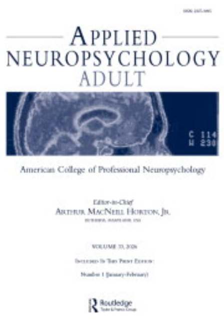

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Eye tracking during conventional neuropsychological assessments of spatial neglect

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ABSTRACT

Spatial neglect (SN) is a common cognitive disorder after stroke, characterized by lateralized attention deficits. Correctly identifying SN and its subtypes is crucial for treatment and recovery. Following, we examined eye movement measurements as an addition to a conventional test for assessing SN. We recorded eye movements during the presentation of the Cookie Theft image for people with left-sided SN (n=13), right-sided SN (n=3), and controls (n=6). Participants with SN were neurological patients. People with left-sided SN allocated more attention to the right side of the screen (i.e. proportion of right fixations, fixation time, and mean fixation location) relative to controls, especially during the early viewing phase (i.e. the first 25% of the viewing duration). Many of these differences were also evident at an individual level. For people with left-sided SN, allocating more attention to the right side of the screen (i.e. gaze position) was strongly correlated with neglect severity (i.e. Catherine Bergego Scale scores). Eye tracking metrics derived from neuropsychological assessments can be clinically relevant and suitable for individual-level analyses. By enabling a fine-grained assessment of attention allocation/gaze position, eye tracking could give added benefit to neuropsychological assessments of SN.

KEYWORDS
Eye tracking; lateralized attention bias; neuropsychological assessment; spatial neglect

Introduction

Spatial neglect (SN) is a common cognitive disorder after stroke, characterized by lateralized attention deficits (Bisiach, 1988; Kinsbourne, 1987). SN is associated with poor motor recovery, functional outcomes, independence during basic and instrumental activities of daily living, and increased informal caregiver burden (Chen, Hreha, et al., 2015; Nijboer et al., 2014). SN affects 43-80% of patients after acute, right-hemispheric stroke, and 20-62% of patients with a left hemispheric stroke (Appelros et al., 2002; Chen et al., 2015; Esposito et al., 2021; Nijboer et al., 2013; Ringman et al., 2004). Although spontaneous recovery can occur in the first weeks or months for people with SN, 30–40% will still show signs of SN one-year post-stroke (Karnath et al., 2011; Nijboer et al., 2013, 2014). The variability in these estimates is in part due to the homogeneity of assessment methods used, which vary in their degree of sensitivity (Azouvi et al., 2006; Lindell et al., 2007). This variability is troublesome, as correctly identifying SN and its subtypes has implications for treatment and recovery (Spaccavento et al., 2017).

Eye tracking might complement neuropsychological tests for SN and provide an objective means of assessing improvement during rehabilitation (for review see Cox & Davies, 2020). Although eye tracking has been used to assess SN during different types of behavioral experiments to understand its underlying mechanisms (e.g. Elshout et al., 2021; Van der Stigchel & Nijboer, 2010), the tasks in these experiments are generally not the same as those used during standard neuropsychological assessments (e.g. Hougaard et al., 2021; Kaufmann et al., 2020). Only a few studies have combined eye tracking with standard neuropsychological tasks (Primativo et al., 2015; Upshaw et al., 2019). Building on these studies, the main aim of the current paper was to examine the potential of eye movement measurements as an addition to one of the *conventional* neuropsychological clinical tests for assessing SN.

Lateralized attention deficits are typically assessed with pen-and-paper tests as part of a neuropsychological assessment (Azouvi et al., 2006; Rode et al., 2017), for instance by using a cancelation task (Albert, 1973). Another commonly deployed test of SN is the Cookie Theft image (Figure 1a; Kaplan et al., 2001), which is included in the National Institute of Health Stroke Scale (Lyden et al., 1999). The number of items identified (i.e. content units) negatively correlates with lesion volume in SN (Agis et al., 2016). For people with right SN (R-SN), the ratio of items identified on the left, relative to the right, highly correlates other clinical measures of neglect, such as scene copying, gap detection,

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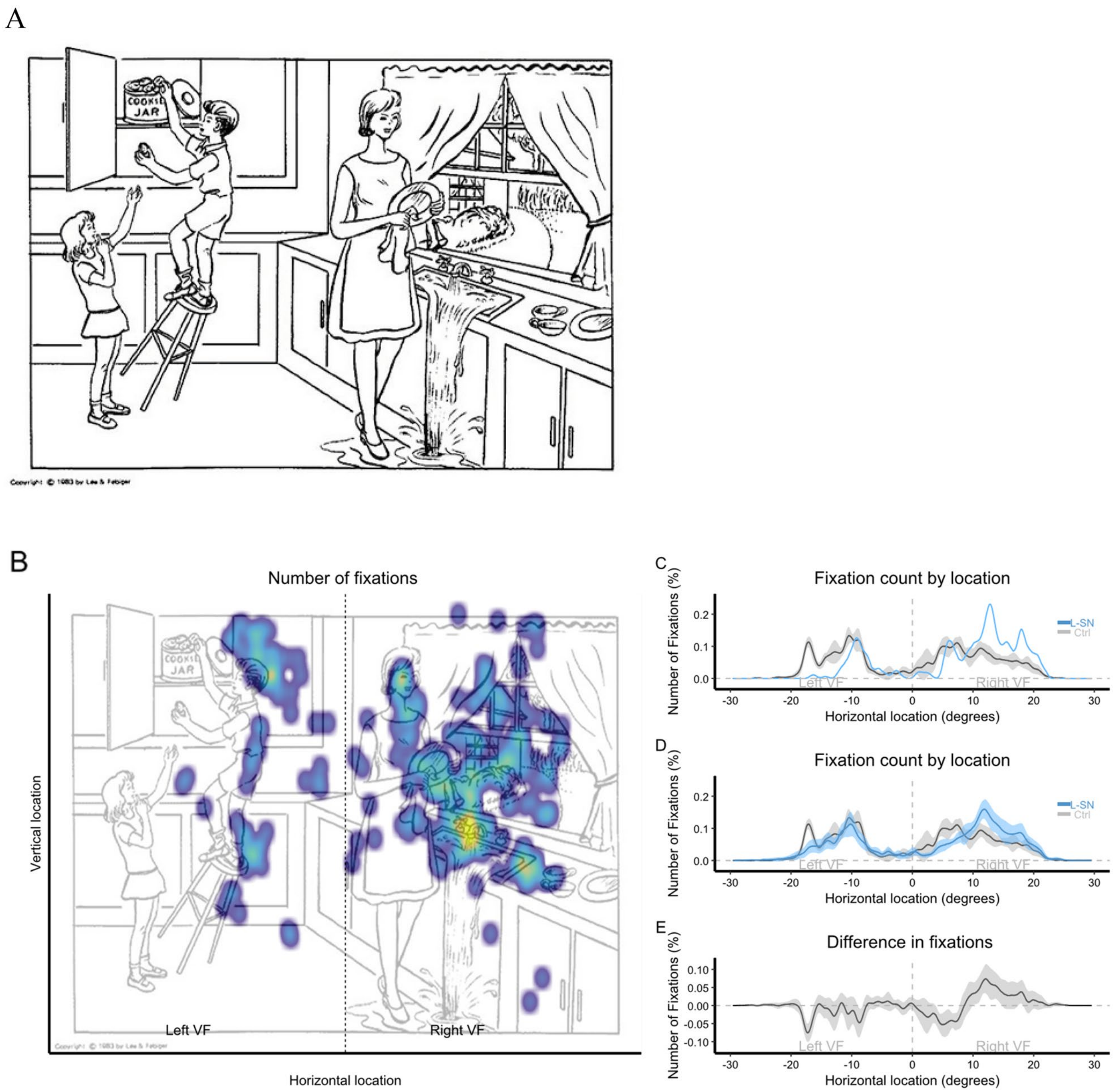

Figure 1. The figures depict the number of fixations expressed by their horizontal location. In panel A, the original image of the cooking theft image is displayed (Kaplan et al., 2001). In panel B, an example heatmap is presented from one individual with left-sided spatial neglect (L-SN), who made 355 fixations and spent 92.9s viewing the Cookie Theft image. Panel C shows the percentage of fixations by the horizontal location (i.e., averaged across the vertical location) for the data from panel B (i.e. from one individual with L-SN), and the mean data for controls with a 95% confidence interval (CI) fitted. Panel D also shows the percentage of fixations by their horizontal location, but with mean data for the L-SN group (n = 13; blue) and the control group (n = 6; grey) with 95% CIs fitted. Panel E shows the difference between the two group means (D), after subtracting the mean percentage of fixations of controls from that of the L-SN group. A positive value on the y-axis indicates that people with L-SN made more fixations at that location than controls (E). The vertical dotted line (B, C, D, E) shows the horizontal center of the image and separates the left visual field (VF) and the right VF, which also corresponds to the left side and right side of the panel, respectively. The horizontal dotted line (C, D, E) indicates a value of zero.

and line bisection (Stein et al., 2022). Furthermore, this ratio was negatively associated with hypoperfusion of the frontal middle cerebral artery (Stein et al., 2022), based on FHV (FLAIR hyperintense vessels) scores (Reyes et al., 2017). Although using a battery of clinical tests is advantageous to any single test (e.g. Stein et al., 2022; Williams et al., 2025), the evidence summarized above demonstrates the clinical relevance of the Cookie Theft image in SN.

Pen-and-paper tests, however, can make patients aware of their deficits, and thus symptoms of SN can be masked by compensatory strategies, such as top-down attentional control (Bonato, 2012; Van der Stigchel & Nijboer, 2018). In contrast, behavioral assessments rely more on bottom-up attentional processes (Azouvi, 2017), and thus do not enable the patient to use compensatory strategies to the same extent as pen-and-paper tests. For instance, the Catherine Bergego Scale (CBS; Azouvi et al., 2003; Bergego et al., 1995) is a behavioral assessment of the presence of and severity SN (i.e. not just the visual components of SN) in personal, peripersonal, and extrapersonal space, and is thought to reflect SN in everyday behavior, and is recommended for clinical use (Williams et al., 2025). Behavioral assessments may therefore be more sensitive in detecting attention deficits than pen-and-paper tests (Azouvi et al., 2002; 2003). However, behavioral assessments may still be subject to compensatory strategies, although to a lesser extent than pen-and-paper tests. Behavioral assessments complement pen-and-paper tests in clinical assessments of SN when there is time and resources available to deploy them (Azouvi, 2017). In those cases where time and/or resources are scarce, sensitive measures of attentional deficits are therefore needed that add minimal burden to clinical practice (Moore et al., 2022).

Several studies have looked at SN patients' eye movements during free visual exploration tasks, which measure features of bottom-up attention (Paladini et al., 2019). For instance, eye movements can be recorded during free visual exploration of natural scenes or images of urban places (Cazzoli et al., 2011; Fellrath & Ptak, 2015; Kaufmann et al., 2020; Kaufmann et al., 2020; Kaufmann et al., 2019; Ossandón et al., 2012; Paladini et al., 2019; Pflugshaupt et al., 2004; Ptak et al., 2009). A common finding is that people with SN make more fixations to and spend more time fixating on the ipsilateral side of the image, such as in Kaufmann et al. (2020). They found that right-hemispheric stroke patients showed a rightward bias during free visual exploration, as indicated by the mean horizontal fixation location. This bias was also associated with SN in everyday behavior (i.e. CBS scores). Furthermore, eye movements during a standard neuropsychological tests (i.e. the Cookie Theft image; Kaplan et al., 2001) were found to differ between a small group of stroke patients with and without SN (Primativo et al., 2015). These studies demonstrate that eye movements can be relevant to understanding SN in everyday behavior and that they can be integrated with standard neuropsychological tests. It has also been suggested that eye tracking can compensate for some of the limitations of traditional clinical measures of SN (Williams et al., 2025), especially for combined use. Finally, eye movements contain various features that can be used to dissociate between stroke patients and healthy controls (Brouwer et al., 2022; Delazer et al., 2018), and have been proposed as an additional tool to evaluate the acute phases of SN (e.g. Kaufmann et al., 2020; Kudo et al., 2021) and to assess SN subtypes (Upshaw et al., 2019). However, it remains unclear what eye tracking metrics that can be captured during standard neuropsychological tests are most relevant for understanding SN.

With the increasing availability of eye movement data in neuropsychological clinics and the ease of measuring eye movements, there exists great potential in incorporating eye movement measurements into standard neuropsychological tests (Primativo et al., 2015; Upshaw et al., 2019). However, the specific eye movement features that provide the most valuable information about spatial biases in SN remain unknown. Eye movements offer a wide range of outcome measures, such as fixation duration and spatial distribution of fixations, necessitating studies that investigate the significance of individual measures in this field. Furthermore, eye movements also allow insights into the temporal dynamics of viewing behavior. It is well established that eye movements are predominantly driven by stimulus-driven factors during the initial phases of exploration, while top-down factors play a more significant role in the later phases (van Zoest et al., 2017). Considering the compensatory nature of top-down strategies, the most pronounced indicators of SN are typically evident during the initial phases of exploration (Pflugshaupt et al., 2004).

Taken together, eye tracking can be used to improve the assessment of SN (Williams et al., 2025), and thereby benefit its treatment and recovery (Spaccavento et al., 2017). Research has shown that eye tracking metrics are relevant to SN in everyday behavior (i.e. CBS scores; Kaufmann et al., 2020) and can be integrated in routine clinical assessments (Primativo et al., 2015; Upshaw et al., 2019). We sought to extend this work by investigating which eye tracking metrics that can be derived from a routine clinical assessment are most relevant to SN in everyday behavior, and if these metrics can be used for individual-level analyses. Specifically, to examine the potential of eye movement measurements in a conventional neuropsychological clinical test (in this case, the Cookie Theft image; Kaplan et al., 2001), we investigated 1) the relation between eye movement measures with outcomes of conventional outcome measures, 2) whether differences for an *individual* patient can be detected in eye-movements and also 3) *which* eye movements best correlated with traditional outcome measures. For this final sub-aim, we also considered the temporal dynamics by examining the earlier and later parts of the gaze behavior separately. Because of the visual imbalance between the left and right side of the Cookie Theft image, we analyzed L-SN and right-sided SN (R-SN) separately. We did not directly compare these two groups statistically due to the low number of patients in the R-SN group. We considered gaze and fixation time indicative of attention allocation.

Materials and method

Informed written consent was obtained from all participants prior to any data collection.

Participants

The study complied with the Declaration of Helsinki and was approved by the Ethical Committee of the University Medical Center Utrecht (NL64626.041.18). Patients with SN after stroke were included during admittance to the Hoogstraat Rehabilitation center or the Parkgraaf rehabilitation center. As part of usual care, patients were assessed for SN during a neuropsychological screening. The screening included a digitized shape cancelation test (Aglioti et al., 1997), a digitized line bisection test (McIntosh et al., 2005) and the CBS (Azouvi et al., 2003; Bergego et al., 1995). The latter was completed by nurses involved in the post-stroke care. Patients were included when at least one of three SN screening tests was deviant from the normal range (i.e., omission difference of 2 or more between contralesional and ipsilesional side at shape cancelation test (Van der Stoep et al., 2013), 2 or more of 4 lines deviant on a line bisection test (8 repetitions of 4 different lines; Van der Stoep et al., 2013) or CBS score > 6 (Ten Brink et al., 2013). Further inclusion criteria were: 1) the SN was caused by stroke (left or right ischemic or intracerebral hemorrhagic lesion), 2) between 18 and 85 of age, and 3) sufficient ability to comprehend and to communicate. Exclusion criteria were: 1) traumatic head injury, 2) severe aphasia, and 3) insufficient understanding of the task. When expected discharge was within four weeks, patients were excluded to minimize dropouts.

Seven age matched healthy controls were included to obtain cutoff scores for the eye movement data. The size of the control group was determined pragmatically, based on the time and resources available.

Procedure and tests

All participants took part in a trial of visual scanning therapy with or without congruent movement training (Elshout et al., 2021; Elshout et al., 2019). The Cookie Theft image (Kaplan et al., 2001) depicts a boy and a girl attempting to steal cookies from a jar, and a woman doing dishes with an overflowing sink (Figure 1a). Participants were asked to describe everything that they saw in the image. There were 8 features that could each give 1 point, if described by the participant. There were 4 features on the left side (little boy, the little girl, the cookie jar and the stool) and 4 features on the right side (the mother, the plates, the water, and the window) of the image. The Cookie Theft image has been criticized for having a cultural, linguistic, and socioeconomic bias (Poisson et al., 2022; Steinberg et al., 2022), and the visual features of the image are not perfectly balanced. Consequently, several modified versions of the image have since been developed (e.g. https://osf.io/shwcn/, Berube et al., 2019). Further revisions are also needed to balance the visual features of the image, to improve its clinical value in SN assessment.

Participants were seated at a table in a dimly lit room, and were approximately 57 cm away from the screen, as indicated by a line marked on the table. After the Eyelink calibration was completed (9 calibration points), participants were presented with a fixation cross in the center of the screen (27-inch monitor [Iiyama ProLite] with a resolution of 2400 × 1350 pixels, 59.9 × 33.8 cm, ±29.6° horizontal visual angle and ±16.9° vertical visual angle relative to the center of the screen) for 2s, before the Cookie Theft image was presented. There were no time constraints, and participants indicated when they were finished with the task. Participants' verbal responses were recorded.

During the presentation of the Cookie Theft image, eye movements were recorded using an Eyelink 1000 (SR Research Ltd Ottawa ON), sampling at 250 Hz, and stored for offline analysis. The Eyelink classification algorithm was used to detect saccades and fixations. We visually inspected fixation plots for all participants.

Demographic and stroke related characteristics

We retrieved age, sex, time since stroke, etiology, neglected side (i.e. L-SN, or R-SN), Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) score, Barthel Index (Collin et al., 1988), and Motricity Index (Collin & Wade, 1990; Kwakkel et al., 1999) from the electronic patient files.

Analyses

Description of inclusion

To identify and remove poor quality recordings, we excluded data from participants who spent less than 50% of their total viewing time fixating on the screen or who spent less than 50% of the fixation time looking at the screen. We established this criterion during the preprocessing of the data prior to conducting any inferential statistics, to exclude cases where there would be too little data available to reliably calculate outcome measures. This criterion resulted in the exclusion of four participants (one control, three L-SN). On average, the excluded cases spent 22.1% of the time fixating on the screen, whilst the included cases spent 74.7%. Did not observe any systematic variation between groups. Furthermore, the data from one person in the L-SN group was missing. The final sample size was therefore 13 in the L-SN group, three in the right-sided spatial neglect (R-SN) group, and six in the control group.

Sixteen people with SN after stroke (M_{age} = 57.4 years, SD = 11.7; 7 female; 14 right handed) participated. On average, they participated 80.3 days post stroke (SD = 36.4, range = 26–164). Thirteen participants were classed as having left-sided spatial neglect (L-SN group), and three as having right-sided spatial neglect (R-SN group). Six age-matched control participants (M_{age} = 54.6 years, SD = 5.1; 5 female) were recruited (control group), who had no history of brain damage.

Pre-processing

The pre-processing of the eye tracking data was done in MATLAB 2020a (The Math Works, Inc), using Edf2Mat toolbox (Etter & Biedermann, 2018) and custom scripts. Statistical analyses were performed in JAMOVI (version 1.6.23; JAMOVI Project, 2020) and in R (3.6.3; R Core Team, 2013) with the psycho package (Makowski, 2018), and figures were produced with the ggplot2 package (Wickham, 2016).

Standard outcome measures of the Cookie Theft task. To evaluate the basic outcome, we report the number of items that L-SN and R-SN groups report and the viewing time. Performance on the Cookie Theft Task did not influence inclusion and was not used to evaluate the neglected side of space.

Evaluating the various eye movement outcome measures. For each participant, we calculated the number of fixations (using the standard Eyelink fixation detection algorithm), their duration, and their location. We removed fixations that were shorter than 80 ms (Heeman et al., 2019), or longer than 2000 ms (e.g. Elshout et al., 2021). We defined the center of the image as ± two degrees visual angle from the center of the horizontal axis. We classed fixations that fell outside this range as being left or right. For each participant, we calculated the ratio of fixations, and the cumulative fixation duration made on the right side of the image, relative to the left. We expressed these ratios as a percentage where 0% indicates that all fixations/all the fixation time was on the left side of the screen, and 100% that they were all on the right side of the screen.

We also calculated the mean horizontal fixation location (e.g. Kaufmann et al., 2020) by averaging the x-coordinates for all the fixations that a participant made. These outcome measures were expressed for the entire viewing time and split into four time-bins (i.e., 0-25%, 26-50%, 51-75%, 76-100% of total viewing time, determined for each individual participant). We expected attentional biases to be most evident in the first time-bin (Pflugshaupt et al., 2004). We therefore include analyses of fixation location and duration for the first time-bin and the overall viewing time.

Each outcome measure was compared between the two spatial neglect groups (L-SN, R-SN) and a control group to establish measures that were indicative of spatial neglect. Due to the relatively small sample size, we only report on inferential statistics for the L-SN group and the control group. We included data from the R-SN group in our figures for descriptive purposes. To compensate for the uneven sample size, we used Welsch's t-tests for between-group comparisons (Delacre et al., 2017) and report Hedge's g^* (Delacre et al., 2021). Given the exploratory nature of the manuscript, we also considered it appropriate to include 95% confidence intervals (CIs) alongside point estimates of effect size (Cumming, 2014; McIntosh, 2017). We considered an alpha below .05 as statistically significant. We did not correct for multiple comparisons. As we lack statistical power to discriminate between ambiguous effects and true null-effects, and to avoid over interpreting non-significant results, we followed recommendations and describe all p-values > .05 as non-significant (Makin & Orban de Xivry, 2019).

Individual-level analysis. We performed individual-level analyses to demonstrate the potential value of our approach when group-level analyses are not sufficient and/or informative (e.g. when making decisions about an individual patient). We used Crawford-Howell t-tests (Crawford & Garthwaite, 2012; Crawford & Howell, 1998) to compare the data from a single patient to the control group. We performed one-sided tests that assume that patients with L-SN will show a rightward bias, relative to controls, and that patients with R-SN would show a leftward bias.

Associations between eye movement measures and clinical measures. For the L-SN group, we explored correlations between the behavioral data and clinical measures indicative of spatial neglect severity.

Results

Standard outcome measures of the cookie theft task

The behavioral data is numerically similar for the L-SN and R-SN groups (see Table 1).

The viewing time was numerically similar for the control group ($M = 205.00$ s, $SD = 34.52$) and left SN group ($M = 219.31$ s, $SD = 120.10$), although people in the right SN group spent comparatively less time viewing the image ($M = 154.67$ s, $SD = 38.08$).

Evaluating the various eye movement outcome measures

First, we examined the viewing behavior at a descriptive level (Figure 1). We created heatmaps showing the number of fixations and their location for each participant (e.g., Figure 1B). However, the visual features of the Cookie Theft image are not perfectly balanced, which limits the practical and/or clinical value of interpreting individual level data without a reference group and requires that left and right SN need to be treated separately. We therefore compared the data of people with SN by expressing the data in the horizontal/x-axis only (i.e., averaging across the vertical/y-axis), and plotted the percentage of fixations by location (Figures 1C, 1D, & 1E) with a 95% confidence interval (CI). This approach can be used to express data from a single participant relative to a reference group (Figure 1C), or to compare two groups (Figure 1D). These results show that both groups attended to many of the same features in the Cookie Theft image, yet the people with left SN tended to show a preference for the information that was further to the right of the image in both visual fields.

When we split the data into four time-bins based on an individual's viewing time (i.e., 0-25%, 26-50%, 51-75%, 75-100% of their total viewing time) we saw the most pronounced differences between groups for the first time-bin (Figure 2). Relative to controls, people with L-SN tended to fixate more on the right side of the Cookie Theft image, and people with R-SN tended to fixate more on the left side.

Table 1. Demographical and task results per group (left-sided spatial neglect [L-SN], right-sided spatial neglect [R-SN]).

Clinical variables	L-SN	R-SN
Group size	13	3
Average age in years (SD)	59.1 (10.9)	50.3 (14.6)
Sex	8 female	1 female
Handedness	12 right-handed	2 right-handed
Time post-stroke in days (SD)	72.7 (31.1)	113.0 (46.5)
Average Shape Cancelation Test (SD)	4,5 (7,3)	16,0 (8,5)
Average Line Bisection Test in mm (abs) (SD)	11,5 (1,3)	16,3 (1,4)
Average Catherine Bergego Scale (SD)	11,6 (9,6)	11,8 (11,6)
No. items identified on left side of Cookie Theft image	2.33 (1.9, range 0–4)	3.50 (0.7, range 3–4)
No. items identified on right side of Cookie Theft image	3.2 (1.6, range 0–4)	3.0 (0.0, range 3-3)
Viewing time on Cookie Theft image in seconds	109.9 (65.6)	65.8 (29.2)

Next, we examined the participants' behavior for the total viewing time of the Cookie Theft image. Due to only having data for three people with R-SN, we did not include them in the subsequent analyses, and report only on group differences between L-SN and controls.

Although people with L-SN showed a preference to the right side of the screen that was numerically greater than that of controls, there were no significant group differences. Specifically, there was no significant difference in the percentage of fixations on the right side of the screen (Figure 3A) between L-SN ($M = 63.4\%$, $SD = 18.4$) and controls ($M = 55.6\%$, $SD = 5.1$), $t_{Welch}(15.3) = -1.42$, $p = .176$, $g^* = -0.64$ [−1.43, 0.16]. There was no significant difference in the percentage of fixation time on the right side of the screen (Figure 3B) between L-SN ($M = 63.3\%$, $SD = 17.9$) and controls ($M = 56.1\%$, $SD = 5.9$), $t_{Welch}(16.2) = -1.31$, $p = .210$, $g^* = -0.51$ [−1.29, 0.29]. There was also no significant difference in the mean fixation location (Figure 3C) between L-SN ($M = 3.76°$, $SD = 5.07$) and controls ($M = 0.61°$, $SD = 1.63$), $t_{Welch}(16.1) = -2.03$, $p = .059$, $g^* = -0.79$ [−1.60,

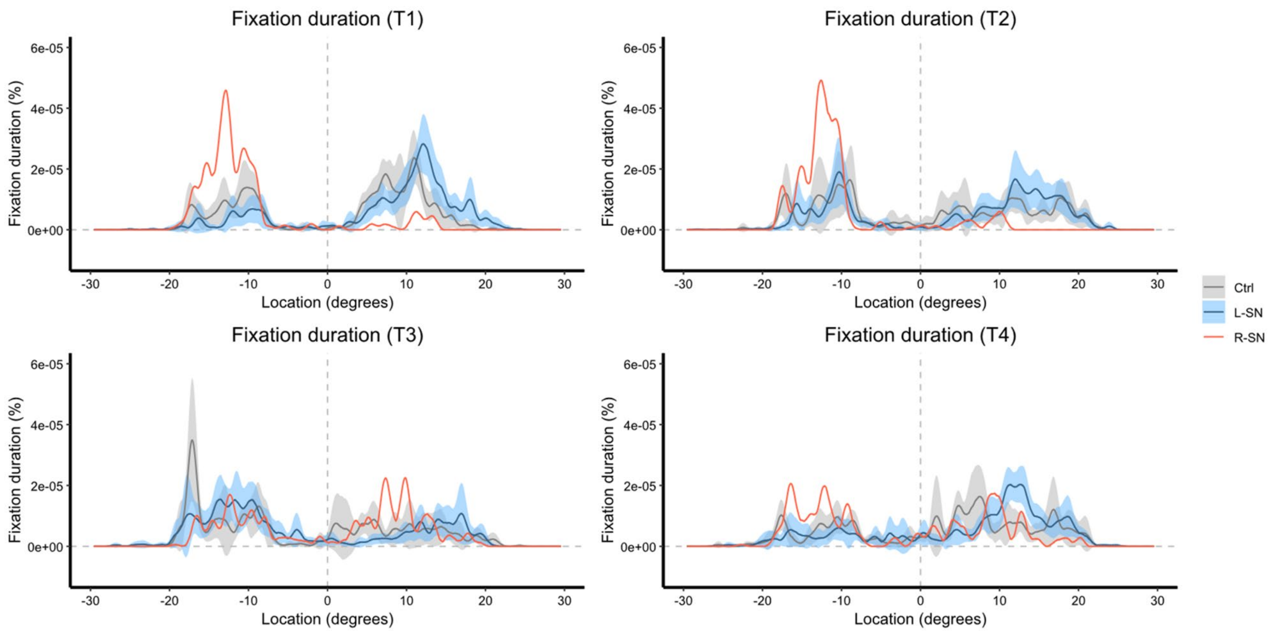

Figure 2. The figures depict fixation duration expressed by their horizontal location for the left-sided spatial neglect (L-SN; n = 13; blue) and control (n = 6; grey) groups with 95% CIs fitted, and for the right-sided spatial neglect group (R-SN; n = 3; red). Each panel depicts one of the four time-bins (i.e., 0-25%, 26-50%, 51-75%, 75-100% of total viewing time for T1, T2, T3, and T4, respectively). The vertical dotted line shows the horizontal center of the image, which separates the left visual field (VF) and the right VF. The horizontal dotted line indicates a value of zero.

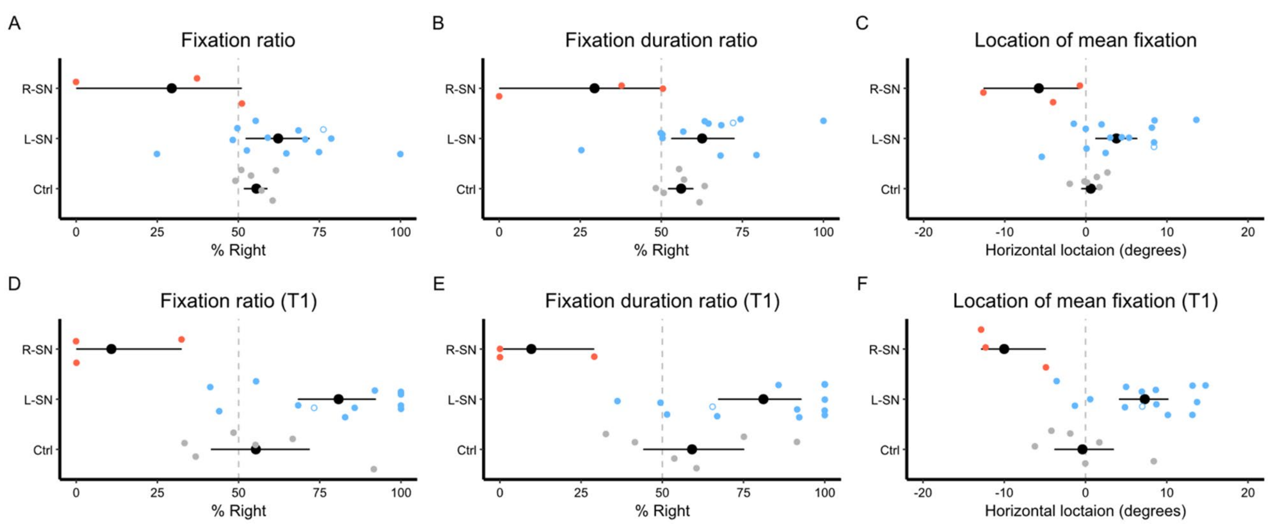

Figure 3. Eye tracking data whilst viewing the Cookie Theft image are depicted, split by Group (left-sided spatial neglect [L-SN; blue], right-sided spatial neglect [R-SN; red], and controls [Ctrl; grey]). Panels A, B, and C show data from the total viewing duration, whereas panels D, E, and F show data from the first time-bin (i.e. the first 25% of the viewing duration). The percentage of fixations made on the right side of the image are expressed for the number of fixations (A, D) and fixation duration (B, E). The average horizontal location of each fixation (C, F) is expressed in pixels. Black dots show the group mean, and the whiskers indicate the 95% confidence interval. The dotted lines show 50% (A, B, D, E) or the center of the screen (C, F). Colored dots show an individual participant's percentage (A, B, D, E) or mean (C, F). The hollow blue dot indicates the patient (Figure 1B,C) included in the individual-level analyses.

0.04]. We therefore did not observe any significant differences in the viewing behavior of people with L-SN and controls for the total viewing time of the Cookie Theft image.

There were more pronounced differences between the two groups when we analyzed the data for the first time-bin. People with L-SN ($M = 80.2\%$, $SD = 21.9$) had a greater percentage of fixations on the right side of the screen during the first time-bin than controls ($M = 55.3\%$, $SD = 21.5$; Figure 4D), $t_{Welch}(9.97) = -2.33$, $p = .042$, $g^* = -1.09$ [−2,06, −0.08]. Although numerically greater, there was no significant difference between L-SN ($M = 79.9\%$, $SD = 23.0$) and controls ($M = 59.2\%$, $SD = 21.9$) in the percentage of the duration spent looking at the right side of the image (Figure 4E), $t_{Welch}(10.4) = -1.91$, $p = .085$, $g^* = -0.88$ [−1.83, 0.09]. There was, however, a significant difference in the mean fixation location during the first time-bin (Figure 4F) between L-SN ($M = 7.29°$, $SD = 5.96$) and controls ($M = -0.37°$, $SD = 5.15$), $t_{Welch}(11.3) = -2.87$, $p = .015$, $g^* = -1.31$ [−2.30, −0.29]. During the first time-bin, people with L- SN made more fixations on the right side of the screen than controls, and that their fixations were further to the right than controls.

For the remaining three time-bins, there were no significant differences between people with left SN and controls on these three outcome measures, $ts_{Welch} \leq 1.21$, $ps \geq .278$.

Individual-level analysis

Eight patients showed a significant bias in the ratio of fixations on the contralesional side of the screen relative to controls (6 L-SN, 2 R-SN), $ts(5) \geq 2.4$, $ps \leq .033$. Six of the patients also showed a bias in the fixation duration ratio, relative to controls (4 L-SN, 2 R-SN), $ts(5) \geq 2.5$, $ps \leq .026$. Eight patients showed a bias in the mean fixation location (6 L-SN, 2 R-SN), relative to controls, $ts(5) \geq 2.2$, $ps \leq .041$. Combining these measures did not improve detection, as there was complete overlap between the patients who significantly differed from controls across the measures.

Associations between eye movement measures and clinical measures

We observed strong correlations between the eye tracking parameters and the CBS for the L-SN group (Figure 4). For the overall viewing time in the L-SN group, there was a significant positive association between CBS and the percentage fixations made on the right side of the image, $r(11) = .67$ [.19, .89], $p = .012$, the percentage of the duration spent looking at the right side of the image, $r(11) = .69$ [.23, .90], $p = .009$, and the mean fixation location, $r(11) = .70$ [.24, .90], $p = .008$. A similar pattern was observed for the first time-bin in the L-SN group, as the CBS scores were

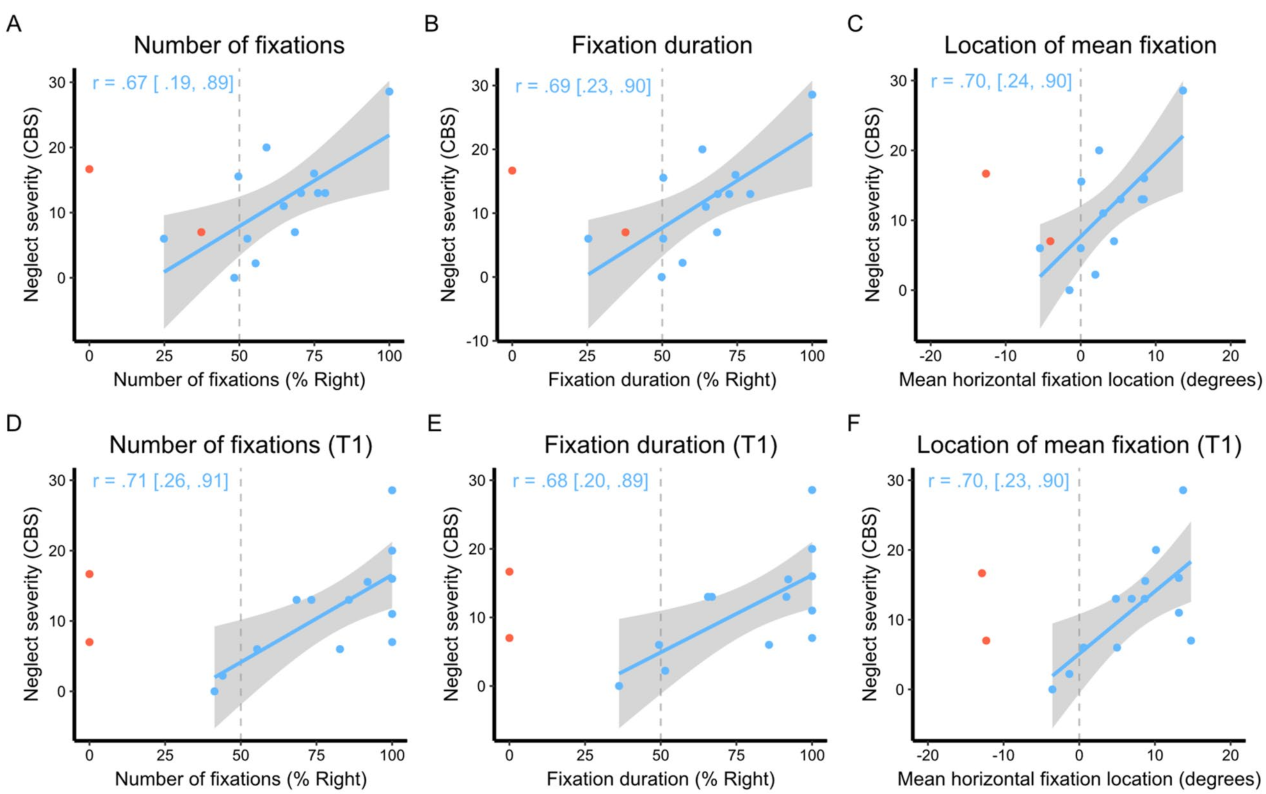

Figure 4. Correlations between eye tracking data and spatial neglect severity (Catherine Bergego Scale [CBS]) are depicted for people with left-sided spatial neglect (L-SN; blue) and people with right-sided spatial neglect (R-SN; red). The y-axis indicates individual level CBS scores (all panels). Panels A, B, and C show data from the entire task, whereas panels D, E, and F show data from the first time-bin (i.e., the first 25% of the viewing duration). The percentage of fixations (A, D) durations (B, E) are shown for the right side of the image. The average horizontal location of each fixation (C, F) is expressed in pixels. The solid line illustrates the slope of the correlation and the shaded area its 95% confidence interval for people with L-SN. The correlation coefficients (i.e., *r*) and its 95% confidence interval (blue text) are presented for people with L-SN. The dotted lines show 50% (A, B, D, E) or the center of the screen (i.e. zero degree visual angle; C, F). Colored dots show individual level data.

significantly correlated with the percentage fixations made on the right side of the image, $r(11) = .71$ [.26, 91], $p = .007$, the percentage of the viewing duration on the right side, $r(11) = .68$ [.20, .89], $p = .011$, and the mean fixation location, $r(11) = .70$ [.23, .90], $p = .008$. We considered that one participant with the highest CBS score (28.6/30) might be skewing these results, although their data was not found to have an extreme influence on the prediction models (i.e., Cook's distance was below typical cutoffs for extreme values). When we excluded this participant from the correlational analyses there were no longer any significant associations between CBS and the eye tracking parameters for the overall viewing time ($rs(10) \leq .51$, $ps \geq .091$). For the first time-bin, the correlations between CBS and eye tracking measures remained significant after excluding the participant with an extreme CBS score ($rs(10) \geq .68$, $ps \leq .016$). These results show that eye-tracking parameters during free exploration of the Cookie Theft image are closely associated to a clinical measure of spatial neglect.

We also observed a positive associations between the eye tracking parameters and star cancelation omissions for the L-SN group (Fig. S1), although these were not statistically significant for the overall viewing time ($rs(11) \leq .52$, $ps \geq .071$) or for the first time-bin ($rs(11) \leq .53$, $ps \geq .061$).

We did not observe any associations between the eye tracking parameters and line bisection scores for the L-SN group (Fig. S2) for the overall viewing time ($rs(11) \leq .16$, $ps \geq .685$) or for the first time-bin ($rs(11) \leq .27$, $ps \geq .375$).

Discussion

We investigated fixation patterns during free exploration of the Cookie Theft image in people with and without SN, with the aim of exploring the benefits of using eye tracking in standard neuropsychological assessments of lateralized attention bias. For people with L-SN, we found that they tended to allocate more attention to the right side of the screen, as indicated by a numerically higher proportion of fixations, proportion of fixation time, and the mean fixation location, relative to controls. These differences were not statistically significant when we analyzed fixations from the entire task. When we looked at the first time-bin (i.e., the first 25% of a participant's viewing time) people with left spatial neglect had a greater proportion of fixations on the right side of the screen, and the location of their mean fixation was further to the right than controls. We also showed that some of these differences were evident in individual-level analyses, when we analyzed data from one participant relative to the control group. The tendency to allocate more attention to the right side of the screen was correlated with spatial neglect severity. Specifically, we found strong correlations between CBS scores and proportion of fixations on the right, proportion of fixation time on the right, and the mean fixation location for people with left spatial neglect. These findings were mirrored for people with right spatial neglect, although these data were only explored at a descriptive level due to the small sample size. In line with previous research (e.g. Primativo et al., 2015; Upshaw et al., 2019), our findings therefore show that measuring eye movements during a standard neuropsychological assessment of lateralized attention bias enables relatively simple metrics to be derived, which are relevant to the clinical manifestation of SN.

Interestingly, both fixation outcome measures (proportion of lateralized fixations and location of mean fixation) were able to distinguish between people with L-SN from the control group, but only during the initial phases of exploration. This finding highlights the importance of a (relatively) fine-grained temporal analysis of eye movement behavior during neuropsychological assessment, also when only a single trial is used. It is well-known that the initial phases of exploration are dominated by bottom-up information, with top-down factors (such as compensation strategies) having an influence on behavior only later during exploration (for a review, see van Zoest et al., 2017). Because rehabilitation is aimed at introducing compensation strategies (e.g. Longley et al., 2021), subtle behavioral differences between people with and without SN might not become apparent when taking an entire trial into account, especially during the more chronic phases in which people with SN receive extensive training (Nijboer et al., 2013). Although the present study only reports the results of one neuropsychological test, it is likely that similar spatial asymmetries in other neuropsychological tests might also only be present during the initial phases of behavior, especially given that all neuropsychological tests are subject to compensatory strategies (Bonato, 2012). Alternatively, experimental tests have been developed that are sensitive to early orientation of attention in SN (e.g. Pflugshaupt et al., 2004).

Our study suggests that eye tracking can give added benefit to neuropsychological assessments of lateralized attention bias, consistent with previous research (e.g. Upshaw et al., 2019). At a descriptive level, relatively simple metrics can be computed that quantify lateralized attention biases, even from a single trial. We also found that these metrics were associated with spatial neglect severity (i.e. CBS scores; Azouvi et al., 2003; Bergego et al., 1995), which suggests that they are relevant to the clinical manifestation of SN. These findings are consistent with previous research showing an association between eye movements and spatial neglect severity (e.g. Kaufmann et al., 2020; Kudo et al., 2021). Our study extends these findings by showing that such associations can be detected in a single trial and are evident at an individual level, thus placing minimal demands on patients' time. A strength of our study is that the eye tracking was embedded in a routine neuropsychological assessment, using a single trial with stroke patients. Therefore, no additional experimental tasks were required to obtain the current findings, providing the opportunity to apply these techniques in the (relatively) acute phase post stroke. The early phase is the most pressing for rehabilitation (Nijboer et al., 2013), and correctly identifying SN and its subtypes has direct implications for treatment and recovery (Spaccavento et al., 2017). It is therefore important to find sensitive measures of attention bias that can be implemented at this stage, (Spaccavento et al., 2017), which further highlights the potential value of incorporating eye tracking measures into routine assessment of SN. By following the clinical progression of patients and any changes in their attention bias, prediction models for recovery could be developed, and thereby inform clinical decision-making (e.g. individualized rehabilitation strategies, or discharge planning). Our study also serves as a proof-of-concept, demonstrating that eye tracking can be implemented in routine clinical practice. One limitation of the Cookie Theft task is the imbalance of the visual features of the image, which requires that left and right SN need to be treated separately. Furthermore, due to our small sample size we have only visually analyzed the patterns seen in patients with R-SN.

When relating the eye movement metrics to more traditional neuropsychological outcome measures, we observed that outcome measures of the line bisection test did not correlate with these measures of attention allocation, in contrast to the CBS and the star cancelation tests (albeit not statistically significant for the latter task). This finding is reminiscent of results of earlier studies in which the strength of spatial biases observed in an experimental task correlated significantly with asymmetries on an object cancelation test, but not with a line bisection test (e.g. Van der Stigchel & Nijboer, 2018). Such observations are generally explained by differences in the underlying mechanisms required for successful performance on these two types of tests: in contrast to shape cancelation tests, successful performance on line bisection tests depends primarily on an object-based, allocentric representation of space, unrelated to any spatial bias in the detection of elements in the contralesional visual field (McIntosh et al., 2017). It is therefore likely that the attention allocation measures reported here predominantly reflect space-based neglect, and not object-based neglect. This line of thinking aligns with proposals to consider SN a syndrome with strong individual differences, determined by lesion extent and location (e.g. Corbetta & Shulman, 2011; Husain, 2019). According to these ideas, different outcome measures should index different aspects of the neglect syndrome.

Although eye tracking paradigms may be sensitive enough to be a diagnostic tool for SN (Kaufmann et al., 2021), there are benefits to integrating it into conventional neuropsychological assessments. Clinical practice presents a less controlled environment than a research setting, which could make it more likely for issues to arise with the accuracy and precision of the eye tracking data, for instance, due to errors with calibration, issues with the stability of pupil detection, and variable lighting conditions (Carter & Luke, 2020). For instance, data from 3 out of 19 patients had to be removed due to poor quality in our study, which illustrates the potential challenge of integrating eye tracking into routine clinical assessment. The small sample size also limits the conclusions that can be drawn. Future research should include more balanced group sizes and collect normative data for cognitive measures of SN and their associated eye tracking metrics, to facilitate individual level analyses. The combined use of conventional assessment tools may thus serve as a way of detecting poor eye tracking data whilst also retaining important diagnostic information (Cox & Davies, 2020). Furthermore, combining eye tracking with conventional assessment tools is in light with recent recommendations to combine multiple measurements of spatial neglect to overcome limitations with the validity and reliability of any single measure. To further overcome limitations of the current study, ecological measures of attention (e.g. using portable eye tracking glasses during dynamic assessments of SN; Ten Brink et al., 2016), and neuroimaging measures (e.g. lesion mapping) could be used in combination with conventional measures of spatial neglect with combined eye tracking.

Conclusion

With eye tracking techniques becoming more accessible (both technically and financially), adding eye tracking recordings to standard neuropsychological assessment is expected to increase. One clear benefit of eye tracking is the lack of intrusion during the assessment, especially compared to other psychophysiological measures, such as EEG (electroencephalogram). Eye tracking outcome measures provide insight into the current content of visual working memory (Van der Stigchel & Hollingworth, 2018), arousal levels (e.g. via the pupil; Strauch et al., 2022; Ten Brink et al., 2023), and the location of covert attention (Carrasco, 2011). Recent studies have used novel machine learning techniques to successfully predict whether a participant belonged to a stroke or the control group, for instance during exploring a virtual supermarket (Brouwer et al., 2022). Although these studies make clear that eye movement data contain a rich set of signatures for detecting cognitive deficits, revealing which features are most important to distinguish different groups can be difficult using these techniques. Therefore, combining novel machine learning approaches with detailed exploration of behavior (as in the current study) might provide promising development for analyzing eye movements during neuropsychological assessments.

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Data availability statement

Due to the nature of the research, supporting data is not available.

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