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Behavioural Neurology

Eyetracking during free visual exploration detects neglect more reliably than paper-pencil tests

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ABSTRACT

Neglect after stroke is most accurately diagnosed by a systematic, ecological observation during everyday behaviour using the Catherine Bergego Scale (CBS). However, the CBS is time-consuming and often omitted in clinical settings, especially stroke units. In this study, we aimed to explore if video-oculography during free visual exploration (FVE), which can be performed in few minutes, is sensitive in mirroring neglect in everyday behaviour and whether it is more sensitive than conventional neuropsychological paper-pencil tests. In this retrospective, observational, multicentre study, we identified 78 patients in our database with subacute right-hemispheric stroke, with and without neglect in everyday behaviour, diagnosed by the CBS, who also performed FVE. 40 age-matched healthy participants served as controls. The sensitivity to detect neglect was compared between FVE (i.e., mean gaze position on the horizontal axis) and conventional neuropsychological paper-pencil tests, i.e., Random Shape Cancellation, Line Bisection, Two-Part Picture, Bells, Star Cancellation, Letter Cancellation, Sensitive Neglect, and Five-Point. FVE correctly identified neglect in 85%of patients, with an AUC-value of .922 in ROC-analysis. Conventional neuropsychological paper-pencil tests, considered alone or in combination, showed heterogeneous results, and identified neglect significantly less often (21.74%–68.75%). Moreover, there was a significant correlation between mean gaze position and CBS scores, providing evidence for the relationship between FVE and neglect in everyday behaviour. Furthermore, VLSM analyses suggested that the absence of a pathological rightward bias in FVE might depend on the integrity of the second branch of the right Superior Longitudinal Fascicle (SLF II), a white-matter tract connecting cortical areas critical for visual attention. Video-oculography during FVE has a high sensitivity and specificity to diagnose neglect after stroke and it is more sensitive than conventional neuropsychological paper-pencil tests. It can be performed in short time and has the potential to be used as a fast

Abbreviations: AUC, Area under the Curve; CBS, Catherine Bergego Scale; CoC, Center of Cancellation; FVE, Free Visual Exploration; ROC Analysis, Receiver Operating Characteristic Analysis.

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and accurate screening tool that allows the initiation of comprehensive neuropsychological diagnostics and therapy from early on.

1. Introduction

Spatial neglect is characterised by the failure to attend or respond to the contralesional hemispace and is a strong, negative predictor of functional outcome after stroke (Heilman, Watson, & Valenstein, 1993; Nijboer, van de Port, Schepers, Post, & Visser-Meily, 2013; Nijboer, Kollen, & Kwakkel, 2014). Neglect has been reported to occur in 43–80% of patients after acute, right-hemispheric stroke and in 20–62% of patients after left-hemispheric stroke (Azouvi et al., 2002; Ringman, Saver, Woolson, Clarke, & Adams, 2004; Stone et al., 1991). One of the causes of this considerable variability in neglect detection rates lies in the inhomogeneity of assessment methods, which present with substantial differences in their sensitivity (Azouvi et al., 2006; Lindell et al., 2007). Neuropsychological paper-pencil tests are administered in a structured manner and require voluntary, top-down orienting of attention, that may partly lead to a compensation of neglect-related deficits (Bonato, 2012). Correspondingly, a systematic, ecological observation during everyday behaviour, i.e., with the Catherine Bergego Scale (CBS) (Azouvi et al., 2003), during which the role of automatic, bottom-up orienting of attention is more important (Azouvi, 2017), has been shown to be more sensitive in detecting neglect (Azouvi et al., 2003). The implementation of the CBS often requires extensive observations, which might be time-consuming and delay appropriate therapeutic interventions, and which might not be realisable in all clinical settings such as stroke units. Hence, a screening tool with shorter and easier administration, but which sensitively predicts and correlates with neglect in everyday behaviour, would be helpful.

Therefore, in the present study, we aimed to test the sensitivity of eye movement measurement during Free Visual Exploration (FVE) in detecting neglect in everyday behaviour, based on the fact that this task relies on automatic, bottom-up orienting of attention, similarly to everyday behaviour itself (Paladini et al., 2019; Pflugshaupt et al., 2004). To this end, we compared the sensitivity of video-oculography during FVE and of various, conventional neuropsychological paper-pencil tests, in a sample of 78 right-hemispheric subacute stroke patients, who were diagnosed with neglect or not according to their everyday behaviour, by means of the CBS.

Additionally, voxel-based lesion-symptom mapping (VLSM) was used to investigate the neural correlates between eye movement measurements and the area of brain lesion.

2. Materials and methods

2.1. Participants

This is a retrospective, observational study, including 78 patients [age: mean = 64.68, SD = 15.376 years; 58.97% male, 73 patients were right-handed (3 left-handed, 2 ambidextrous)] with or without left-sided spatial neglect after a first right-hemispheric subacute stroke (time since stroke: mean = 18.284 days, SD = 35.741; lesion overlay Fig. 1), who were treated at the Luzerner Kantonsspital and the Inselspital Bern, Switzerland. Forty age-matched healthy participants [age: mean = 64.675 years, SD = 14.942; 53% male, 35 right-handed (4 left-handed, 1 ambidextrous)] served as controls (no age difference between patients and controls; $t(116) = .002$, $p = .999$).

Inclusion criteria were a first ever right-hemispheric stroke, normal or corrected-to-normal visual acuity, signature of informed consent, and the availability of data concerning video-oculography, Random Shape Cancellation Test, Line Bisection Test, Two-Part Picture Test, as well as MRI (see also Fig. 2. Participants' inclusion flow-chart). Patients with a psychiatric disease were excluded.

In right-hemispheric stroke patients, neglect behaviour in everyday life was assessed with the CBS. In right-hemispheric stroke patients with neglect (n = 60) the mean total CBS score was 12.27 (SD = 7.83, range = 1–28), reflecting mild to moderate neglect in everyday behaviour (Azouvi et al., 2003).

Informed consent was obtained from all participants (i.e., patients and healthy controls) and was an inclusion criterion. The study was approved by the local Ethics Committees and was performed according to the latest version of the Declaration of Helsinki.

2.2. Video-oculography

Video-oculography was used to assess the spatial distribution, on the horizontal plane, of visual fixations during FVE, a paradigm that has repeatedly been used to analyse visual attentional allocation (Cazzoli, Nyffeler, Hess, & Müri, 2011; Fellrath & Ptak, 2015; Kaufmann et al., 2020; Müri et al., 2013; Nyffeler et al., 2008; Osandón et al., 2012; Paladini et al., 2019; Pflugshaupt et al., 2004; Ptak, Golay, Müri, & Schnider, 2009). Hereby, 12 images of natural scenes or urban public places, and their 12 mirrored versions (mirrored along the vertical axis) were presented on a screen (Paladini et al., 2019). Each of the images was presented for 7 sec, and was preceded by a central, black fixation-cross on a grey background (1 sec), in order to enforce a common

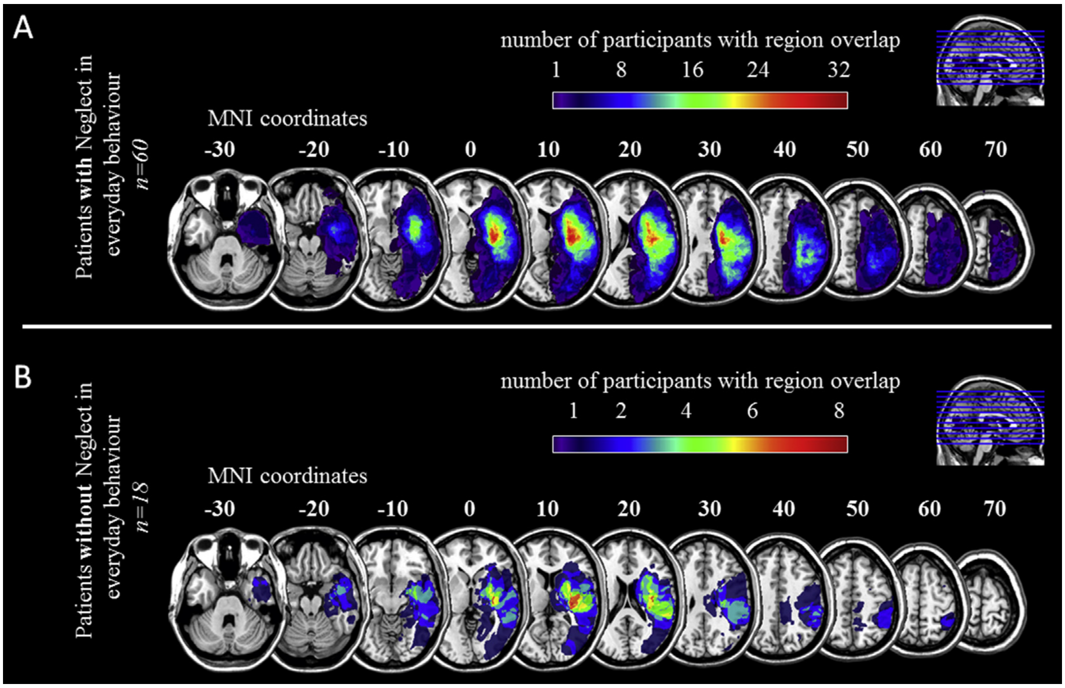

Fig. 1 – Lesion overlay of patients with neglect in everyday behaviour after right-hemispheric stroke (n = 60. Panel A) and without neglect in everyday behaviour (n = 19, Panel B). The color-coded legend is determined by the number of patients with damage to a specific brain region. Lesion overlap maps are plotted on the CH2 template available in MRIcron (http://www.mccauslandcenter.sc.edu/crnl/tools). Axial slices are oriented according to the neurological convention. The z-position of each axial slice, in MNI coordinates, is indicated by the numbers at the top of the figure, and also depicted by the blue lines on the sagittal slice.

central starting point of visual exploration for all participants. All participants were instructed to freely explore the images. In total, one session of video-oculography took less than 10 min, including the explanation of the task as well as the 3 × 3 points grid calibration and validation of the eye-tracking systems prior to the experiment. During video-oculography, participants were seated in front of the screen. Their head was positioned on a chin-and-forehead rest, to both ensure that their mid–sagittal plane was aligned with the middle of the screen at a constant distance, and to minimise head movements. Eye movements were recorded using a remote, infrared-based, video-eye-tracking system (T120, TobiiTechnology, Stockholm, Sweden or Eye-Link 1000Plus System, SR Research, Ottawa, Canada; Compatibility of eye-movement data between the two systems was tested in healthy controls, which revealed no difference in mean gaze position on the horizontal axis [2-tailed independent t-test; t (38) = .574, p = .570)]. All fixations with a duration between 100 and 2000 msec were included in the fully automated off-line data analyses (fixations excluded = 6.252%; Carpenter, 1988; Salthouse & Ellis, 1980). After initial implementation of the R script, individual results for FVE data can be calculated within seconds.

First, the mean gaze position in FVE was compared between patients with and without neglect and with healthy controls, by means of a univariate ANOVA.

In order to assess whether neglect indexes in FVE (mean gaze position) would be related to neglect behaviour in everyday life (CBS score), Pearson's correlations between these variables were computed (2-tailed) in right-hemispheric stroke patients with neglect in everyday behaviour.

In FVE, the presence of neglect was defined according to the spatial distribution of fixations, i.e., when a patient presented with a mean gaze position on the horizontal axis of at least 2.326 SDs above the average of healthy controls (higher values indicating a rightward-shifted spatial distribution of fixations), resulting in a cut-off of >1.627°. In an additional analysis, we assessed early attentional orientation during FVE (Pflugshaupt et al., 2004). Hereby, the landing point of the first fixation on each picture (left or right screen half) was determined, and the proportion of left- and rightward first fixations was computed for every participant. Since early attentional orienting in healthy participants preferentially occurs towards the left hemifield (Pflugshaupt et al., 2004), neglect was defined as present if, in a particular patient, the proportion of leftward first fixations was at least 2.326 SDs below the average of healthy controls, resulting in a cut-off of <31.187%. By choosing a SD of 2.326 to define our cut-off values for FVE indexes (i.e., mean gaze position and proportion of leftward first fixations), we assured a predicted cumulative probability of 99% that the values of a given healthy control subject would be found within this range cut-off threshold. Furthermore, we used Receiver Operating Characteristic (ROC) analyses in order to critically assess the cut-off classifiers based on the mean gaze position (±2.326 SD) in healthy controls, as well as in order to evaluate the

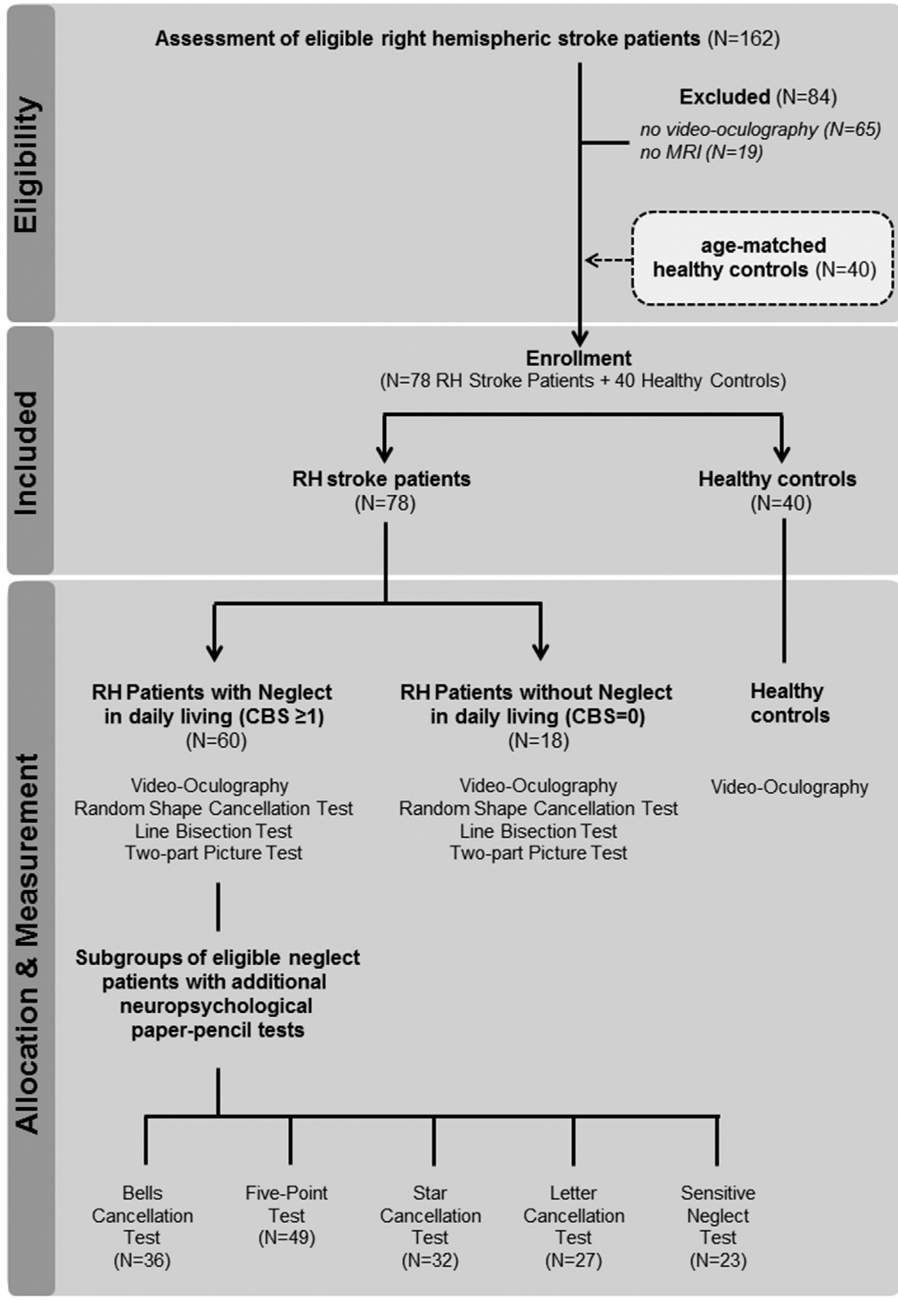

Fig. 2 – Participants' inclusion flow-chart.

discriminating power of FVE indexes and of neuropsychological paper-pencil tests in right-hemispheric stroke patients with and without neglect in everyday behaviour. Hereby, the classifier performance was depicted by means of the area under the curve (AUC), representing the expected performance (Fawcett, 2006).

2.3. *Neuropsychological paper-pencil tests*

All 78 stroke patients were administered with three conventional neuropsychological paper-pencil tests that are generally used in the neglect test battery in both involved neurorehabilitation clinics: Random Shape Cancellation Test (Weintraub & Mesulam, 1988), Line Bisection Test (Wilson, Cockburn, & Halligan, 1987a), and Two-Part Picture Test (Brunila, Jalas, Lindell, Tenovuo, & Hamalainen, 2003) (mean time point for neuropsychological paper-pencil assessment = 1.949 days (SD = 8.962) before FVE). The presence of neglect was defined according to current, established cut-offs for these tests: Random Shape Cancellation CoC>.081 (Weintraub & Mesulam, 1988), Line Bisection mean relative rightward deviation of>11% (Wilson et al., 1987a); Two-Part Picture Asymmetry Score of<.46 (Brunila et al., 2003).

To compare the diagnostic accuracy of FVE and neuropsychological paper-pencil tests in classifying right-hemispheric stroke patients with and without neglect in everyday behaviour, the area under the curve (AUC) was calculated by means of ROC analyses and compared between tests (Fawcett, 2006; Swets, Dawes, & Monahan, 2000).

Furthermore, in our data base additional neuropsychological paper-pencil tests were documented in some of the neglect patients (please, see respective n below). Thus, these tests were included in an additional analysis, comparing FVE and conventional neuropsychological tests in the respective subgroups. The presence of neglect in the additional neuropsychological paper-pencil tests was defined according to current, established cut-offs: Bells [n = 36, CoC>.081 (Gauthier, Dehaut, & Joanette, 1989; Rorden & Karnath, 2010)], Letter Cancellation [n = 27, CoC>.083 (Rorden & Karnath, 2010; Weintraub & Mesulam, 1985)], Star Cancellation [n = 32, CoC>.08 (Wilson et al., 1987a)], Five-Point [n = 49, CoC>.081 (Kaufmann et al., 2018; Regard, Strauss, & Knapp, 1982)], Sensitive Neglect [n = 23, single version CoC>.081, dual version CoC>.118 (Reinhart, Leonhard, & Kerkhoff, 2016)].

2.4. Data analysis

In patients with neglect in everyday behaviour as measured with the CBS, we assessed how sensitive video-oculography during FVE is as a test for detecting neglect. To this end, the detection rate (i.e., % of patients in whom neglect was detected), as defined by means of the mean gaze position during FVE, was compared to the detection rate as defined by the common, above-mentioned neuropsychological paper-pencil tests.

In a subsequent analysis, early attentional orienting during FVE [i.e., the direction of the first fixation, leftward or rightward (Pflugshaupt et al., 2004)] was compared to early attentional orienting during Random Shape Cancellation Test performance (i.e., the starting point, in terms of the first cancellation).

To compare the detection rates between FVE and neuropsychological paper-pencil tests, we used the exact McNemar's test for dichotomous data (2-tailed).

All statistical analyses were performed using SPSS (IBM Corp, Released 2017, IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp). For all statistical tests, a significance level of $\alpha = 5\%$ was used.

In order to investigate the neuroanatomical underpinnings of neglect severity as assessed by FVE, lesion maps of neglect patients were analysed using voxel-based lesion-symptom mapping (VLSM), which is part of the freely available NPM software (https://www.mccauslandcenter.sc.edu/crnl/). Hereby, lesion correlates of the mean gaze position (in degrees of visual angle) and the proportion of pictures with early orientation towards the right (in %) were analysed using the Brunner–Munzel test for continuous data. Only voxels that were lesioned in at least 20% of the patients were included. The significance threshold was adjusted by means of a false discovery rate (FDR) correction. As proposed by Medina and colleagues (Medina, Kimberg, Chatterjee, & Branch Coslett, 2010), multiple comparisons were controlled for using a permutation-based thresholding (Kimberg, Coslett, & Schwartz, 2007), applying 4000 iterations.

3. Results

3.1. Neglect patients show a rightward shift in free visual exploration

78 right-hemispheric stroke patients meeting the inclusion criteria (i.e., availability of data concerning video-oculography, Random Shape Cancellation Test, Line Bisection Test, Two-Part Picture test, and MRI) were retrospectively identified in our database.

60 of these patients presented with neglect in everyday behaviour (i.e., CBS ≥1), and 18 patients did not (CBS = 0). 57 patients presented with ischaemic and 21 with haemorrhagic stroke. 25 patients showed left visual field defects as assessed by means of Goldman-Perimetry (isopter III/4; 15 incomplete Hemianopia, 10 Quadrantanopia).

An univariate ANOVA revealed a significant group difference in the mean gaze position during FVE ($F(2, 50.792) = 45.339$, adjusted by means of the Welch-test, partial $\eta^2 = .879$, corresponding to a large effect; Fig. 3a). Bonferroni-corrected post-hoc analyses revealed a significant horizontal shift of the mean gaze position towards the right screen half in patients with neglect in everyday behaviour (mean = 4.266°, SD = 3.379°) as compared to healthy controls (mean = −.013°, SD = .705°) and to right-hemispheric stroke patients without neglect in everyday behaviour (mean = −.031°, SD = .846°).

3.2. Free visual exploration results are related to neglect behaviour in everyday life

Pearson's correlations showed a significant relationship between mean gaze position during FVE and 9 out of the 10 CBS items (Table 1). No significant correlation was found between mean gaze position and CBS item 4 ("Forgets to clean the left side of mouth after eating"), which reflects personal neglect. A strong correlation was also found between mean gaze position and the total CBS score ($r = .563$, $p < .001$). Overall, patients with a more pronounced rightward shift in FVE showed more severe neglect signs during everyday behaviour (Fig. 3b). In addition, Pearson's correlations between the mean gaze position in FVE and the *conventional neuropsychological tests* scores evidenced significant relationships, with correlation values varying from small-medium to strong (Random Shape Cancellation Test: $r = .593$, $p < .001$; Line Bisection Test: $r = .277$, $p = .032$, Two-Part Picture Test: $r = -.442$, $p < .001$). Scatterplots depicting the Pearson's correlation between the mean gaze position during FVE and single CBS items in right-hemispheric stroke patients with neglect are presented in the Supplementary material.

3.3. ROC analyses

The ROC analyses for the mean gaze position in FVE showed that our cut-off of 2.326 SD is indeed too conservative and that the cut-off needed to be reduced to 1.333°. ROC analysis confirmed the validity of our new cut-off of 1.333°, showing a sensitivity of 85.0% and a specificity of 94.4%. Hereby, positive and negative predictive values were optimal, with 98.1% and 65.4%, respectively.

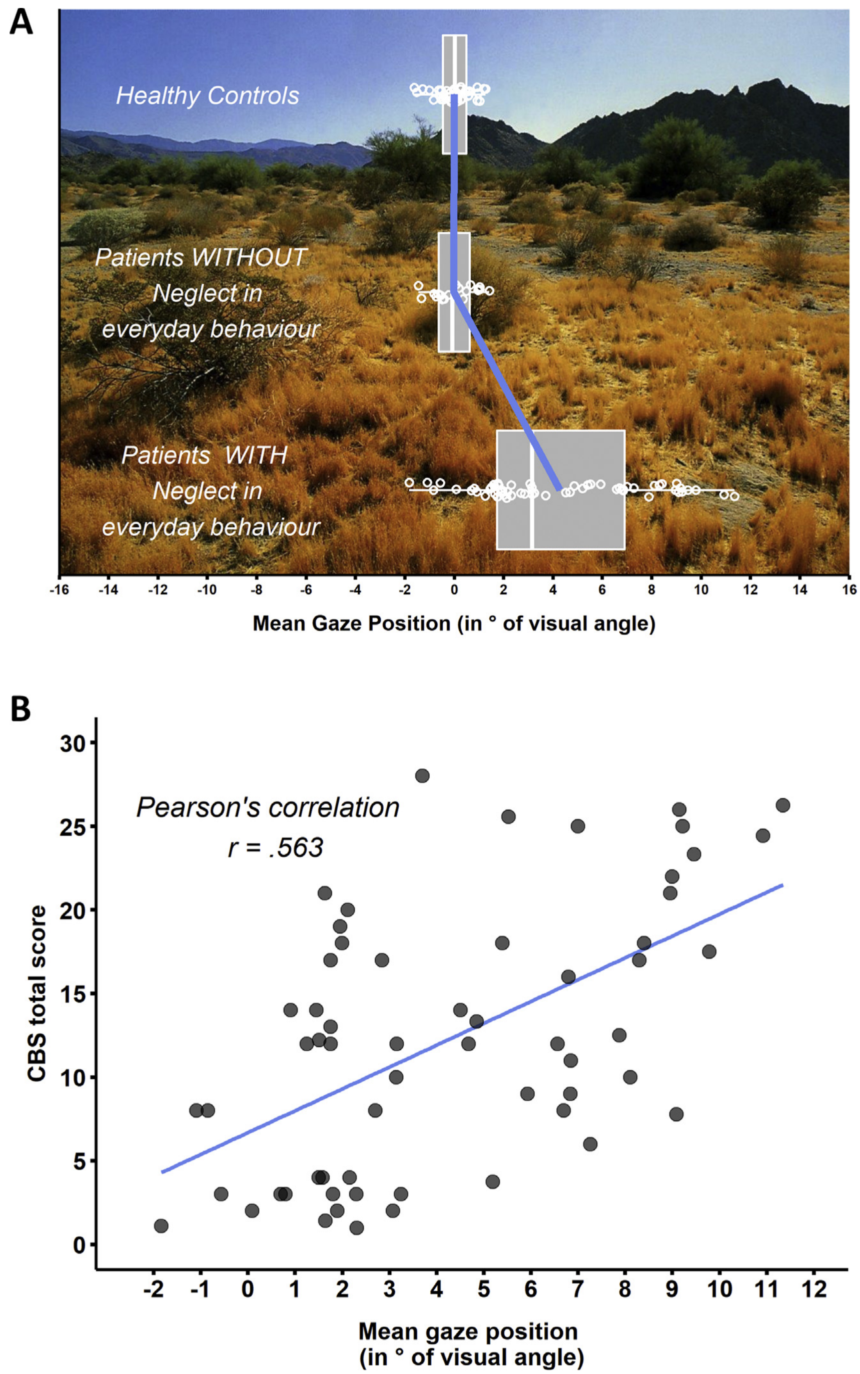

Fig. 3 – (A) Whisker plots for the mean horizontal gaze position (in ° of visual angle) compared between right-hemspheric stroke patients with ($n = 60$) and without ($n = 18$) neglect in everyday behaviour, and healthy controls ($n = 40$). Mean values per group are indicated by the blue line, and individual data by white dots. Each box represents the lower (Q1) to the upper (Q3) quartiles, with whiskers extending to the minimum and maximum of 1.5 times the interquartile range. An exemplary image, used in the FVE paradigm, is shown in the background. (B) Depiction of the Pearson's correlation between the mean gaze position during FVE and the CBS total scores in right-hemispehric stroke patients with neglect. The regression line is shown in blue. Grey dots represent the patients' individual CBS total scores (y-axis) and the corresponding mean gaze position during FVE (x-axis).

The ROC analyses for the early orientation in FVE (cut-off of 2.326 SD above norms) showed a sensitivity of 83.3% and a specificity of 61.1%. Hereby, positive and negative predictive values were 87.7% and 52.3%, respectively.

Furthermore, ROC analyses revealed excellent AUC values for mean gaze position in right-hemispheric stroke patients (AUC = .922), followed by Early Orientation in FVE (AUC = .891), Random Shape Cancellation Test CoC

Table 1 – Correlations between FVE (mean gaze position in ° of visual angle) and CBS Items.

CBS item	Description	Pearson's correlation (r) with mean gaze position in FVE (in ° of visual angle)	*p*-values
1	Forgets to groom or shave the left part of face	.285	.027*
2	Experiences difficulty in adjusting left sleeve or slipper	.485	.000***
3	Forgets to eat food on the left side of plate	.476	.000***
4	Forgets to clean the left side of mouth after eating	.224	.085
5	Experiences difficulty in looking towards the left	.536	.000***
6	Forgets about a left part of body	.518	.000***
7	Has difficulty in paying attention to noise or speech from the left	.396	.002**
8	Collides with people/objects on the left side	.466	.000***
9	Experiences difficulty in finding way towards the left when traveling in familiar places or in the rehabilitation unit	.347	.007*
10	Experiences difficulty finding personal belongings in the (bath)room/ when they are on the left side	.502	.000***
Total score		.563	.000

(AUC = .781), Two-Part Picture Test (AUC = .751), Line Bisection Test (AUC = .687), and Early Orientation in Random Shape Cancellation Test (AUC = .681; Fig. 4).

3.4. *Video-oculography is significantly more sensitive in detecting neglect in everyday behaviour than neuropsychological paper-pencil tests*

Using a cut-off of 1.333° for the mean gaze position in FVE, 85% of the neglect patients were correctly identified. Significantly less neglect patients were detected using single *conventional neuropsychological tests*, such as the Line Bisection (detection rate 41.67%; McNemar's Test $p < .001$), Two-Part Picture (detection rate 46.67%; McNemar's Test $p < .001$), and Random Shape Cancellation (detection rate 51.67%; McNemar's Test $p < .001$).

A combination of two or three of these *conventional neuropsychological tests* detected neglect more often (detection rate of 60%–68.3%) than any single neuropsychological test alone (Fig. 4). However, significantly more neglect patients were correctly identified using FVE compared to any combination of two neuropsychological paper-pencil-tests (McNemar's test; Line Bisection and Two-Part Picture $p = .003$; Random Shape Cancellation and Two-Part Picture $p = .001$; Random Shape Cancellation and Line Bisection $p = .003$) or a combination of three neuropsychological paper-pencil-tests ($p = .031$).

Significantly more neglect patients were detected by assessing early orientation during FVE (83.33%) than during Random Shape Cancellation (68.33%; McNemar's Test $p = .049$; Fig. 5).

3.5. *Additional neuropsychological tests*

In different subgroups of patients, which received *additional neuropsychological tests* such as the Bells, Five-Point, Star Cancellation, Letter Cancellation, and Sensitive Neglect, the detection rate of neglect was investigated. While the neglect detection rate based on these additional tests showed heterogeneous results in the different subgroups of patients (ranging from 21.74% to 68.75%), the neglect detection rate based on video-oculography was always found to be higher and more consistent (ranging from 77.78 to 93.75%, Fig. 5).

The proportion of neglect patients detected by FVE was significantly higher than the proportion detected by any of the *additional neuropsychological tests* (McNemar's test; FVE *vs* Bells $p = .012$; FVE *vs* Five-Point $p = .001$; FVE *vs* Star Cancellation $p < .001$; FVE *vs* Letter Cancellation $p = .012$; FVE *vs* Sensitive Neglect: single $p = .004$, dual $p = .039$).

3.6. *Neuroanatomical underpinnings of neglect severity as assessed by free visual exploration*

A VLSM analysis of continuous behavioural data concerning the mean gaze position did not reveal any significant results. However, the analysis of continuous behavioural data concerning early orientation (i.e., % of pictures with early orientation to the left) revealed a significant lesion cluster (186 Voxels; Brunner–Munzel test; false discovery rate, FDR-corrected, significance threshold of .05; 4000 permutations), located within the second branch of the right superior longitudinal fasciculus (SLF II; MNI coordinates 25, -9, 36; see Fig. 6). Correspondingly, patients who initially oriented their attention more frequently towards the right hemifield, were significantly more likely to present with a lesion within the right SLF II.

4. Discussion

In the present study, we demonstrate that video-oculography during FVE: a) is able to detect significantly more patients who present with neglect in everyday behaviour than any of the single conventional neuropsychological paper-pencil tests, or even combinations thereof; and, b) is significantly related to neglect as observed in everyday behaviour. Furthermore, while the sensitivity of the different neuropsychological tests substantially varies in different neglect patient subgroups, it remains constantly high in FVE. This suggests that FVE may be used as an accurate neglect screening tool in stroke patients that allows the initiation of comprehensive neuropsychological diagnostics and therapy from early on. Furthermore, VLSM analyses suggested that the absence of a pathological rightward bias in FVE might depend on the integrity of the second branch of the right

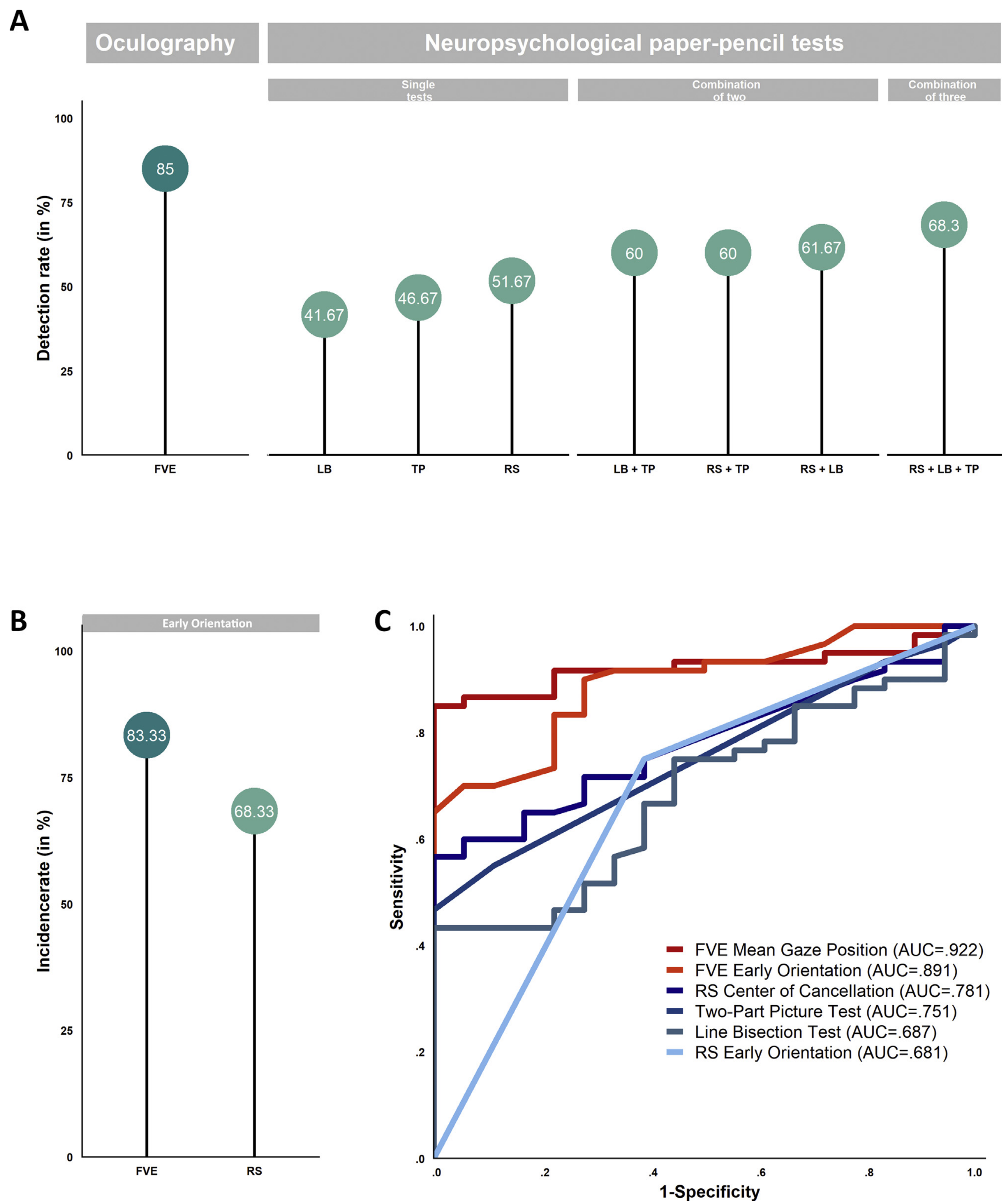

Fig. 4 – (A) Neglect detection rate based on video-oculography during FVE (mean gaze position in ° of visual angle) was significantly higher compared to the ones of three conventional neuropsychological paper-pencil tests (Random Shape (RS), Line Bisection (LB), Two-Part Picture (TP); McNemar's test $p < .001$), alone or in combination (combination of two, McNemar's test $p \leq .003$; combination of three, McNemar's test $p = .031$), in a sample of sixty neglect patients. (B) Neglect detection rate based on video-oculography compared between early orientation in FVE (the landing point, left or right screen half, of the first fixation on each picture) and early orientation in the Random Shape Cancellation Test (RS). The proportion of neglect patients detected by early orientation in video-oculography was significantly higher than the proportion detected by early orientation in Random Shape Cancellation test (McNemar's test, $p = .049$). (C) ROC analyses curves for the different tests;

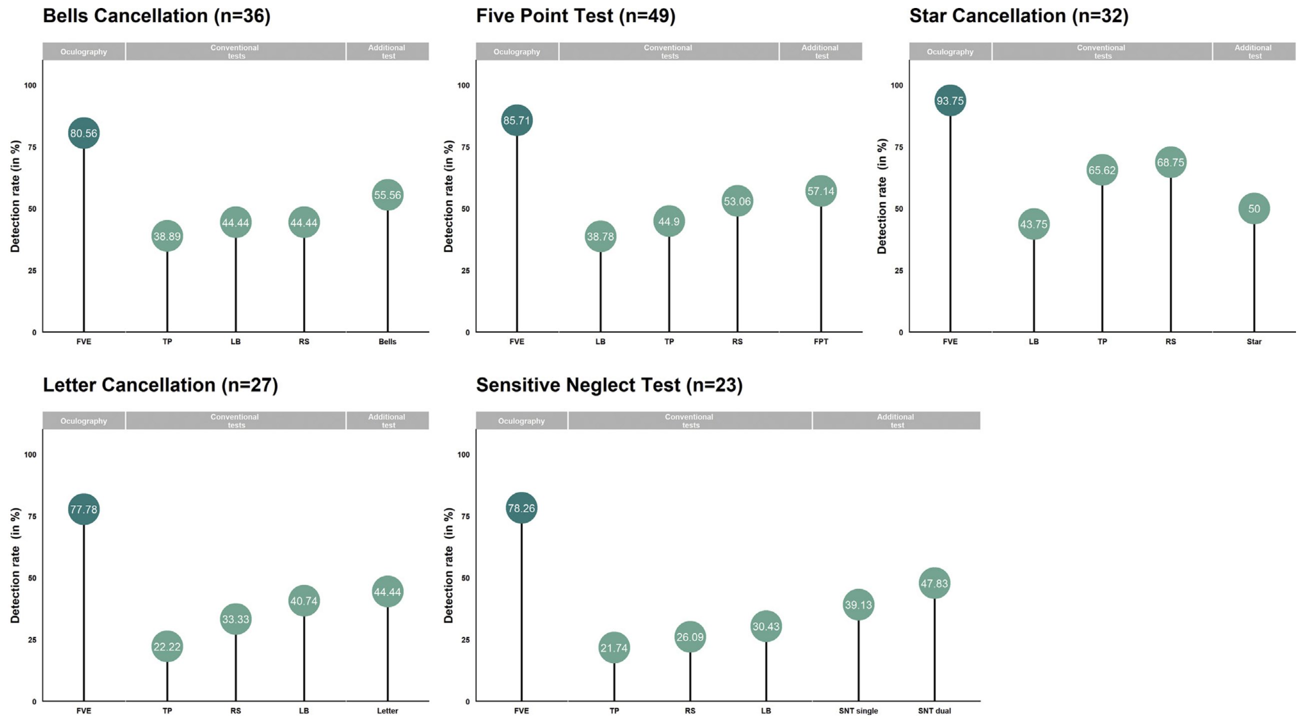

Fig. 5 – Neglect detection rate based on video-oculography during FVE (mean gaze position in ° of visual angle), and on the three conventional neuropsychological tests [Random Shape Cancellation Test (RS), Line Bisection (LB), Two-Part Picture Test (TP)], as well as on additional neuropsychological tests, measured within different patients' subgroups: Bells Test (n = 36), Five-Point Test (FPT, n = 49), Star Cancellation Test (n = 32), Letter Cancellation Test (n = 27) and Sensitive Neglect Test (n = 23). FVE significantly detected more neglect patients correctly than any of the additional neuropsychological tests.

Superior Longitudinal Fascicle (SLF II), a white matter tract connecting cortical areas critical for visual attention, and whose lesion is strongly related to the occurrence of neglect (Thiebaut de Schotten et al., 2014).

Video-oculography during FVE was found to be significantly more sensitive in detecting neglect in everyday behaviour than any conventional neuropsychological paper-pencil tests, such as the Random Shape Cancellation Test (Weintraub & Mesulam, 1988), the Line Bisection Test (Wilson et al., 1987a), and the Two-Part Picture Test (Brunila et al., 2003). Mean horizontal gaze position in FVE correctly identified neglect in 85% of the patients, whereas single neuropsychological tests had always a detection rate below 52%. This finding was confirmed by ROC analyses, which showed excellent diagnostic values for FVE (i.e., mean gaze position in ° of visual angle) with very high sensitivity and specificity.

In line with the findings by Azouvi and colleagues (Azouvi et al., 2006), a combination of two or three paper-pencil tests detected more patients than a single neuropsychological test. Yet, the sensitivity of these combined tests did not exceed 68.3%.

A further finding of our study is that the sensitivity of additional, commonly applied neuropsychological tests to diagnose neglect [such as the Bells Test (Gauthier et al., 1989), Five-Point Test (Regard et al., 1982), Star Cancellation Test (Wilson, Cockburn, & Halligan, 1987b), Letter Cancellation Test (Weintraub & Mesulam, 1988), and Sensitive Neglect Test (Reinhart et al., 2016)] was very heterogeneous within different subgroups of neglect patients, i.e., correctly identifying neglect in 21.74–68.75% of the patients. Conversely, video-oculography during FVE produced more homogeneous results in the same patients' subgroups, and detected neglect significantly more often (77.78–93.75%).

Previous studies have suggested that neglect severity, as reflected in different neuropsychological paper-pencil tests, critically depends on patients' lesion location. For instance, there are known dissociations between cancellation and line bisection tests with partly dissociable lesion correlates (Toba et al., 2018; Verdon, Schwartz, Lovblad, Hauert, & Vuilleumier, 2010).

In line with these observations, our results demonstrate that the composition of a particular patients' sample plays an important role for neglect severity to be correctly estimated by means of a particular neuropsychological paper-pencil tests. At the same time, our results illustrate that neglect in everyday behaviour can be more consistently detected by assessing FVE with video-oculography which is crucial for a screening tool.

FVE Mean Gaze Position, FVE Early Orientation, Random Shape Cancellation CoC, Random Shape early orientation, Line Bisection Test and Two-Part Picture Test. The analyses revealed the largest area under the curve (AUC) for the mean gaze position in FVE (AUC = .922).

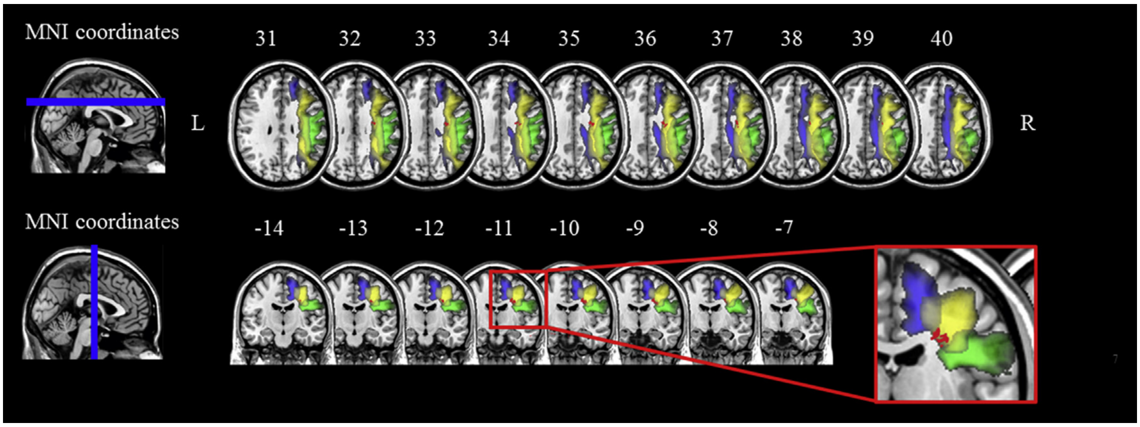

Fig. 6 – Results of the VLSM analysis showed that neglect patients with rightward early orientation are more likely to show a lesion within SLF II. Lesion voxels that were a significant predictor of a rightward early orientation are depicted in red (significance level $p < .05$, based on the Brunner–Munzel test, FDR-corrected, 4000 permutations). The significant lesion cluster (186 voxels) is located within the second branch of the Superior Longitudinal Fasciculus (SLF II; MNI coordinates: 26, −10, 34). SLF I is depicted in blue, SLF II in yellow and SLF III in green, according to published probabilistic diffusion tensor imaging tractography atlases (Rojkova et al., 2016; Thiebaut de Schotten et al., 2014; the probability for voxels to belong to the SLF tracts were set at > 50% (i.e., above chance). Lesion cluster, and probabilistic tracts are displayed on the CH2 template in MNI space, as available in MRIcron (http://www.mccauslandcenter.sc.edu/crnl/tools). The axial and coronal slices are oriented according to the neurological convention. The position of each slice in MNI space is indicated by numbers at the top of the respective figure panel, and depicted by the blue lines on the respective slice (left-hand side of the figure).

In comparison to healthy controls and right-hemispheric stroke patients without neglect, neglect patients showed a significant rightward shift of visual attention, as measured by their mean horizontal gaze position. The values concerning mean horizontal gaze position observed in our participants during FVE are similar to the ones reported by previous oculomotor studies, both for healthy controls (Fellrath & Ptak, 2015; Kaufmann et al., 2020; Paladini et al., 2019; Pflugshaupt et al., 2004) and neglect patients (Delazer, Sojer, Ellmerer, Boehme, & Benke, 2018; Fellrath & Ptak, 2015; Kaufmann et al., 2020; Paladini et al., 2019).

We also found a significant correlation between the horizontal distribution of visual fixations and neglect behaviour in everyday activities, as assessed with the CBS, suggesting that FVE resembles the complexity and attentional demands of real-life situations. Interestingly, FVE significantly correlated with 9 out of the 10 single CBS items. Only CBS item number 4, which quantifies personal neglect ("Forgets to clean the left side of mouth after eating"), did not correlate with FVE. This is also true for item 1 ("Forgets to groom or shave the left part of face") which showed significant but had the lowest correlation with FVE. This nicely fits with the results of earlier reports, showing that visual exploration is able to quantify neglect within the peripersonal/extrapersonal space, but has limited sensitivity in measuring personal neglect (Baas et al., 2011; Cocchini, Beschin, & Jehkonen, 2001). Therefore, in the clinical setting, a combination of FVE and CBS, could be beneficial to assess different components of neglect. FVE could be used as an initial and fast screening tool for peripersonal/extrapersonal neglect assigning patients to further evaluation with the CBS which in turn comprehensively assesses personal, peripersonal and extrapersonal neglect in real-life situations during a longer observational period. Moreover, after the screening with FVE, a more detailed neuropsychological assessment with a comprehensive neglect battery such as the Behavioural Inattention Test (BIT (Wilson et al., 1987b)) could be administered.

Early orientation towards the ipsilesional side has been reported to be a sensitive parameter to detect neglect (Azouvi et al., 2006; De Renzi, Gentilini, Faglioni, & Barbieri, 1989; Gainotti, D'Erme, & Bartolomeo, 1991; Mattingley, Bradshaw, Bradshaw, & Nettleton, 1994; Pflugshaupt et al., 2004). In our study, early orientation during FVE detected neglect significantly more often (in 83.33% patients) than early orientation during the Random Shape Cancellation Test (in 68.33% patients). This difference in sensitivity may be explained by the fact that, in conventional neuropsychological tests, early orientation can be assessed only on one occasion (e.g., the side of space, left or right, in which the first cancellation in a paper-pencil cancellation test occurs). In contrast, in video-oculography during FVE, several pictures are presented, allowing to assess early orientation on multiple occasions during the same task (i.e., for every picture, the side of space, left or right, in which the first fixation takes place). Behavioural performance in neglect patients can be highly variable, even within the same testing session, i.e., neglect patients may also produce normal responses to contralesional stimuli, the probability of these normal responses being, however, lower than in healthy individuals (Anderson, 2008). Therefore, the opportunity to assess early orientation multiple times during the same testing session seems pivotal for an accurate detection of neglect.

Using VLSM analyses, in order to investigate the neuronal underpinnings of neglect severity as assessed by video-oculography during FVE, we showed that the absence of pathological biases in early orientation might depend on the integrity of the right SLF II. SLF II fibres have been previously suggested to subtend the direct communication between prefrontal components of the dorsal attentional network [including the Frontal Eye Field (FEF), which is critically involved in FVE (Leigh et al., 2015)] and parietal components of the ventral attentional network (Thiebaut de Schotten et al., 2011). The ventral network, mainly interconnected by the SLF III, mediates the identification of salient stimuli; the dorsal network, interconnected by the SLF I, mediates shifts of goal-directed attention towards these stimuli; the SLF II would ensure communication between these two networks (Corbetta & Shulman, 2002; Thiebaut de Schotten et al., 2011). Accordingly, a disruption of SLF II fibres results in contralesional visual neglect (Vallar et al., 2014).

There may be multiple reasons as to why FVE is more sensitive in detecting neglect in everyday behaviour than single paper-pencil neuropsychological tests, or even combinations thereof. First, these tasks might rely on different neural mechanisms (Toba et al., 2018). Second, most paper-pencil tasks in neglect diagnostics are based on structured task instructions, involving top-down processes. For instance, in cancellation tests, patients are asked to find a predefined target among several distractors, requiring a certain search strategy. In contrast, in FVE tasks, no explicit instruction is given, i.e., the behaviour is much more bottom-up driven, and more independent from task-specific search strategies (Azouvi, 2017; Paladini et al., 2019; Pflugshaupt et al., 2004). Third, in FVE tasks requiring patients to explore images of natural scenes or urban public places, visual attention is more likely to be attracted towards the ipsilesional side of space by salient features (Paladini et al., 2019). In contrast, in neuropsychological paper-pencil tests, targets and distractors are similar in shape and colour, and are evenly distributed across space, saliency thus probably playing a less important role.

Our study has several implications. In stroke units and acute neurological services, a time-consuming, multidisciplinary observation by means of the CBS is often difficult to perform and therefore omitted. In contrast, video-oculography during FVE only lasts some minutes, including calibration and validation of the video-oculography device, and may therefore be a valuable initial screening tool. With a fast and accurate neglect diagnosis, further comprehensive diagnostics using the CBS and a comprehensive neuropsychological test battery (e.g., BIT) assessing different dimensions of neglect (e.g., personal, peripersonal and extrapersonal neglect, anosognosia, etc.) can be initiated from early on to facilitate rehabilitative treatment. This may potentially lead to a better outcome, a reduced length of hospitalisation and may therefore save considerable costs. Furthermore, the present data suggest that neglect would go unnoticed in an important proportion of patients if solely paper-pencil neuropsychological tests would be used for its initial screening; this is true even when the results of two or three tests are combined, or additional information concerning early orientation is taken into account.

Also, FVE may be used as well in left-hemispheric stroke patients with language deficits. Visual exploration is spontaneous, requires only little effort from the patient, and might be more robust than neuropsychological neglect tests, in which compliance with test instructions is very often compromised by aphasia. Furthermore, FVE might be used as outcome variable in the context of visual attention research to assess the impact of neglect treatment in clinical trials. Based on its high sensitivity in detecting neglect, FVE could potentially identify even small changes associated with specific neglect treatment (i.e., neuropsychological trainings, brain stimulation, etc.). Furthermore, with virtually unlimited sets of pictures FVE offers the possibility to be repeated several times. However, further studies might investigate these aspects.

A potential limitation of our study is that we examined the sensitivity of FVE retrospectively. Due to the lack of complete data for the additional neuropsychological tests in patients with or without left-sided spatial neglect, a proper ROC analysis could not be performed for these measures. Besides that, neuropsychological testing was limited to a small number of tests and did not include comprehensive screening batteries such as the BIT, which would also contain items pertaining other aspects of neglect (e.g., constructional). Future studies are needed to investigate prospectively whether FVE can potentially predict the extent of the detrimental effects of neglect on everyday behaviour in an early phase after stroke.

Our study shows that video-oculography during FVE, in particular mean gaze position, is a robust and sensitive screening tool to diagnose neglect in everyday behaviour after subacute, right-hemispheric stroke. It correlates with every-day neglect behaviour, and, probably due to its reliance on bottom-up visual attention, is significantly more sensitive than conventional neuropsychological paper-pencil tests.

Notes

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. No part of the study procedures and study analysis was preregistered prior to the research being conducted.

Author contributions

Brigitte C. Kaufmann: Conceptualization, Methodology, Formal Analysis, Investigation, Methodology, Visualization, Writing-Original Draft.

Dario Cazzoli: Investigation , Methodology, Formal Analysis, Writing-Review & Editing.

Tobias Pflugshaupt: Methodology, Writing-Review & Editing.

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Tobias Nef: Software, Resources, Writing-Review & Editing.

Thomas Nyffeler: Conceptualizaiton, Supervision, Writing-Original Draft, Funding acquisition.

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Data availability

The conditions of our ethics approval do not permit public archiving of the data supporting the conclusion of this study. Readers seeking access to the data should contact the lead author Prof. Thomas Nyffeler. Requestors must complete a formal data sharing agreement to obtain the data. All data that are necessary and sufficient to replicate all data processing steps and analyses will be shared to requestors who meet these requirements. Access to the data will be permitted as part of a collaboration upon a case-by-case decision. Legal copyright restrictions (copyright owner: alamy.de) do not permit us to publicly archive the full set of pictures used in the paradigm of this study. The R script used for individual analysis of FVE data can be accessed at https://osf.io/ebwtx/.

Declaration of competing interest

None declared.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2020.04.021.

REFERENCES

Anderson, B. (2008). Neglect as a disorder of prior probability. *Neuropsychologia, 46*(5), 1566–1569. https://doi.org/10.1016/j.neuropsychologia.2007.12.006.

Azouvi, P. (2017). The ecological assessment of unilateral neglect. *Annals of Physical and Rehabilitation Medicine, 60*(3), 186–190. https://doi.org/10.1016/j.rehab.2015.12.005.

Azouvi, P., Bartolomeo, P., Beis, J., Perennou, D., Pradat-Diehl, P., & Rousseaux, M. (2006). A battery of tests for the quantitative assessment of unilateral neglect. *Restorative Neurology and Neuroscience, 24*, 273–285.

Azouvi, P., Olivier, S., de Montety, G., Samuel, C., Louis-Dreyfus, A., & Tesio, L. (2003). Behavioral assessment of unilateral neglect: Study of the psychometric properties of the Catherine Bergego Scale. *Archives of Physical Medicine and Rehabilitation, 84*, 51–57. https://doi.org/10.1053/apmr.2003.50062.

Azouvi, P., Samuel, C., Louis-Dreyfus, A., Bernati, T., Bartolomeo, P., Beis, J. M., et al. (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.

Baas, U., deHaan, B., Karnath, H. O., Müri, R. M., Perig, W. J., Wurtz, P., et al. (2011). Personal neglect - a disorder of body representation? *Neuropsychologia, 49*(5), 898–905. https://doi.org/10.1016/j.neuropsychologia.2011.01.043.

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.

Brunila, T., Jalas, M., Lindell, J. A., Tenovuo, O., & Hamalainen, H. (2003). The two part picture in detection of visuospatial neglect. *The Clinical Neuropsychologist, 17*(1), 45–53. https://doi.org/10.1076/clin.17.1.45.15632.

Carpenter, R. H. (1988). *Movements of the Eyes* (2nd ed.). London, England: Pion Limited.

Cazzoli, D., Nyffeler, T., Hess, C. W., & Müri, R. M. (2011). Vertical bias in neglect: A question of time? *Neuropsychologia, 49*, 2369–2374. https://doi.org/10.1016/j.neuropsychologia.2011.04.010.

Cocchini, G., Beschin, N., & Jehkonen, M. (2001). The fluff test: A simple task to assess body representational neglect. *Neuropsychological Rehabilitation, 11*(1), 17–31. https://doi.org/10.1080/09602010042000132.

Corbetta, M., & Shulman, G. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience, 3*, 201–205.

De Renzi, E., Gentilini, M., Faglioni, P., & Barbieri, C. (1989). Attentional shift towards the rightmost stimuli in patients with left visual neglect. *Cortex, 25*, 231–237. https://doi.org/10.1016/S0010-9452(89)80039-5.

Delazer, M., Sojer, M., Ellmerer, P., Boehme, B., & Benke, T. (2018). Eye-tracking provides a sensitive measure of exploration deficits after acute right MCA stroke. *Frontiers In Neurology, 9*(359). https://doi.org/10.3389/fneur.2018.00359.

Fawcett, T. (2006). An introduction to ROC analysis. *Pattern Recognition Letters, 27*, 861–876. https://doi.org/10.1016/j.patrec.2005.10.010.

Fellrath, J., & Ptak, R. (2015). The role of visual saliency for the allocation of attention: Evidence from spatial neglect and hemianopia. *Neuropsychologia, 73*, 70–81. https://doi.org/10.1016/j.neuropsychologia.2015.05.003.

Gainotti, G., D'Erme, P., & Bartolomeo, P. (1991). Early orientation of attention toward the half space ipsilateral to the lesion in patients with unilateral brain damage. *Journal of Neurology, Neurosurgery and Psychiatry, 54*, 1082–1089. https://doi.org/10.1136/jnnp.54.12.1082.

Gauthier, L., Dehaut, F., & Joanette, Y. (1989). The Bells test: A quantitative and qualitative test for visual neglect. *International Journal of Clinical Neuropsychology, 11*, 49–54.

Heilman, K. M., Watson, R. T., & Valenstein, E. (1993). *Neglect and related disorders*. New York Oxford University Press.

Kaufmann, B. C., Frey, J., Pflugshaupt, T., Wyss, P., Paladini, R. E., Vanbellingen, T., & Nyffeler, T. (2018). The spatial distribution of perseverations in neglect patients during a nonverbal fluency task depends on the integrity of the right putamen. *Neuropsychologia, 115*, 42–50. https://doi.org/10.1016/j.neuropsychologia.2018.01.025.

Kaufmann, B. C., Knobel, S. E. J., Nef, T., Müri, R. M., Cazzoli, D., & Nyffeler, T. (2020). Visual exploration area in neglect: A new analysis method for video-oculography data besed on foveal vision. *Frontiers in Neuroscience, 13*. https://doi.org/10.3389/fnins.2019.01412.

Kimberg, D. Y., Coslett, H. B., & Schwartz, M. F. (2007). Power in voxel-based lesion-symptom mapping. *J CognNeurosci, 19*, 1067–1080.

Leigh, J. R., & Zee, D. S. (2015). *The neurology of eye movements* (5 ed.). Oxford Oxford University Press.

Lindell, A. B., Jalas, M. J., Tenovuo, O., Brunila, T., Voeten, M. J. M., & Hämäläinen, H. (2007). Clinical assessment of hemispatial neglect: Evaluation of different measures and dimensions. *The Clinical Neuropsychologist, 21*, 479–497. https://doi.org/10.1080/13854040600630061.

Mattingley, J. B., Bradshaw, J. L., Bradshaw, J. A., & Nettleton, N. C. (1994). Residual rightward attentional bias after apparent recovery from right hemisphere damage: Implications for a multicomponent model of neglect. *Journal ofNeurology, Neurosurgery and Psychiatry, 57*, 597–604. https://doi.org/10.1136/jnnp.57.5.597.

Medina, J., Kimberg, D. Y., Chatterjee, A., & Branch Coslett, H. (2010). Inappropriate usage of the Brunner Munzel test in recent voxel-based lesion-symptom mapping studies. *Neuropsychologia, 48*, 341–343.

Müri, R. M., Cazzoli, D., Nef, T., Mosimann, U. P., Hopfner, S., & Nyffeler, T. (2013). Non-invasive brain stimulation in neglect rehabilitation: An update. *Frontiers in Human Neuroscience, 7*, 248. https://doi.org/10.3389/fnhum.2013.00248.

Nijboer, T. C., Kollen, B. J., & Kwakkel, G. (2014). The impact of recovery of visuo-spatial neglect on motor recovery of the upper paretic limb after stroke. *Plos One, 9*(6). https://doi.org/10.1371/journal.pone.0100584. e100584.

Nijboer, T., van de Port, I., Schepers, V., Post, M., & Visser-Meily, A. (2013). Predicting functional outcome after stroke: The influence of neglect on basic activities in daily living. *Frontiers in Human Neuroscience, 7*, 182. https://doi.org/10.3389/fnhum.2013.00182.

Nyffeler, T., Cazzoli, D., Wurtz, P., Lüthi, M., Von Wartburg, R., Vhaves, S., & Müri, R. M. (2008). Neglect-like visual exploration behaviour after theta burst transcranial magnetic stimulation of the right posterior parietal cortex. *The European Journal of Neuroscience, 27*, 1809–1813. https://doi.org/10.1111/j.1460-9568.2008.06154.x.

Osandón, J. P., Onat, S., Cazzoli, D., Nyffeler, T., Müri, R., & König, P. (2012). Unmasking the contribution of low-level features to the guidance of attention. *Neuropsychologia, 50*. https://doi.org/10.1016/j.neuropsychologia.2012.09.043.

Paladini, R., Wyss, P., Kaufmann, B., Urwyler, P., Nef, T., Cazzoli, D., & Müri, R. (2019). Re-fixation and perseveration patterns in neglect patients during free visual exploration. *European Journal of Neuroscience, 49*, 1244–1252. https://doi.org/10.1111/ejn.14309.

Pflugshaupt, T., Bopp, S. A., Heinemann, D., Mosimann, U. P., von Wartburg, R., Nyffeler, T., et al. (2004). Residual oculomotor and exploratory deficits in patients with recovered hemineglect. *Neuropsychologia, 42*, 1203–1211. https://doi.org/10.1016/j.neuropsychologia.2004.02.002.

Ptak, R., Golay, L., Müri, R. M., & Schnider, A. (2009). Looking left with left neglect: The role of spatial attention when active vision selects local image features for fixation. *Cortex, 45*.

Regard, M., Strauss, E., & Knapp, P. (1982). Children's production on verbal and non-verbal fluency tasks. *Perceptual and Motor Skills, 55*, 839–844. https://doi.org/10.2466/pms.1982.55.3.839.

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

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.

Rojkova, K., Volle, E., Urbanski, M., Humbert, F., Dell'Acqua, F., & Thiebaut de Schotten, M. (2016). Atlasing the frontal lobe connections and their variability due to age and education: A spherical deconvolution tractography study. *Brain Structure & Function, 221*, 1751–1766.

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

Salthouse, T. A., & Ellis, C. L. (1980). Determinants of eye-fixation duration. *The American Journal of Psychology, 93*, 207–234.

Stone, S. P., Wilson, B., Wroot, A., Halligan, P. W., Lange, L. S., & Marshall, J. C. (1991). The assessment of visuo-spatial neglect after acute stroke. *Journal of Neurology, Neurosurgery, and Psychiatry, 54*, 345–350. https://doi.org/10.1136/jnnp.54.4.345.

Swets, J. A., Dawes, R. M., & Monahan, J. (2000). Better decisions through science. *Scientific American, 283*, 82–87.

Thiebaut de Schotten, M., Dell'Acqua, F., Forkel, S., Simmons, A., Vergani, F., Murphy, D., et al. (2011). *A Lateralized Brain Network for Visuospatial Attention. Nature Neuroscience*. Nature Publishing Group.

Thiebaut de Schotten, M., Tomaiuolo, F., Aiello, M., Merola, S., Silvetti, M., Lecce, F., et al. (2014). Damage to white matter pathways in subacute and chronic spatial neglect: A group study and 2 single-case studies with complete virtual "in vivo" tractography dissection. *Cerebral Cortex, 24*, 691–706.

Toba, M. N., Migliaccio, R., Batrancourt, B., Bourlon, C., Duret, C., Pradat-Diehl, P., et al. (2018). Common brain networks for distinct deficits in visual neglect. A combined structural and tractography MRI approach. *Neuropsychologia, 115*, 167–178. https://doi.org/10.1016/j.neuropsychologia.2017.10.018.

Vallar, G., Bello, L., Bricolo, E., Castellano, A., Casarotti, A., Falini, A., et al. (2014). Cerebral correlates of visuospatial neglect: A direct cerebral stimulation study. *Hum Brain Mapp, 35*, 1334–1350.

Verdon, V., Schwartz, S., Lovblad, K. O., Hauert, C. A., & Vuilleumier, P. (2010). Neuroanatomy of hemispatial neglect and its functional components: A study using voxel-based lesion-symptom mapping. *Brain, 133*, 880–894.

Weintraub, S., & Mesulam, M. (1985). In I. M.-M. Mesulam (Ed.), *Mental state assessment of young and elderly adults in behavioral neurology*. Philadelphia: F. A. Davis.

Weintraub, S., & Mesulam, M. (1988). Visual hemispatial inattention: Stimulus parameters and exploratory strategies. *Journal of Neurology, Neurosurgery, and Psychiatry, 51*, 1481–1488. https://doi.org/10.1136/jnnp.51.12.1481.

Wilson, B. A., Cockburn, J., & Halligan, P. W. (1987a). Development of a behavioral test of visuospatial neglect. *Archives of Physical Medicine and Rehabilitation, 68*, 98–102.

Wilson, B., Cockburn, J., & Halligan, P. W. (1987b). *The Behavioural Inattention Test Manual*. England: Thames Valley Test Company.