect-Test (Fels & Geissner, 1997), SNT-S/D: Sensitive Neglect Test Single/Dual Task (Reinhart et al., 2016), CoC: Center of Cancellation (Rorden & Karnath,2010).

all participants completed a tutorial to familiarize them with the environment, the task (i.e., crossing the road, letter insertion) and the technical equipment (i.e., using the controller and exploring the virtual environment). Instructions were delivered via headphones and displayed on additional information boards in the virtual environment.

The study took place in a realistic, virtual urban environment, where participants were required to safely cross two parallel, heavily traveled lanes of a road of 300 m in length to each side. The task was to observe the lanes (i.e., watching the cars), cross them safely, post a letter in a mailbox, and return by crossing the street again (see video https://owncloud.gwdg.de/index.php/s/o1RK8KbGlfL1JMn). The experiment consisted of 24 trials, divided into six blocks of four trials each. To increase the level of immersion and minimize the risk of cybersickness, the task was mainly viewed from a first-person perspective to provide a higher sense of embodiment (Gorisse et al., 2017) until the decision was made to cross the road. When participants pressed the controller button to cross the street, they saw an avatar, representing themselves, crossing the street. This was presented from the third-person perspective to minimize the risk of cybersickness (Evin et al., 2020). The avatar's walking speed of 1.45 m/s, which was the average speed of pedestrians in Germany (Morgenroth, 2008), was not adjustable. We also introduced visual distractors, such as virtual humans or birds in the city scenario, and auditory distractors, such as barking dogs or shattering glass during the road crossing to enhance resemblance to real-life scenarios.

Experimental devices and apparatus

The VR task was carried out in a 4 × 4 m room with a swivel chair positioned in the center. We used the HTC Vive Pro Eye, an HMD that features an integrated eye-tracking system, a field of view of 110 degrees and a resolution of 1440 × 1600 pixels per eye. The HMD was connected to a portable workstation with an Intel i7–9700 processor, 16 GB of RAM, and an Nvidia GeForce RTX 2070 graphics card. To interact with the virtual environment (i.e., decide to cross the road or complete the tutorial), participants had to press a button on the back of a controller operated by their dominant hand. For more information on the task development and technical implementation, see Wagner et al. (2021).

Measured iVRoad outcomes

We manipulated variables related to car speed (30 km/h, 50 km/h), gap size (6.5 s, 7.5 s), traffic direction in both lanes (traffic from left, two-way traffic, traffic from right), and the side of the mailbox (left side, right side). A logical adjustment was made to the street scene (e.g., traffic from left automatically became traffic from right with the same speed upon return). Outcome measures included (1) temporal parameters (total experiment time, reaction time, letter insertion time), (2) error patterns (number of errors, lane- and side-related errors, error types, and crossing safety), and (3) head rotation (head poses including head tilt angle along the roll axis and both heading position and head turns along the yaw axis). For error types, we measured low-risk, high-risk, and dangerous errors. In addition, participants rated their difficulty in crossing real roads, both since the stroke and in general. For detailed information on outcome measures, see Table S1.

Statistical analyses

The data processing and analysis were implemented using *R* (*R* Core Team, 2022; version 1.79) and *RStudio* (*RStudio* Team, 2020; version 4.2.1). Key *R* packages were used for extended functionality:

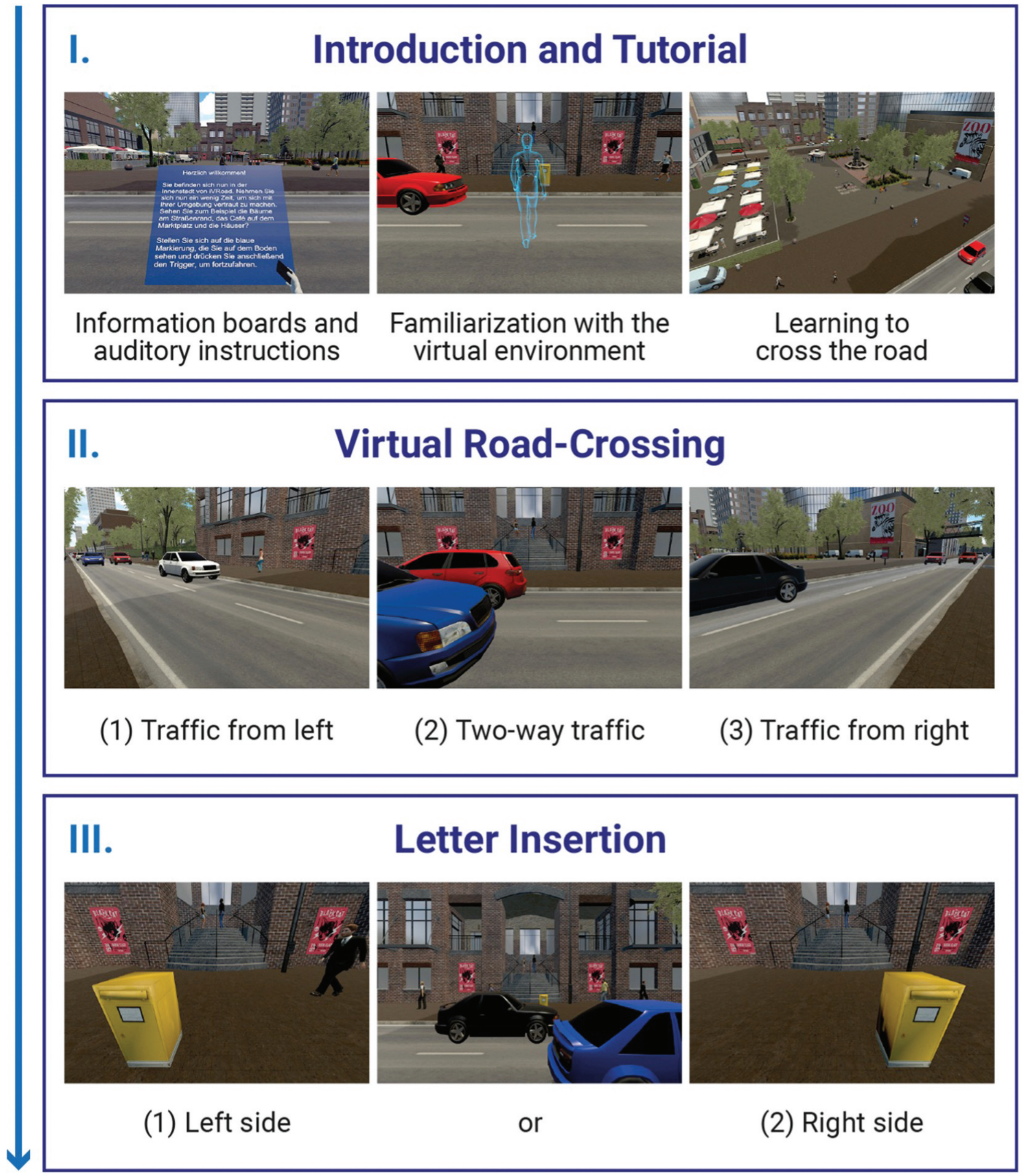

Figure 1. Overview of the immersive virtual road crossing task. The procedure consisted of three parts: (I) instruction and tutorial to familiarize the participants with the system and the task, (II) crossing the roads with three variations of traffic direction, and (III) inserting the letter into the mailbox on either the left or the right side.

tidyverse for data pre-processing (Wickham et al., 2019), *emmeans* (Lenth, 2023) for comparisons and contrasts, *afex* (Singmann et al., 2022) for mixed-design ANOVAs, and *MASS* (Venables et al., 2002) for negative binomial regression. Descriptive statistics and a $p < .05$ criterion for significance were applied. Post-hoc analysis used Tukey's HSD, with Cohen's d for effect sizes and 95% confidence intervals (CI). Data were excluded if participants failed to comprehend the task or comply with experimenter instructions as determined by the therapist. A total of 0.69% (i.e., 10 trials) of the data were missing, with three of these trials missing due to technical issues and not at random.

Crossing safety and self-assessed pedestrian behaviour

The effect of Group and Traffic Direction on crossing safety was evaluated using binomial logistic regression. Predicted probabilities and ORs were calculated. Pearson correlation analyses were used to examine the relationship between self-assessed pedestrian difficulty and number of errors, safe crossing, and high-risk errors.

Detecting neglect and group differences

Temporal parameters. Mixed-design ANOVAs were used to examine the effects of the independent variable Group on three dependent variables of the temporal parameters: total experiment time, average reaction time, and letter insertion time. Specifically, we employed Group as the between-subjects factor, and Traffic Direction (for average reaction time) or Mailbox Side (for letter insertion time) as the within-subjects factors.

Error pattern. Error analysis involved fitting a Poisson regression model, or a negative binomial regression model in cases of overdispersion, by comparing the mean and the variance. The independent variables for the total number of errors were Group and Traffic Direction. Logistic regression models were used for specific error types and predicting performance probabilities. Binomial and multinomial logistic regression analyses were carried out in an interaction model with the factors Group and Traffic Direction (with USN+ and traffic from left as the reference) to determine their influence on the type of error. Results are presented as Odds Ratios (OR) with 95% CIs, standard errors, and p-values.

Head rotation. We tracked the user's head position on the vertical axis (leftward and rightward lateralization and number of head turns along the yaw axis), and on the longitudinal axis (tilting the head to the left and right shoulder)) before road crossing. Head rotation data was analyzed using mixed-design ANOVAs, with Group as the between-subjects factor, and Traffic Direction as the within-subjects factor.

Applicability and feasibility

We assessed cybersickness symptoms before and after the participants were immersed in iVRoad using the 16-item Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) Mixed-design ANOVAs were computed separately for the three SSQ subscores (Nausea, Oculomotor, Disorientation), and the total SSQ score with Group as the between-subjects factor and Measurement Time as the within-subjects factor. We applied two usability tests: System Usability Scale (SUS; Brooke, 1996), and User Satisfaction Evaluation Questionnaire (USEQ; Gil-Gómez et al., 2017). Presence was assessed using the Igroup Presence Questionnaire (IPQ; Schubert et al., 2001). Group differences were analyzed using linear regression models with Group, the respective item as independent variables and the score as dependent variable.

Results

Detecting neglect and group differences

A comprehensive overview of the results on error patterns, temporal parameters, and head rotation measures in the iVRoad task is presented in Figure 2.

Crossing safety and self-assessed pedestrian behaviour

For successful trials, the USN+ group exhibited the lowest absolute and relative frequency of safe road-crossings ($N = 168$, 67%) compared to USN- ($N = 259$, 78%) and HC ($N = 322$, 81%). Binomial logistic regression with the Group*Traffic Direction interaction to predict safe road-crossings showed a significant effect only for Group, $\chi^2(2, N = 60) = 7.40$, $p = .02$. Predicted probabilities for safe crossings were 68% for USN+, and 85% for both USN- and HC. We found significant differences in the probabilities of safe road-crossing between the groups, with USN+ having 49% and 56% fewer safe crossings than USN- and HC, respectively. For traffic from left, USN+ showed a 62% ($SE = 0.15$, $z = -2.37$, $p = .047$) and 61% ($SE = 0.15$, $z = -2.38$, $p = .045$) lower likelihood of safe crossing compared to USN- and HC. Similar trends were obtained for traffic from right, with *OR*s of 0.41 for USN+ vs USN- ($SE = 0.16$, $z = -2.31$, $p = .054$), and 0.28 for USN+ vs HC ($SE = 0.11$, $z = -3.34$, $p = .002$). There were no significant group differences in safe crossings for two-way traffic.

Self-assessed street-crossing difficulty also yielded a significant group effect, $F(2, 57) = 5.63$, $p = .006$, $\eta^2 = 0.16$, 95% CI [0.03, 1.00], as HC showed significantly less real-life street-crossing difficulty than the two patient groups (USN+: $t(57) = -3.16$, $p = .007$, $d = 1.05$, USN-: $t(57) = 2.59$, $p = .03$, $d = 0.88$). Although the USN+ subjects showed fewer safe crossings in the VR task, they did not differ from USN- regarding their self-assessed difficulties, $t(57) = 0.61$, $p = .812$. There was a positive and significant correlation between self-rated street-crossing difficulty and errors in iVRoad, $r(58) = .32$, $p = .01$, and negative correlations with low-risk errors, $r(58) = -.29$, $p = .02$, and safe crossings, $r(58) = -.27$, $p = .03$. Group-level correlations between behavioral parameters and self-rated street-crossing difficulty were not significant.

Error pattern

Descriptive statistics for the number of errors associated with traffic direction are shown in Table 3.

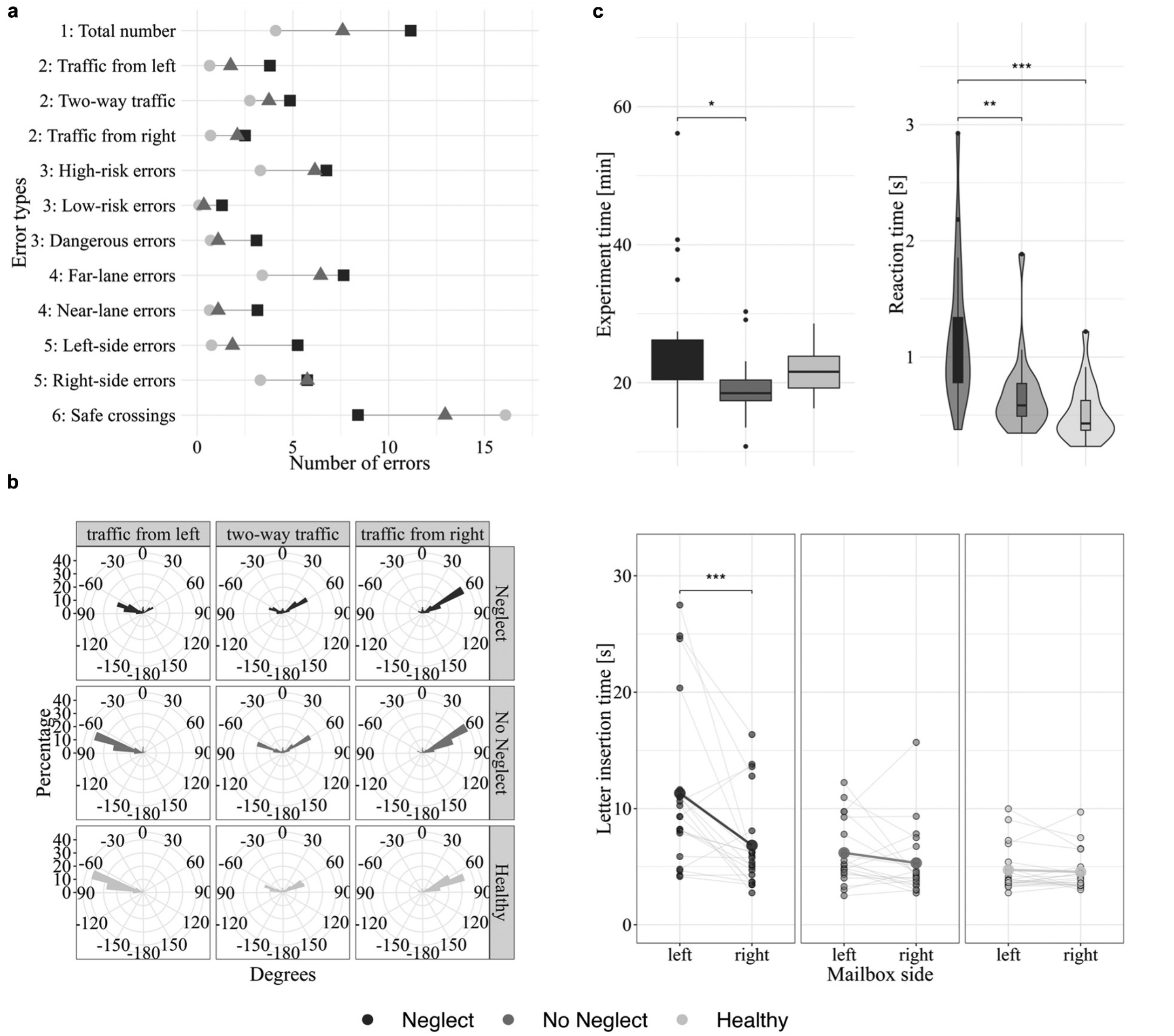

Figure 2. (a) Neglect patients showed significantly longer times in experiment, reaction, and letter insertion for left-sided mailboxes than control groups. (b) Average number of errors and safe crossings for patients with neglect, patients without neglect and healthy controls. (c) Patients with neglect showed more rightward lateralization along the yaw axis, particularly for traffic from left. Error types and group means; safe crossings inverted. 1: Total errors. 2: Errors by traffic direction. 3: Error type. 4: Lane-related errors. 5: Side-related errors. 6: Successful crossings and quality. B:. Negative values represent leftward lateralization, while positive values represent rightward lateralization along the yaw axis.

Table 3. Descriptive statistics for the number of errors associated with traffic direction and group and the results of the group-wise contrast analyses of the negative binomial regression.

	M (*SD*)			Pairwise post-hoc comparisons								
	Group			USN+ vs USN-			USN+ vs HC			USN- vs HC		
Traffic Direction	USN+	USN-	HC	*ratio*	*SE*	*z*	*ratio*	*SE*	*z*	*ratio*	*SE*	*z*
Two-way traffic	4.85 (2.30)	3.75 (2.10)	2.75 (1.33)	1.29	0.30	1.34	1.76*	0.36	2.77	1.36	0.30	1.46
Traffic from left	3.80 (2.71)	1.75 (1.58)	0.65 (1.09)	2.17**	0.51	3.30	5.85***	1.81	5.49	2.69**	0.93	2.87
Traffic from right	2.50 (2.01)	2.10 (1.86)	0.70 (1.08)	1.19	0.28	0.73	3.57***	1.58	3.93	3.00**	0.99	3.32

*$p < .05$, **$p < .01$, ***$p < .001$; USN+ = Left-sided neglect after right-hemisphere stroke; USN- = No left-sided neglect after right-hemisphere stroke; HC = Healthy controls.

Total number of errors. Negative binomial regression results indicate that Group and Traffic Direction accounted for a significant amount of variance in the outcome, $\chi^2(2) = 53.39$, $p < .001$ and $\chi^2(2) = 41.49$, $p < .001$, respectively. We found a significant interaction between Group and Traffic Direction. $\chi^2(4) = 14.00$, $p = .007$. Overall, the USN+ group made 1.50 ($p = .005$) times more errors than USN- and 3.33 ($p < .001$) times more than HC. Compared to two-way traffic, the number of errors was 56% lower for traffic from the left ($p < .001$) and 58% lower for traffic from the right ($p < .001$). For traffic from the left, USN+ committed more errors compared to USN- ($OR = 2.17$, $p = .003$) and HC ($OR = 5.85$, $p < .001$). This difference, however, remained significant only between USN+ and HC for traffic from the right ($OR = 3.57$, $p < .001$) and two-way traffic ($OR = 1.76$, $p < .01$).

Error type. Multinomial logistic regression analysis on error type, including low-risk, high-risk, and dangerous errors showed a significant interaction between Group and Traffic Direction in predicting error types, $\chi^2(8) = 36.81$, $p < .001$. Most errors were high-risk errors ($N = 324$), followed by dangerous errors ($N = 98$), and low-risk errors ($N = 35$).

Dangerous errors. Dangerous errors did not differ significantly between groups. However, two-way traffic resulted in 57% fewer errors than traffic from left ($p = .04$) and 69% fewer than traffic from right ($p = .002$). USN+ made twice as many dangerous errors for traffic from left than USN, but this was not significant ($p = .591$). For two-way traffic, USN+ made 17 times more dangerous errors than USN- ($SE = 13$, $t = 3.79$, $p < .004$) and 8 times more dangerous errors than HC ($SE = 5$, $t = 3.32$, $p = .01$).

Low-risk errors. HC had very few low-risk errors in all traffic direction conditions (traffic from left: $N = 0$; traffic from right: $N = 0$; two-way traffic: $N = 2$), leading to high ORs compared to both groups, especially for traffic from left (e.g., USN+ vs HC: 799421) and traffic from right (e.g., USN+ vs HC = 543794317). USN+ had a significantly higher likelihood (10.49 times) of making low-risk errors than HC ($SE = 7.71$, $t = 3.19$, $p = .01$), and 2.36 times higher than USN-, although significantly ($SE = 1.07$, $t = 1.88$, $p = .170$). The odds of USN+ for low-risk errors for two-way traffic were five times higher than for USN- ($SE = 4$, $t = 2.10$, $p = .117$) and four times higher than for HC ($SE = 3$, $t = 1.68$, $p = .238$), both of which were not significant.

High-risk errors. Regarding high-risk errors, the strongest effect was observed in two-way traffic. USN+ made significantly fewer high-risk errors in this condition compared to USN- ($OR = 0$, $t = -4.79$. $p < .001$) and HC ($OR = 0$, $t = 4.05$, $p = .002$). Overall, USN+ committed 50% fewer high-risk errors than USN- ($SE = 0.12$, $t = -2.87$, $p = .03$). No significant group differences were found in the *OR*s for traffic from left and right regarding high-risk errors.

Lane-related errors. Following right-hand traffic rules, cars from the left drive in the near lane and cars from the right drive in the far lane. A multinomial logistic regression, with performance as the outcome (success, near-lane error, far-lane error) and Group as the predictor, yielded a significant Group effect, $\chi^2(4) = 110.4$, $p < .001$. All groups made more far-lane than near-lane errors; however near-lane errors were predominantly observed in USN+. Compared to USN-, the ORs for a near-lane error in USN+ was 2.25, and 5.59 compared to HC. Specifically, when an error occurred, the probabilities of an error in the far lane compared to the near-lane were for USN+ at 213% ($SE = 0.59$, $t = 6.05$, $p = .002$), for HC at 494% ($SE = 1.89$, $t = 5.60$, $p = .003$) and for USN- at 667% ($SE = 1.89$, $t = 8.03$, $p < .001$).

A significant interaction between Group and Traffic Direction was found in the binomial logistic regression model with near-lane error as the dependent variable, $\chi^2(4) = 25.67$, $p < .001$. USN+ had a significantly higher likelihood for near-lane errors for two-way traffic than USN- and HC, with *OR*s of 21.46 ($SE = 18.42$, $z = 3.57$, $p = .001$) and 14.22 ($SE = 12.19$, $z = 3.01$, $p = .005$), respectively. The predicted probabilities for a near-lane error in two-way traffic were 27% for USN+, 2% for USN, and 3% for HC.

Side-related errors. The group effect on left-sided errors was significant, $\chi^2(2) = 33.77$, $p < .001$. USN+ participants were 2.84 times more likely to make left-sided errors than USN- ($SE = 0.66$, $z = 4.491$, $p < .001$) and 4.02 times more than HC ($SE = 1.27$, $z = 4.397$, $p < .001$). The predicted probability for a left-sided error was 0.48 for the USN+ group, while it was 0.24 for USN- and 0.19 for HC. No differences were found between USN- and HC ($OR = 1.42$, $SE = 0.48$, $z = 1.014$, $p = .568$). The group effect was particularly strong for two-way traffic, $\chi^2(2) = 35.24$, $p < .001$: USN+ had a higher chance than USN- ($OR = 16.28$, $SE = 12.22$, $z = 3.717$, $p < .001$) and HC ($OR = 11.60$, $SE = 8.75$, $z = 3.249$, $p = .003$) for left-side errors, with no differences between USN- and HC ($OR = 0.71$, $SE = 0.72$, $z = -0.33$, $p = .940$).

Temporal parameters

Total experimental time

There was a significant group effect on total experiment time, $F(2, 57) = 4.55$, $p = .01$; $\eta^2 = 0.14$, 95% CI [0.02, 1.00]. Between-group comparisons showed that USN+ ($M = 25.60$, $SD = 10.22$) took significantly longer to complete the VR task compared to USN- ($M = 19.27$, $SD = 4.54$), $t(57) = 2.98$, $p = .01$, $d = 0.80$. The remaining between-group comparisons were not significant, $t < 1.9$, $p > .15$, $d > 0.53$.

Reaction time

A two-factor mixed-design ANOVA yielded a significant effect of Group on reaction time, $F(2, 57) = 12.84$, $p < .001$, $\eta^2 = 0.23$, 95% CI [0.08, 1.00], but not of Traffic Direction, $F(2.00, 113.85) = 0.61$, $p = .543$, $\eta^2 = 0.002$, 95% CI [0.00, 1.00]. The USN+ group ($M = 1.20$, $SD = 0.77$) had significantly longer reaction times compared to USN- ($M = 0.67$, $SD = 0.42$), $t(57) = 3.76$, $p = .001$, $d = 1.03$, and HC ($M = 0.52$, $SD = 0.32$), $t(57) = 4.82$, $p < .001$, $d = 1.42$. The interaction between Group and Traffic Direction was not significant, $F(3.99, 113.85) = 1.76$, $p = .141$, $\eta^2 = 0.02$, 95% CI [0.00, 1.00].

Letter insertion time

The mixed-design ANOVA revealed significant effects of Group, $F(2, 57) = 9.80$, $p < 0.001$, $\eta^2 = 0.18$, 95% CI [0.04, 1.00], and mailbox side, $F(1, 57) = 11.97$, $p = .001$, $\eta^2 = 0.04$, 95% CI [0.00, 1.00]), on letter insertion time. The USN+ group ($M = 8.88$, $SD = 5.90$) took significantly longer than USN- ($M = 5.75$, $SD = 2.88$), $t(57) = 3.18$, $p = .006$, $d = 0.68$ and HC ($M = 4.63$, $SD = 1.84$), $t(57) = 4.25$, $p < .001$, $d = 0.98$, to insert letters. The significant Group x Mailbox Side interaction, $F(2, 57) = 6.28$, $p = .003$, $\eta^2 = 0.05$, 95% CI [0.00, 1.00], indicated that the USN+ took longer to insert letters on the left side than USN-, $t(57) = 3.54$, $p = .002$, $d = 0.95$ and HC, $t(57) = 4.55$, $p < .001$, $d = 1.28$. No significant differences were found between USN- and HC for left, $t(57) = 1.01$, $p = .573$, $d = 0.61$ or right mailboxes, $t(57) = 2.35$, $p = .056$, $d = 0.32$. USN+ also showed significant within-group differences, taking longer for left side compared to right side mailboxes, $t(57) = 4.86$, $p < .001$, $d = 0.78$.

Head rotation

Heading position

A mixed-design ANOVA revealed a significant three-way interaction between Group, Traffic Direction, and Side, $F(2.65, 75.50) = 7.31$, $p < .001$, $\eta^2 = 0.04$, 95% CI [0.00, 1.00]. Specifically, USN+ rotated their heads significantly less toward the left, especially for traffic from left as compared to USN-, $t(57) = -3.36$, $p = .004$, and HC, $t(57) = -4.49$, $p < .001$. For traffic from left, USN+ had leftward lateralization 61.2% of the time, versus 73.5% for USN- and 77.6% for HC. No significant between-group differences were observed for leftward lateralization in other traffic directions. In a mixed-design ANOVA with Group as between-subjects factor and Side as within-subjects factor, we found a significant interaction between Group and heading position, $F(2, 57) = 9.86$, $p < .001$, $\eta^2 < 0.01$, 95% CI [0.00, 1.00]. USN+ moved their heads less far leftward along the yaw axis than USN-, $t(57) = 2.85$, $p = .02$, and HC, $t(57) = 3.65$, $p = .001$. USN+ also moved their heads significantly less rightward than HC, $t(57) = -4.19$, $p < .001$, but not USN-, $t(57) = -2.07$, $p = .104$. A significant correlation was found between average heading position and left-sided errors in the USN+, $r(18) = .63$, $p = .008$, but not in USN-, $r(18) = .05$, $p = .98$, or HC, $r(18) = .16$, $p = .98$.

Head tilt angle

A significant Group effect was observed for head tilt angle, $F(2, 57) = 4.74$, $p = .01$, $\eta^2 = 0.14$, 95% CI [0.02, 1.00], with USN+ tilting their heads more toward the right shoulder along the roll axis than both USN-, $t(57) = 2.61$, $p = .03$, and HC, $t(57) = 2.72$, $p = .02$, who did not differ, $t(57) = 0.11$, $p = .993$. In the model including Traffic Direction, significant effects were found for Group and head tilt side, $F(2, 57) = 6.42$, $p = .003$, $\eta^2 = 0.14$, 95% CI [0.02, 1.00], as well as for Traffic Direction and head tilt side, $F(2, 57) = 10.94$, $p < .001$; $\eta^2 = 0.02$, 95% CI [0.00, 1.00]. For traffic from the right, USN+ significantly tilted their heads more toward the right shoulder compared to USN-, $t(57) = 4.02$, $p < .001$, and HC, $t(57) = 4.27$, $p < .001$. Similar results were found for two-way traffic with USN+ tilting their heads significantly more toward the right shoulder compared to HC, $t(57) = 2.53$, $p = .04$, and USN-, $t(57) = 2.66$, $p = .03$. No significant differences were found for traffic from the left.

Head turns

We found a significant effect of Group, $F(2, 57) = 4.93$, $p = .01$; $\eta^2 = 0.08$, 95% CI [0.00, 1.00] and Traffic Direction, $F(1.66, 94.64) = 50.97$, $p < .001$, $\eta^2 = 0.19$, 95% CI [0.09, 1.00] on the number of head turns before crossing. Specifically, USN+ had more head turns than USN-, $t(57) = 3.04$, $p = .009$, but not more than HC, $t(57) = 2.21$, $p = .078$. For two-way traffic, all groups had increased head turns compared to traffic from left, $t(57) = 8.88$, $p < .001$, or traffic from right, $t(57) = 7.66$, $p < .001$. The interaction between Group and Traffic Direction was significant, $F(3.32, 94.64) = 3.05$, $p = .03$, $\eta^2 = 0.02$, 95% CI [0.00, 1.00]. Specifically, USN+ had significantly more head turns than both USN-, $t(57) = 2.64$, $p = .03$, and HC, $t(57) = 2.65$, $p = .03$, for traffic from left and traffic from right (USN-: $t(57) = 4.23$, $p < .001$, HC: $t(57) = 3.74$, $p = .001$). No significant differences within the USN+ group were found between traffic from right and two-way traffic, $t(57) = -2.39$, $p = .052$, as well as between traffic from left and traffic from right, $t(57) = -0.60$, $p = .81$, as USN+ already had a high number of head turns for traffic from right.

Applicability and usability

Cybersickness

All participants completed iVRoad without any terminations or reports of discomfort. Mixed-design ANOVAs indicated no VR-induced cybersickness across groups according to the SSQ subscales. On average, all groups reported fewer cybersickness-induced symptoms *after* the VR exposure than before it, with a significant decrease over time in the SSQ total score ($\beta = 7.85$, 95% CI [−0.38, 0.24], $t(57) = 3.48$, $p < .001$).

User experience

Most participants (77%) were HMD novices but had experience with computers (3.83/5) and smartphones (4.65/5). The SUS total score was high across groups with an average score above the acceptable range of 77.5 points ($SD = 11.10$). HC scored the highest with 80.88 points ($SD = 11.16$), followed by USN+ with 74.72 points ($SD = 11.43$), and USN- with 75.38 points ($SD = 10.46$), without significant differences, $F(2, 57) = 1.44$, $p = .246$; $\eta^2 = 0.05$, 95% CI [0.00, 1.00]. This means, all groups rated the system as easy to use and felt confident using it. USEQ scores a measure of user satisfaction with virtual rehabilitation systems, averaged 26.22 (SD = 2.79), showing no significant group differences. Participants reported comfort with iVRoad ($M = 4.53$, $SD = 0.62$), control over the system ($M = 4.32$, $SD = 0.62$), enjoyment ($M = 4.42$, $SD = 0.70$), and found the system's information comprehensible ($M = 4.57$, $SD = 0.56$).

Presence

The IPQ results revealed that most participants felt spatially present in the virtual environment ($M = 4.45$, $SD = 1.07$). Involvement scores showed high variability ($M = 3.42$, $SD = 1.65$), and the realism was rated as medium ($M = 2.95$, $SD = 1.30$). Participants generally reported a sense of being in the virtual environment, as indicated by the IPQ mean score of 3.83 ($SD = 1.59$). No significant differences were found between the three groups for spatial presence, $F(2, 57) = 1.88$, $p = .162$; $\eta^2 = 0.06$, 95% CI [0.00, 1.00], involvement, $F(2, 57) = 0.70$, $p = .503$; $\eta^2 = 0.02$, 95% CI [0.00, 1.00], or overall sense of being in the virtual environment, $F(2, 57) = 0.90$, $p = .456$; $\eta^2 = 0.03$, 95% CI [0.00, 1.00].

Motivation and overall impression

Participants enjoyed the VR activity ($M = 4.18$, $SD = 0.68$) and reported low anxiety levels ($M = 4.60$, $SD = 0.59$) during the task. They rated both iVRoad ($M = 4.37$, $SD = 0.61$) and the technical devices ($M = 4.17$, $SD = 0.81$) enjoyable. The VR task was perceived as novel and demanding, with most participants expressing willingness to use the HMD regularly ($M = 3.60$, $SD = 1.08$), particularly for cognitive training (USN+: $M = 4.05$, $SD = 0.94$; USN-: $M = 3.85$, $SD = 1.09$). No group differences were found regarding motivation and overall impression of iVRoad.

Discussion

The present study was conducted with neurological patients in the chronic phase after stroke. We aimed to develop and evaluate novel measures of an immersive virtual road-crossing paradigm (iVRoad) for the detection of discrete neglect symptoms. In this study, we measured and analyzed several VR behavioral parameters to identify neglect-specific behavioral patterns. Our results revealed that patients with chronic neglect exhibited general differences in temporal measures (i.e., higher total experiment time, reaction time, and letter insertion time). Additionally, there were neglect-typical side-related differences in patterns of successful and erroneous crossings (i.e., higher number of errors overall and in relation to Traffic Direction, specific error types, lane- and side related errors). Furthermore, differences were observed in head rotation measures (i.e., heading position, head tilt angle, and head turns).

Patients with chronic neglect make more and distinct errors in road-crossing

The presence of a chronic spatial neglect can be inferred based on the direction-specific error patterns made during road crossing. Chronic neglect patients committed more errors in general, as well as in neglect-specific error types, which may indicate spatial attentional and temporal deficits. As expected, the groups differed in the side on which errors occurred. While the healthy controls and the no neglect group had a higher incidence of errors with cars coming from the right, the neglect group had a higher proportion of errors on the left. Furthermore, they made fewer safe crossings, again, particularly for traffic from the left.

The traffic direction condition was a significant predictor of the number and type of errors. Neglect patients were more likely to commit errors for traffic from left, and they made more dangerous errors on the near lane (near-lane error) for two-way traffic. Both control groups made more high-risk errors on the far lane, particularly in two-way traffic, and near-lane errors hardly occurred. These results align with previous studies indicating that far-lane errors are most frequent in healthy adults, especially older pedestrians, in two-way traffic (Cavallo et al., 2019; Fontaine & Gourlet, 1997). Dommes et al. (2014) identified the most dangerous scenario for older pedestrians crossing a road with bidirectional traffic is a sufficient gap in the near lane and a short gap in the far lane. The neglect group, however, exhibited a higher incidence of both dangerous and low-risk errors when faced with traffic from the left. This suggests that they do not pay enough attention to the left, as evidenced by the decrease in heading to the left side and increased number of errors for left-sided traffic. Nevertheless, they seem to compensate for their deficit by making more head turns, which results in a late onset of the crossing. In addition, they are unable to calculate their own speed in relation to the approaching cars. These results highlight both general and specific attentional deficits in chronic neglect.

Temporal measures detect neglect-specific behaviour

An overall slower information processing speed was observed in the USN+ group, reflected in slower reaction times, higher total experimental time, and higher letter insertion times, particularly for left-side mailboxes. These results provide support for lateralized as well as non-lateralized attentional deficits in neglect and reflect behavioral delays, particularly in the left spatial hemispace. For instance, the traffic from left and two-way traffic conditions elicited longer reaction times in neglect patients compared to the two other two groups. This may suggest a reduced speed of information processing or, alternatively, compensatory behavior. Notably, patients with neglect exhibited a greater number of head turns than other groups, especially for traffic coming from the left. However, the reaction times within the USN+ group did not differ by traffic direction, demonstrating the potential of iVRoad to detect non-lateralized deficits associated with neglect (Ogourtsova et al., 2018; Villarreal et al., 2021). Letter insertion time also revealed spatial differences between the groups and within the chronic neglect group, as patients with neglect had higher letter insertion times in general, and especially for letters on the left side. In addition, the chronic neglect patients in our study exhibited non-lateralized attentional deficits, as indicated by increased total experimental time and overall reaction times, regardless of traffic direction. Compared to the USN- group, the longer reaction times observed for traffic from left and right suggest that neglect may be associated with slower processing on both sides of space, as previously reported (Buxbaum et al., 2004). This finding also suggests that deficits associated with neglect go beyond the lateralized attentional deficits as they are not restricted to one side (Corbetta & Shulman, 2011). These findings have important implications for the clinical assessment of chronic neglect, highlighting the need for a more comprehensive assessment of both spatial and non-spatial selective attention using temporal measures.

Patients with chronic neglect committed more low-risk errors, indicating delayed responses in road-crossing initiation. For low-risk errors, the time between two approaching cars was sufficiently long for healthy controls to allow the road to be crossed safely. Thus, low-risk errors in neglect subjects indicate that they started too late to cross the road in time. These results align with prior studies suggesting temporal measures as sensitive indicators of neglect (Schendel & Robertson, 2002). Reaction times have been used to measure attention in various tasks (e.g., computerized tasks: TAP, Starry Night test; VR task: Kim et al., 2010) and total experiment time in VR to quantify neglect-specific behavior (Mesa-Gresa et al., 2011; Weiss et al., 2003). These findings collectively support the use of temporal measures for identifying subtle or compensated neglect symptoms.

VR head movement measures are sensitive neglect indicators

VR monitoring of head movements revealed valuable insights into neglect-typical behavior. Head rotation measures, both along yaw and roll axes, and the number of head turns before crossing were sensitive to neglect-specific behavior. Our results showed differences in head movement parameters between the groups depending on traffic direction. Specifically, the neglect group had less leftward lateralization along the yaw axis than the no neglect and healthy groups for traffic from the left. This difference was also significant for traffic from right. Moreover, the neglect group tilted their heads further to the right shoulder than the other groups, especially for traffic from right. They also exhibited a higher number of head turns for left/right traffic and traffic from left, underscoring the importance of head movements. Given that participants in the study were mainly chronic patients, the higher number of head turns may be an indicator of compensatory behavior.

The neglect group did not exhibit longer or more rightward lateralization along the yaw axis compared to the no neglect and healthy groups. However, their head movement was less stable with unidirectional traffic. This aligns to the chronic phase of neglect symptoms, as patients with acute neglect still show a marked deviation of head position to the right (Karnath et al., 1998). In contrast, the neglect group exhibited significantly less leftward lateralization than the other groups for traffic from left. Although the pronounced rightward head rotation seen in the acute phase was no longer evident, our results suggest that patients with chronic neglect still exhibit distinct patterns of head movement. Specifically, they demonstrate more head turns along the yaw axis and tilt their head further to the right shoulder along the roll axis, particularly in varied traffic directions.

iVRoad has the potential to be used clinically

The iVRoad task introduces a novel approach to behavioral assessment using VR technology, providing objective measures such as head rotation and error patterns in a safe clinical environment. This technology requires minimal space and therapist involvement, allowing for controlled and automated data collection. The increasing integration of VR into both households and clinical settings strengthens the need for the adoption of clinically validated VR tasks. In addition, the iVRoad task significantly enhances the ecological validity of cognitive assessments by providing realistic and dynamic simulations.

All groups completed the VR task comfortably. They easily learned to use the controller and in line with Huygelier et al. (2022), post-VR cybersickness scores were lower than before, suggesting that the VR exposure did not negatively affect patients' well-being. Symptoms occurring prior to the VR task suggest that those typically associated with cybersickness (Brandt & Dieterich, 2017) are rather unspecific and may generally occur in right hemisphere stroke patients. In addition, neglect has been associated with a decreased awareness of symptoms (Jehkonen et al., 2001), and VR's attention-engaging impact may have contributed to a reduction in the symptoms reported after the task. High usability scores and motivation combined with willingness to use VR for clinical purposes demonstrate its potential in neuropsychological settings. Most participants showed interest in cognitive training using VR, underscoring the feasibility of immersive VR for chronic right-hemispheric post-stroke patients with and without neglect.

Selection of difficulty parameters

Choosing appropriate difficulty parameters was crucial for detecting neglect-specific behavior. The VR task was designed to have moderate difficulty, ensuring that errors were made by all groups without an excessive number of errors overall. Two-way traffic led to more errors in all groups, with USN+ showing more near-lane errors and dangerous crossings. In addition, their head tilt angle was greater to the right. The attentional-perceptual deficits associated with neglect were particularly evident for two-way traffic with longer reaction times, and more errors. Manipulating the traffic direction also revealed neglect-specific behavior in head movements, including heading position, head tilt angle, and head turns. The letter insertion task differentiated between groups, highlighting its potential usefulness not only for storytelling but also in applications beyond a clinical setting.

These findings illustrate the importance of task complexity, stimulus density, attention allocation, and dual tasks for the detection of neglect. Andres et al. (2019) showed that dual tasks were more sensitive in detecting compensated neglect symptoms compared to standard neglect tests, such as the cancellation task. Similarly, Azouvi et al. (2002) reported behavioral assessments that evaluate functional performance in daily life situations were more sensitive in assessing neglect deficits compared to paper-and-pencil tests. This aligns with our findings that behavioral assessments in VR were good predictors to identify neglect.

Clinical implications and study limitations

Assessing the driving ability of individuals post-stroke is highly relevant. Neglect symptoms are often overlooked in chronic assessments. Our findings reveal dangerous behaviors, such as increased errors and slower reaction times in pedestrian scenarios, despite similar self-assessments compared to no neglect patients. This lack of awareness is typical in neglect. Increased head turns suggest attempted compensation but fail to prevent errors, especially with inadequate leftward checks for left-approaching traffic. This may increase the risk of errors, as patients tend to start crossing the road late and fail to accurately assess their speed in comparison to the speed of approaching cars.

Future studies should focus on developing advanced methods for measuring neglect severity and subtypes with iVRoad. One potential approach would be the use of adaptive testing or data-driven techniques to quickly obtain results and provide individually tailored cognitive rehabilitation programs with clinical immersive VR tools. This approach would lead to faster and more accurate test results, as well as improved monitoring of follow-up care of neglect symptoms and a reduction in testing time.

A limitation of the study is that the avatar's walking speed in the virtual environment was not adjustable, potentially leading to unrealistic experiences for some participants. This fixed speed was necessary to accommodate participants with hemiparesis and to minimize the risk of cybersickness. Furthermore, we used a self-reported CBS score, which might be problematic due to anosognosia observed in neglect (Chen & Toglia, 2019). We acknowledge that group assignment in relation to the USN+ group is a limitation of this study. Given the low sensitivity of the neglect tests for mild and compensated neglect symptoms, the neglect classification was based on clinical testing and clinical staff evaluation. Despite these limitations, the VR task could still be conducted in a clinical setting and used to examine cognitive functions that might be challenging to assess in real world scenarios due to mobility or gait limitations. Furthermore, it offers the potential to assess and monitor the presence of neglect symptoms from early stages using a task that mirrors everyday situations.

Conclusion

Our study provides evidence that iVRoad is a viable tool for detecting symptoms of neglect in patients with chronic right-hemispheric strokes. The use of spatio-temporal experimental manipulations, such as varying traffic directions, combined with temporal parameters, error patterns, and head movements everyday life situations was particularly effective in detecting chronic left-sided neglect. Reaction times, left-sided errors, and lateral head movements for traffic from left were particularly sensitive in identifying the presence of neglect. A first step toward an improved assessment of neglect, particularly of mild or well-compensated neglect symptoms, has been made using iVRoad as part of a comprehensive behavioral evaluation for neglect. Furthermore, our results indicate that the use of a road-crossing task was feasible, highly usable, and enjoyable in chronic right-hemispheric stroke patients with and without neglect, as well as healthy participants. Furthermore, iVRoad was highly feasible from patients' perspective and applicable without any adverse effects related to cybersickness interfering with task completion. These results suggest that VR-based methods can improve our detection of discrete neglect syndromes that may otherwise be overlooked.

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References

Aimola, L., Schindler, I., Simone, A. M., & Venneri, A. (2012). Near and far space neglect: Task sensitivity and anatomical substrates. *Neuropsychologia*, *50*(6), 1115–1123. https://doi.org/10.1016/j.neuropsychologia.2012.01.022

Andres, M., Geers, L., Marnette, S., Coyette, F., Bonato, M., Priftis, K., & Masson, N. (2019). Increased cognitive load reveals unilateral neglect and altitudinal extinction in chronic stroke. *Journal of the International Neuropsychological Society:*, *25*(6), 644–653. https://doi.org/10.1017/S1355617719000249

Anthes, C., Garcia-Hernandez, R. J., Wiedemann, M., & Kranzlmüller, D. (2016). State of the art of virtual reality technology. In *2016 IEEE Aerospace Conference* (pp. 1–19). IEEE. https://doi.org/10.1109/AERO.2016.7500674

Aravind, G., & Lamontagne, A. (2017). Dual tasking negatively impacts obstacle avoidance abilities in post-stroke individuals with visuospatial neglect: Task complexity matters! *Restorative Neurology and Neuroscience*, *35*(4), 423–436. https://doi.org/10.3233/RNN-160709

Azouvi, P. (1996). Functional consequences and awareness of unilateral neglect: Study of an evaluation scale. *Neuropsychological Rehabilitation*, *6*(2), 133–150. https://doi.org/10.1080/713755501

Azouvi, P., Samuel, C., Louis-Dreyfus, A., Bernati, T., Bartolomeo, P., Beis, J. M., Chokron, S., Leclercq, M., Marchal, F., Martin, Y., Montety, G. D., Olivier, S., Perennou, D., Pradat-Diehl, P., Prairial, C., Rode, G., Siéroff, E., Wiart, L., & Rousseaux, M. (2002). Sensitivity of clinical and behavioural tests of spatial neglect after right hemisphere stroke. *Journal of Neurology, Neurosurgery & Psychiatry*, *73*(2), 160–166. https://doi.org/10.1136/jnnp.73.2.160

Barrett, A. M., Buxbaum, L. J., Coslett, H. B., Edwards, E., Heilman, K. M., Hillis, A. E., Milberg, W. P., & Robertson, I. H. (2006). Cognitive rehabilitation interventions for neglect and related disorders: Moving from bench to bedside in stroke patients. *Journal of Cognitive Neuroscience*, *18*(7), 1223–1236. https://doi.org/10.1162/jocn.2006.18.7.1223

Bartolomeo, P., & Chokron, S. (2002). Orienting of attention in left unilateral neglect. *Neuroscience and Biobehavioural Reviews*, *26*(2), 217–234. https://doi.org/10.1016/S0149-7634(01)00065-3

Bonato, M. (2012). Neglect and extinction depend greatly on task demands: A review. *Frontiers in Human Neuroscience*, *6*, 195. https://doi.org/10.3389/fnhum.2012.00195

Bowen, A., McKenna, K., & Tallis, R. C. (1999). Reasons for variability in the reported rate of occurrence of unilateral spatial neglect after stroke. *Stroke*, *30*(6), 1196–1202. https://doi.org/10.1161/01.STR.30.6.1196

Brandt, T., & Dieterich, M. (2017). The dizzy patient: Don't forget disorders of the central vestibular system. *Nature Reviews Neurology*, *13*(6), 352–362. https://doi.org/10.1038/nrneurol.2017.58

Brink, A., Elshout, J., Nijboer, T. C. W., & van der Stigchel, S. (2020). How does the number of targets affect visual search performance in visuospatial neglect? *Journal of Clinical and Experimental Neuropsychology*, *42*(10), 1010–1027. https://doi.org/10.1080/13803395.2020.1840520

Brink, A., Verwer, J., Biesbroek, J., Visser-Meily, J., & Nijboer, T. (2017). Differences between left- and right-sided neglect revisited: A large cohort study across multiple domains. *Journal of Clinical and Experimental Neuropsychology*, *39*(7), 707–723. https://doi.org/10.1080/13803395.2016.1262333

Broeren, J., Samuelsson, H., Stibrant-Sunnerhagen, K., Blomstrand, C., & Rydmark, M. (2007). Neglect assessment as an application of virtual reality. *Acta Neurologica Scandinavica*, *116*(3), 157–163. https://doi.org/10.1111/j.1600-0404.2007.00821.x

Brooke, J. (1996). *SUS: A "quick and dirty"*. Usability Scale.

Buxbaum, L. J., Dawson, A. M., & Linsley, D. (2012). Reliability and validity of the virtual reality lateralized attention test in assessing hemispatial neglect in right-hemisphere stroke. *Neuropsychology*, *26*(4), 430–441. https://doi.org/10.1037/a0028674

Buxbaum, L. J., Ferraro, M., Veramonti, T., Farnè, A., Whyte, J., Ladavas, E., Frassinetti, F., & Coslett, H. B. (2004). Hemispatial neglect: Subtypes, neuroanatomy, and disability. *Neurology*, *62*(5), 749–756. https://doi.org/10.1212/01.WNL.0000113730.73031.F4

Buxbaum, L. J., Palermo, M. A., Mastrogiovanni, D., Read, M. S., Rosenberg-Pitonyak, E., Rizzo, A. A., & Coslett, H. B. (2008). Assessment of spatial attention and neglect with a virtual wheelchair navigation task. *Journal of Clinical and Experimental Neuropsychology*, *30*(6), 650–660. https://doi.org/10.1080/13803390701625821

Cavallo, V., Dommes, A., Dang, N.-T., & Vienne, F. (2019). A street-crossing simulator for studying and training pedestrians. Transportation research part f. *Transportation Research Part F: Traffic Psychology and Behaviour*, *61*, 217–228. https://doi.org/10.1016/j.trf.2017.04.012

Chen, P., Hreha, K., Fortis, P., Goedert, K. M., & Barrett, A. M. (2012). Functional assessment of spatial neglect: A review of the Catherine Bergego Scale and an introduction of the Kessler Foundation Neglect Assessment Process. *Topics in Stroke Rehabilitation*, *19*(5), 423–435. https://doi.org/10.1310/tsr1905-423

Chen, P., & Toglia, J. (2019). Online and offline awareness deficits: Anosognosia for spatial neglect. *Rehabilitation Psychology*, *64*(1), 50–64. https://doi.org/10.1037/rep0000207

Cherix, R., Carrino, F., Piérart, G., Khaled, O. A., Mugellini, E., & Wunderle, D. (2020). Training pedestrian safety skills in youth with intellectual disabilities using fully immersive virtual reality - A feasibility study. In H. Krömker (Ed.), *Lecture notes in computer science. HCI in mobility, transport, and automotive systems. Driving behaviour, Urban and smart mobility* (Vol. 12213, pp. 161–175). Springer International Publishing. https://doi.org/10.1007/978-3-030-50537-0_13

Clancy, T. A., Rucklidge, J. J., & Owen, D. (2006). Road-crossing safety in virtual reality: A comparison of adolescents with and without ADHD. *Journal of Clinical Child and Adolescent Psychology*, *35*(2), 203–215. https://doi.org/10.1207/s15374424jccp3502_4

Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual Review of Neuroscience*, *34*(1), 569–599. https://doi.org/10.1146/annurev-neuro-061010-113731

Deb, S., Carruth, D. W., Sween, R., Strawderman, L., & Garrison, T. M. (2017). Efficacy of virtual reality in pedestrian safety research. *Applied Ergonomics*, *65*, 449–460. https://doi.org/10.1016/j.apergo.2017.03.007

Deouell, L. Y., Sacher, Y., & Soroker, N. (2005). Assessment of spatial attention after brain damage with a dynamic reaction time test. *Journal of the International Neuropsychological Society*, *11*(6), 697–707. https://doi.org/10.1017/S1355617705050824

Dommes, A., Cavallo, V., Dubuisson, J. B., Tournier, I., & Vienne, F. (2014). Crossing a two-way street: Comparison of young and old pedestrians. *Journal of Safety Research*, *50*, 27–34. https://doi.org/10.1016/j.jsr.2014.03.008

Edwards, D. F., Hahn, M. G., Baum, C. M., Perlmutter, M. S., Sheedy, C., & Dromerick, A. W. (2006). Screening patients with stroke for rehabilitation needs: Validation of the post-stroke rehabilitation guidelines. *Neurorehabilitation and Neural Repair*, *20*(1), 42–48. https://doi.org/10.1177/1545968305283038

Esposito, E., Shekhtman, G., & Chen, P. (2021). Prevalence of spatial neglect post-stroke: A systematic review. *Annals of Physical and Rehabilitation Medicine*, *64*(5), 101459. https://doi.org/10.1016/j.rehab.2020.10.010

Evin, I., Pesola, T., Kaos, M. D., Takala, T. M., & Hämäläinen, P. (2020). 3PP-R: Enabling natural movement in 3rd person virtual reality. *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 438–449. https://doi.org/10.1145/3410404.3414239

Farnè, A., Buxbaum, L. J., Ferraro, M., Frassinetti, F., Whyte, J., Veramonti, T., Angeli, V., Coslett, H. B., & Làdavas, E. (2004). Patterns of spontaneous recovery of neglect and associated disorders in acute right brain-damaged patients. *Journal of Neurology, Neurosurgery, and Psychiatry*, *75*(10), 1401–1410. https://doi.org/10.1136/jnnp.2002.003095

Feldstein, I. T., & Dyszak, G. N. (2020). Road crossing decisions in real and virtual environments: A comparative study on simulator validity. *Accident; Analysis and Prevention*, *137*, 105356. https://doi.org/10.1016/j.aap.2019.105356

Fels, M., & Geissner, E. (1997). Neglect-Test (NET)—Ein Verfahren zur Erfassung visueller Neglectphänomene. *Zeitschrift für Klinische Psychologie und Psychotherapie*, *28*(4), 298–299. https://doi.org/10.1026//0084-5345.28.4.298

Fontaine, H., & Gourlet, Y. (1997). Fatal pedestrian accidents in france: A typological analysis. *Accident Analysis & Prevention*, *29*(3), 303–312. https://doi.org/10.1016/S0001-4575(96)00084-X

Fordell, H., Bodin, K., Bucht, G., & Malm, J. (2011). A virtual reality test battery for assessment and screening of spatial neglect. *Acta Neurologica Scandinavica*, *123*(3), 167–174. https://doi.org/10.1111/j.1600-0404.2010.01390.x

Gil-Gómez, J. A., Manzano-Hernández, P., Albiol-Pérez, S., Aula-Valero, C., Gil-Gómez, H., & Lozano-Quilis, J. A. (2017). Useq: A short questionnaire for satisfaction evaluation of virtual rehabilitation systems. *Sensors*, *17*(7), 1589. https://doi.org/10.3390/s17071589

Gorisse, G., Christmann, O., Amato, E. A., & Richir, S. (2017). First- and third-person perspectives in immersive virtual environments: Presence and performance analysis of embodied users. *Frontiers in Robotics and AI*, *4*, 33. https://doi.org/10.3389/frobt.2017.00033

Grattan, E. S., Skidmore, E. R., & Woodbury, M. L. (2018). Examining anosognosia of neglect. *OTJR: Occupation, Participation and Health*, *38*(2), 113–120. https://doi.org/10.1177/1539449217747586

Gupta, V., Knott, B. A., Kodgi, S., & Lathan, C. E. (2000). Using the "VREye" system for the assessment of unilateral visual neglect: Two case reports. *Presence Teleoperators & Virtual Environments*, *9*(3), 268–286. https://doi.org/10.1162/105474600566790

Heilman, K. M., Valenstein, E., & Watson, E. (1994). The what and how of neglect. *Neuropsychological Rehabilitation*, *4*(2), 133–139. https://doi.org/10.1080/09602019408402270

Heilman, K. M., Valenstein, E., & Watson, R. T. (2000). Neglect and related disorders. *Seminars in Neurology*, *20*(4), 463–470. https://doi.org/10.1055/s-2000-13179

Holland, C., & Hill, R. (2010). Gender differences in factors predicting unsafe crossing decisions in adult pedestrians across the lifespan: A simulation study. *Accident Analysis and Prevention*, *42*(4), 1097–1106. https://doi.org/10.1016/j.aap.2009.12.023

Husain, M. (2008). Hemispatial neglect. In G. Goldenberg & B. L. Miller (Eds.), *Handbook of clinical neurology. Neuropsychology and behavioural neurology* (pp. 359–372). Elsevier. https://doi.org/10.1016/S0072-9752(07)88018-3

Huygelier, H., Schraepen, B., Lafosse, C., Vaes, N., Schillebeeckx, F., Michiels, K., Note, E., Vanden Abeele, V., Van Ee, R., & Gillebert, C. R. (2022). An immersive virtual reality game to train spatial attention orientation after stroke: A feasibility study. *Applied Neuropsychology: Adult*, *29*(5), 915–935. https://doi.org/10.1080/23279095.2020.1821030

Jannink, M. J. A., Aznar, M., de Kort, A. C., van de Vis, W., Veltink, P., & van der Kooij, H. (2009). Assessment of visuospatial neglect in stroke patients using virtual reality: A pilot study. *International Journal of Rehabilitation Research*, *32*(4), 280–286. https://doi.org/10.1097/MRR.0b013e3283013b1c

Jehkonen, M., Ahonen, J. P., Dastidar, P., Koivisto, A. M., Laippala, P., Vilkki, J., & Molnár, G. (2001). Predictors of discharge to home during the first year after right hemisphere stroke: Predictors of discharge to home. *Acta Neurologica Scandinavica*, *104*(3), 136–141. https://doi.org/10.1034/j.1600-0404.2001.00025.x

Jehkonen, M., Laihosalo, M., & Kettunen, J. E. (2006). Impact of neglect on functional outcome after stroke: A review of methodological issues and recent research findings. *Restorative Neurology and Neuroscience*, *24*(4–6), 209–215.

Kaimara, P., Oikonomou, A., & Deliyannis, I. (2021). Could virtual reality applications pose real risks to children and adolescents? A systematic review of ethical issues and concerns. *Virtual Reality*, *26*(2), 697–735. https://doi.org/10.1007/s10055-021-00563-w

Kaiser, A. P., Villadsen, K. W., Samani, A., Knoche, H., & Evald, L. (2022). Virtual reality and eye-tracking assessment, and treatment of unilateral spatial neglect: Systematic review and future prospects. *Frontiers in Psychology*, *13*, 787382. https://doi.org/10.3389/fpsyg.2022.787382

Karnath, H.-O. (2015). Spatial attention systems in spatial neglect. *Neuropsychologia*, *75*, 61–73. https://doi.org/10.1016/j.neuropsychologia.2015.05.019

Karnath, H. O., Niemeier, M., & Dichgans, J. (1998). Space exploration in neglect. *Brain: A Journal of Neurology*, *121*(12), 2357–2367. https://doi.org/10.1093/brain/121.12.2357

Karnath, H. O., & Rorden, C. (2012). The anatomy of spatial neglect. *Neuropsychologia*, *50*(6), 1010–1017. https://doi.org/10.1016/j.neuropsychologia.2011.06.027

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kerkhoff, G., Neumann, G., & Neu, J. (2020). *Ratgeber neglect: Leben in einer halbierten welt*. Hogrefe.

Kerkhoff, G., & Schenk, T. (2012). Rehabilitation of neglect: An update. *Neuropsychologia*, *50*(6), 1072–1079. https://doi.org/10.1016/j.neuropsychologia.2012.01.024

Kim, D. Y., Ku, J., Chang, W. H., Park, T. H., Lim, J. Y., Han, K., Kim, I. Y., & Kim, S. I. (2010). Assessment of post-stroke extrapersonal neglect using a three-dimensional immersive virtual street crossing program. *Acta Neurologica Scandinavica*, *121*(3), 171–177. https://doi.org/10.1111/j.1600-0404.2009.01194.x

Knobel, S. E. J., Kaufmann, B. C., Gerber, S. M., Cazzoli, D., Müri, R. M., Nyffeler, T., & Nef, T. (2020). Immersive 3D virtual reality cancellation task for visual neglect assessment: A pilot study. *Frontiers in Human Neuroscience*, *14*, 180. https://doi.org/10.3389/fnhum.2020.00180

Knobel, S. E. J., Kaufmann, B. C., Gerber, S. M., Urwyler, P., Cazzoli, D., Müri, R. M., Nef, T., & Nyffeler, T. (2021). Development of a search task using immersive virtual reality: Proof-of-concept study. *JMIR Serious Games*, *9*(3), e29182. https://doi.org/10.2196/29182

Kwon, S., Park, W., Kim, M., & Kim, J. M. (2020). Relationship between line bisection test time and hemispatial neglect prognosis in patients with stroke: A prospective pilot study. *Annals of Rehabilitation Medicine*, *44*(4), 292–300. https://doi.org/10.5535/arm.19112

Lenth, R. V. (2023). Emmeans: Estimated marginal means, aka Least-Squares means. R package version 1.8.8.

Lobjois, R., Benguigui, N., & Cavallo, V. (2013). The effects of age and traffic density on street-crossing behaviour. *Accident; Analysis and Prevention*, *53*, 166–175. https://doi.org/10.1016/j.aap.2012.12.028

Mesa-Gresa, P., Lozano, J. A., Llórens, R., Alcañiz, M., Navarro, M. D., & Noé, E. (2011). Clinical validation of a virtual environment test for safe street crossing in the assessment of acquired brain injury patients with and without neglect. In P. Campos, N. Graham, J. Jorge, N. Nunes,

P. Palanque, & M. Winckler (Eds.), *Lecture notes in computer Science: Vol. 6947. human-computer interaction – INTERACT 2011* (Vol. 6947, pp. 44–51). Springer. https://doi.org/10.1007/978-3-642-23771-3_4

Moore, M., Milosevich, E., Beisteiner, R., Bowen, A., Checketts, M., Demeyere, N., Fordell, H., Godefroy, O., Laczó, J., Rich, T., Williams, L., Woodward-Nutt, K., & Husain, M. (2022). Rapid screening for neglect following stroke: A systematic search and European Academy of Neurology recommendations. *European Journal of Neurology*, *29*(9), 2596–2606. https://doi.org/10.1111/ene.15381

Morgenroth, O. (2008). *Zeit und Handeln: Psychologie der Zeitbewältigung* (1. Aufl ed.). Kohlhammer.

Morrongiello, B. A., Corbett, M., Milanovic, M., Pyne, S., & Vierich, R. (2015). Innovations in using virtual reality to study how children cross streets in traffic: Evidence for evasive action skills. *Injury Prevention: Journal of the International Society for Child and Adolescent Injury Prevention*, *21*(4), 266–270. https://doi.org/10.1136/injuryprev-2014-041357

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The montreal cognitive assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Nijboer, T. C. W., Kollen, B. J., & Kwakkel, G. (2013). Time course of visuospatial neglect early after stroke: A longitudinal cohort study. *Cortex; a Journal Devoted to the Study of the Nervous System and Behaviour*, *49*(8), 2021–2027. https://doi.org/10.1016/j.cortex.2012.11.006

Nijboer, T. C. W., & van der Stigchel, S. (2019). Visuospatial neglect is more severe when stimulus density is large. *Journal of Clinical and Experimental Neuropsychology*, *41*(4), 399–410. https://doi.org/10.1080/13803395.2019.1566444

Ogourtsova, T., Archambault, P. S., & Lamontagne, A. (2018). Post-stroke unilateral spatial neglect: Virtual reality-based navigation and detection tasks reveal lateralized and non-lateralized deficits in tasks of varying perceptual and cognitive demands. *Journal of Neuroengineering and Rehabilitation*, *15*(1), 34. https://doi.org/10.1186/s12984-018-0374-y

Oxley, J., Charlton, J. L., & Fildes, B. N. (2005). *The effect of cognitive impairment on older pedestrian behaviour and crash risk* (244 ed.). Monash Accident Research Centre.

Oxley, J., Fildes, B. N., Ihsen, E., Charlton, J. L., & Day, R. H. (1999). Age differences in road crossing decisions based on Gap Judgements. *Annual Proceedings/Association for the Advancement of Automotive Medicine*, *43*, 279–300.

Papić, Z., Jović, A., Simeunović, M., Saulić, N., & Lazarević, M. (2020). Underestimation tendencies of vehicle speed by pedestrians when crossing unmarked roadway. *Accident Analysis and Prevention*, *143*, 105586. https://doi.org/10.1016/j.aap.2020.105586

Parton, A., Malhotra, P., & Husain, M. (2004). Hemispatial neglect. *Journal of Neurology, Neurosurgery, and Psychiatry*, *75*(1), 13–21.

Pedroli, E., Serino, S., Cipresso, P., Pallavicini, F., & Riva, G. (2015). Assessment and rehabilitation of neglect using virtual reality: A systematic review. *Frontiers in Behavioural Neuroscience*, *9*, 226. https://doi.org/10.3389/fnbeh.2015.00226

Peskine, A., Rosso, C., Box, N., Galland, A., Caron, E., Rautureau, G., Jouvent, R., & Pradat-Diehl, P. (2011). Virtual reality assessment for visuospatial neglect: Importance of a dynamic task. *Journal of Neurology, Neurosurgery, and Psychiatry*, *82*(12), 1407–1409. https://doi.org/10.1136/jnnp.2010.217513

Petzoldt, T. (2014). On the relationship between pedestrian gap acceptance and time to arrival estimates. *Accident Analysis and Prevention*, *72*, 127–133. https://doi.org/10.1016/j.aap.2014.06.019

Reinhart, S., Leonhard, E., & Kerkhoff, G. (2016). Sensitive Neglect Test (SNT) single and dual task.

Rengachary, J., d'Avossa, G., Sapir, A., Shulman, G. L., & Corbetta, M. (2009). Is the posner reaction time test more accurate than clinical tests in detecting left neglect in acute and chronic stroke? *Archives of Physical Medicine and Rehabilitation*, *90*(12), 2081–2088. https://doi.org/10.1016/j.apmr.2009.07.014

Ridene, T., Leroy, L., & Chendeb, S. (2015). Innovative virtual reality application for road safety education of children in Urban areas. In G. Bebis, R. Boyle, B. Parvin, D. Koracin, I. Pavlidis, R. Feris, T. McGraw, M. Elendt, R. Kopper, E. Ragan, Z. Ye, & G. Weber (Eds.), *Lecture notes in computer science. Advances in visual computing* (Vol. 9475, pp. 797–808). Springer International Publishing. https://doi.org/10.1007/978-3-319-27863-6_75

Ringman, J. M., Saver, J. L., Woolson, R. F., Clarke, W. R., & Adams, H. P. (2004). Frequency, risk factors, anatomy, and course of unilateral neglect in an acute stroke cohort. *Neurology*, *63*(3), 468–474. https://doi.org/10.1212/01.WNL.0000133011.10689.CE

Rorden, C., & Karnath, H.-O. (2010). A simple measure of neglect severity. *Neuropsychologia*, *48*(9), 2758–2763. https://doi.org/10.1016/j.neuropsychologia.2010.04.018

Schendel, K. L., & Robertson, L. C. (2002). Using reaction time to assess patients with unilateral neglect and extinction. *Journal of Clinical and Experimental Neuropsychology*, *24*(7), 941–950. https://doi.org/10.1076/jcen.24.7.941.8390

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence Teleoperators & Virtual Environments*, *10*(3), 266–281. https://doi.org/10.1162/105474601300343603

Simpson, G., Johnston, L., & Richardson, M. (2003). An investigation of road crossing in a virtual environment. *Accident Analysis & Prevention*, *35*(5), 787–796. https://doi.org/10.1016/S0001-4575(02)00081-7

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. (2022). Afex: Analysis of factorial experiments (version 1.2-0) [R package].

Spreij, L. A., Ten Brink, A. F., Visser-Meily, J. M. A., & Nijboer, T. C. W. (2020). Increasing cognitive demand in assessments of visuo-spatial neglect: Testing the concepts of static and dynamic tests. *Journal of Clinical and Experimental Neuropsychology*, *42*(7), 675–689. https://doi.org/10.1080/13803395.2020.1798881

Tanaka, T., Sugihara, S., Nara, H., Ino, S., & Ifukube, T. (2005). A preliminary study of clinical assessment of left unilateral spatial neglect using a Head Mounted Display system (HMD) in rehabilitation engineering technology. *Journal of Neuroengineering and Rehabilitation*, *2*(1), 31. https://doi.org/10.1186/1743-0003-2-31

Ugur, C., Gücüyener, D., Uzuner, N., Ozkan, S., & Ozdemir, G. (2000). Characteristics of falling in patients with stroke. *Journal of Neurology, Neurosurgery, and Psychiatry*, *69*(5), 649–651. https://doi.org/10.1136/jnnp.69.5.649

Vallar, G. (2001). Extrapersonal visual unilateral spatial neglect and its neuroanatomy. *Neuroimage: Reports*, *14*(1 Pt 2), S52–8. https://doi.org/10.1006/nimg.2001.0822

Venables, W. N., Ripley, B. D., & Venables, W. N. (2002). *Modern applied statistics with S* (4th ed.). Springer.

Villarreal, S., Linnavuo, M., Sepponen, R., Vuori, O., Bonato, M., Jokinen, H., & Hietanen, M. (2021). Unilateral stroke: Computer-based assessment uncovers non-lateralized and contralesional visuoattentive deficits. *Journal of the International Neuropsychological Society*, *27*(10), 959–969. https://doi.org/10.1017/S1355617720001393

Villarreal, S., Linnavuo, M., Sepponen, R., Vuori, O., Jokinen, H., & Hietanen, M. (2020). Dual-task in large perceptual space reveals subclinical hemispatial neglect. *Journal of the International Neuropsychological Society*, *26*(10), 993–1005. https://doi.org/10.1017/S1355617720000508

Wagner, S., Belger, J., Joeres, F., Thöne-Otto, A., Hansen, C., Preim, B., & Saalfeld, P. (2021). iVRoad: Immersive virtual road crossing as an assessment tool for unilateral spatial neglect. *Computers & Graphics*, *99*, 70–82. https://doi.org/10.1016/j.cag.2021.06.013

Weiss, P. L. T., Naveh, Y., & Katz, N. (2003). Design and testing of a virtual environment to train stroke patients with unilateral spatial neglect to cross a street safely. *Occupational Therapy International*, *10*(1), 39–55. https://doi.org/10.1002/oti.176

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., . . . Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wilmut, K., & Purcell, C. (2022). Why are older adults more at risk as pedestrians? A systematic review. *Human Factors: The Journal of the Human Factors & Ergonomics Society*, *64*(8), 1269–1291. https://doi.org/10.1177/0018720821989511

Wilson, B., Cockburn, J., & Halligan, P. (1987). *Behavioural inattention test manual*. Tames Valley Test Company.

Wu, H., Ashmead, D. H., Adams, H., & Bodenheimer, B. (2018). Using virtual reality to assess the street crossing behaviour of pedestrians with simulated macular degeneration at a roundabout. *Frontiers in ICT*, *5*, Article 27. https://doi.org/10.3389/fict.2018.00027

Yasuda, K., Muroi, D., Hirano, M., Saichi, K., & Iwata, H. (2018). Differing effects of an immersive virtual reality programme on unilateral spatial neglect on activities of daily living. *BMJ Case Reports*, bcr-2017–222860. https://doi.org/10.1136/bcr-2017-222860Y