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Visual search in relation to spatial working memory

by

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Abstract

The organization of visual search can be measured using the star cancellation test, but it is not yet clear which cognitive components influence performance on such visual search tests. Many theories have proposed a close interaction between visual search and working memory. Our aim was to examine whether visual search organization is related to spatial working memory (SWM). In the current study, 116 stroke patients and 28 healthy controls performed a computerized star cancellation test and a non-lateralized SWM test. Two groups, a group with (SWM+) and without (SWM–) SWM deficits, were formed based on performance of the control group (mean + 2.5 SD). We compared performance between the two stroke groups on the outcome measures regarding disorganized search: the number of *delayed perseverations*, *intersection rate* (the number of intersections, controlled for total number of markings), and *consistency* of search direction (best *r*). Comparisons were made for both a visible (i.e. marks appeared at the clicked location) and invisible condition (i.e. no marks appeared at the clicked location) of the star cancellation test. Furthermore, we calculated correlations between the severity of the SWM deficit and the organization of visual search. The SWM+ group made more delayed perseverations, made more intersections, and searched less consistent in both conditions compared to the SWM– group, indicating a relationship between SWM capacity and organization of visual search. Furthermore, a small positive correlation was found between the SWM threshold and intersection rate in both the visible and invisible condition of the star cancellation test, a small negative correlation for the SWM threshold and consistency of search direction in both conditions, and a small positive correlation for the SWM threshold and perseverations, but only in the invisible condition. This indicates a relation between SWM severity and organization of visual search. Together, these findings suggest that there is a small relation between SWM and visual search.

Keywords: stroke, star cancellation, spatial working memory, visual search

Introduction

In the Netherlands, about 47.000 people suffer a stroke each year (Schievink, Douven, Aalten, & Köhler, 2015). Stroke often leads to cognitive impairment, causing significant problems in daily life (Azouvi, 2016; Nijboer, Kollen, & Kwakkel, 2013). One of the potential cognitive problems is disorganized visual search: not being able to efficiently find an item of interest among other objects and information (Oh & Kim, 2004). During a standard visual search test, subjects look for a target among distractors (Wolfe, 2002). Examples of tests that can be used to measure visual search in stroke patients are cancellation tests. In these tests, patients have to mark several targets that are interspersed with distractors. The most used cancellation test is the star cancellation test, originally developed to measure spatial inattention (Wilson, Cockburn, & Halligan, 1987). Measurements of search organization can additionally be determined, such as the number of *perseverations* (i.e. revisits of already marked targets), the *number of intersections* with paths between previous marked targets or the *intersection rate* (i.e. number of intersections divided by the amount of marked targets), all reflecting the organization of the search (Rabuffetti et al., 2012; Ten Brink, Van der Stigchel, Visser-Meily, & Nijboer, 2016). Furthermore, the *consistency* of the search direction throughout the task can be measured with best *r* (i.e. Pearson correlation coefficient) (Mark, Woods, Ball, Roth, & Mennemeier, 2004; Rabuffetti et al., 2012; Ten Brink et al., 2016).

Typically, healthy subjects mark the targets by rows or columns in either a horizontal or vertical way across the page. Their search strategy is organized, they make few errors, and they recheck the marked targets (Huang & Wang, 2008; Rabuffetti et al., 2012; Ten Brink et al., 2016). Furthermore, a well-organized search would involve none or few delayed perseverations, a consistent search direction (a high best *r*), little path intersections and thus a low intersection rate. In prior research it was found that stroke patients show less organized search patterns than healthy participants on cancellation tests (Donnelly et al., 1999), thus making more perseverations, search less consistent, and make more intersections (Rabuffetti et al., 2012; Ten Brink et al., 2016).

As said, the organization of visual search can be measured using the star cancellation test, but it is not clear which cognitive components influence performance on the organization of visual search during this test. Many theories have proposed a close interaction between visual search and working memory (Treisman, 1988; Wojciulik, Husain, Clarke, & Driver, 2001; Wojciulik, Rorden, Clarke, Husain, & Driver, 2004; Woodman & Luck, 2004). Working memory is suggested by Baddeley (2001) as a system that enables the temporary maintenance of information, where it is kept available for access by other cognitive processes. The spatial subsystem of working memory is called spatial working memory (SWM; Awh & Jonides, 2001; Della Sala, Logie, Beschin, & Denis, 2004), which is defined as the ability to encode, transform, and maintain spatial information for perception and action (Corbetta, Kincade, & Shulman, 2002). Stroke patients who search inefficient might have trouble keeping track of previously searched locations, which can be due to problems in SWM. An additional confirmation of the role of working memory in the star cancellation test comes from the high amount of perseverations stroke patients make, even when the previous cancellation marks are visible (Husain et al., 2001; Wojciulik et al., 2001, 2004). This indicates that some stroke patients have trouble remembering which targets have already been marked and therefore mark them again.

Such examples implicate that visual search organization and working memory are closely linked. Many studies have investigated visual search in relation to the visual subsystem of working memory (i.e. visual working memory), but there has not been a study that investigated the relation between visual search organizational measures and spatial working memory. The current aim was to examine whether search organization is related to SWM capacity. The organization of search was assessed using several outcome measures derived from the star cancellation test (i.e. delayed perseverations, intersection rate, and consistency of search direction) and the SWM capacity was assessed using a vertical SWM test. We chose to use a vertical SWM test to ensure that the outcome of the test would not be influenced by lateralized attentional deficits that might be present in stroke patients (Malhotra, Mannan, Driver, & Husain, 2004; Malhotra et al., 2005). We predicted that patients with an SWM deficit would have a less structured search organization compared to patients without this deficit.

Second, we examined whether the presence of marks (i.e. a circle on the clicked location) during the cancellation test influenced the relation between SWM capacity and organization of visual search. We expected that when marks were not apparent, the search organization of all stroke patients (i.e. with and without an SWM deficit) would be less structured than when marks were apparent, since the absence of marks maximizes the SWM requirements (Wojciulik et al., 2001). Furthermore, we expected that patients with an SWM deficit searched even less organized compared to patients without an SWM deficit when no marks were present.

Finally, we aimed to examine whether a relation exists between the severity of the SWM deficit and the degree of search organization. We expected that patients with a more severe SWM deficit searched less organized during the star cancellation test

Methods

Participants

Participants consisted of 224 stroke patients who were admitted for inpatient rehabilitation to De Hoogstraat rehabilitation center between October 2015 and January 2017. All patients were screened for neglect (i.e. the failure to report, orient toward or respond to stimuli in the contralesional hemispace) as part of standard stroke care. The inclusion criteria for the current study were: (1) screened for neglect and (2) aged between 18 and 80 years. Exclusion criteria were: no data on the star cancellation test or the SWM test (n = 108). Additionally, 28 healthy controls were included. Inclusion criteria for the controls were: (1) a minimum age of 40 years, in order to match the age of the stroke patients at group level, and (2) no history of neurological or psychiatric disorders. The healthy controls were recruited among friends and relatives of the experimenter. The study was performed in accordance with the standards of the Declaration of Helsinki.

Procedure

Within the first two weeks after admission to rehabilitation, a neuropsychological neglect screening took place as part of standard stroke care. Among other tests, this screening consisted of the star cancellation test (visible and invisible condition), and the SWM test. Instructions were given verbally prior to each test. The duration was approximately five minutes per test and 40 minutes for the total screening. The visible condition of the star cancellation test was administered first, invisible condition of the star cancellation test was administered fourth, and the SWM test was administered last.

The healthy controls also performed the total screening to match the stroke patients and rule out any possible differences (e.g. fatigue).

Apparatus and Software

The star cancellation test and the SWM test were presented on an IIyama ProLite monitor (27 inches, 1920 x 1080 px, 60 Hz). The patients sat in a normally lighted room, in front of the center of the screen. The patients viewed the screen from approximately 90 cm during the star cancellation test and 60 cm during the SWM test.

Outcome Measures

Star cancellation test: The digitized star cancellation test consisted of a field of 54 targets (stars, 11 mm ø), among 75 distractor stars (22 mm ø), words, and letters (widths ranging from

5 to 43 mm and heights of 13 mm). The patient was instructed to click on all targets using the computer mouse. In the visible condition, a blue circle appeared at the clicked location and remained on the screen. In the invisible condition, no circle appeared. The patient indicated verbally when he or she was finished.

First, we computed the number of delayed perseverations. There are two types of perseverations: consecutive perseverations, in which repeated markings at a particular target occur without marking another target first, and delayed perseverations, in which the repetition of a mark at a particular target occurs after marking a different target first (Mark et al., 2004). Only the delayed perseverations were of interest since they included a spatial component. Second, we computed the intersection rate. This is the number of intersections (i.e. the number of crossings with paths between previously marked targets) divided by the number of marked targets. In this way, we corrected for the amount of missed targets, since a lower amount of marked targets equals a lower change of intersections (Dalmaijer, Van der Stigchel, Nijboer, Cornelissen, & Husain, 2015). Finally, we computed the Pearson correlation coefficient (*r)* of the search pattern, which reflected the consistency of search direction in either horizontal or vertical direction during the test (Mark et al., 2004). For each patient, we selected the highest (*best*) *r*-value to which cancellations were pursued orthogonally.

Spatial working memory test: The SWM test was a vertical location discrimination test where patients were asked to focus on a fixation point, continuously, centrally presented as a black open circle (3 mm ø) on a gray background. The test consisted of 32 trials. For 500 ms, only the fixation point was shown. After this, the first stimulus (red dot, 6 mm ø) was shown for 250 ms either above or below the fixation point. This was followed by an interval of 1000 ms and a second stimulus (yellow dot, 6 mm ø) was shown for 250 ms either above or below the first stimulus' position. The fixation point remained visible throughout the entire test and expanded once during the interval.

Patients were asked to report verbally whether they perceived the second stimulus at a location above or below the position of the first stimulus. The experimenter logged the answers using the up and down arrows on a keyboard. There were four practice trials in which feedback was shown on screen (i.e. 'correct!' or 'wrong, try again!').

The distance between the two stimuli was adjusted based on a staircase design. In the first trial, the distance between the stimuli was 412 mm. This distance decreased with 37 mm for each next trial whenever the participant responded correctly. This procedure converged to a spatial difference threshold of 80% (i.e. when 80% of the answers given were correct). This threshold value was our outcome measure for SWM. The experiment was custom made using Python software and the SWM data were analyzed using MATLAB software.

Demographic and Clinical Characteristics

The patients' medical chart was reviewed for demographic information and to give an indication of the patients' sequelae. The following data were obtained: gender, age, handedness, hemisphere of stroke (i.e. left, right, bilateral), time post-stroke in days, global cognitive function score (Montreal Cognitive Assessment; MoCA; Nasreddine, Charbonneau, & Cummings, 2005; or MMSE; Folstein, Folstein, & McHugh, 1975, which is later converted to MoCA using the following formula: (1.124 x MMSE) - 8.165; Solomon et al., 2014), level of independence during daily live activities (Barthel Index; Collin, Wade, Davies, & Horne, 1987), strength in both arms and legs (Motricity Index; Arm and Leg; Collin & Wade, 1990), and presence of language communication deficits (Stichting Afasie Nederland; SAN score; Deelman, Koning-Haanstra, Liebrand, & Van den Burg, 1981).

Statistical Analyses

For each stroke patient, the presence of an SWM deficit was determined based on their SWM threshold value. Data of the control group were used to define the normal range (i.e. the mean SWM threshold + 2.5 SD). Patients with an SWM threshold outside the normal range were assigned to the SWM+ group, whereas patients with an SWM threshold within the normal range were assigned to the SWM– group.

For all variables, the distribution was checked for normality by plotting histograms and computing Z-scores for skewness and kurtosis. Nonparametric tests were used, as data were not normally distributed.

The demographic characteristics were compared between the three groups (i.e. SWM+, SWM–, and the healthy control group). The clinical characteristics and admission to rehabilitation data (hemisphere of stroke, days post-stroke, MoCA, Barthel Index, Motricity Index Arm, Motricity Index Leg, and SAN score) were compared between the two stroke groups (SWM+ and SWM–). The Mann-Whitney test was used to compare continuous variables and the Chi-square test to compare categorical variables.

In order to answer our research questions, an ANOVA was performed for each search organization measure (i.e. delayed perseverations, intersection rate, best *r*), with the factors Group (SWM+ versus SWM–) and Visibility (visible versus invisible). The ANOVA was used despite data were not normally distributed, since interaction effects could be assessed while maintaining a sufficient level of power. First, we examined whether patients in the SWM+ group searched less organized than patients in the SWM– group, by assessing the main effect of Group. Second, we examined whether the presence of marks impacted the results of the stroke patients on the star cancellation test, by assessing the main effect of Visibility. Next, in order to evaluate whether patients with an SWM deficit would search even less organized when markers were invisible, the interaction effect between Group * Visibility was assessed.

Finally, we examined whether a relation existed between the severity of the SWM deficit and disorganized search. We computed Spearman correlations since the data was not normally distributed. Spearman's rho (ρ) was interpreted as small (>.1), moderate (>.3), large (>.5), or very large (>.7; Dancey & Reidy, 2004).

We used an alpha level of .05 to determine statistical significance. Analyses were done using CancellationTools (Dalmaijer et al., 2015), SPSS (IBM, 2013), MATLAB and Microsoft Excel.

Results

Demographic and Clinical Characteristics

The final sample consisted of 116 stroke patients. Demographic and clinical data are shown in Table 1. The stroke patients were divided into two groups based on the mean SWM threshold and SD of the control group, which was 0.70 cm (SD = 0.47 cm). Thus, stroke patients with an SWM threshold of 1.88 cm or higher were assigned to the SWM+ group (n = 31), patients with a lower SWM threshold were assigned to the SWM– group (n = 85).

There was no difference in age between the control group and the SWM+ group, $U = 369.50$, $z = -0.98$ $p = .327$, nor between the control group and the SWM– group, $U = 946.00$, $z = -1.62$ $p = .104$, nor between the SWM+ and SWM– group, $U = 1206.50$, $z = -0.69$ $p = .488$. The three groups were also comparable regarding gender, $\chi^2(2) = 4.81$, $p = .090$.

The hemisphere of stroke did not differ between SWM+ and SWM– patients , $\chi^2(2) = 2.03$, $p = .362$. Furthermore, the two stroke groups differed regarding the number of days post-stroke they were tested, $U = 802.00$, $z = -2.38$, $p = .017$. The patients in the SWM+ group were tested on average 3.75 days later that the SWM– patients. Moreover, the SWM+ and SWM– groups differed regarding MoCA score, $U = 314.50$, $z = -2.47$, $p = .013$. On average, SWM+ patients scored 3.6 points lower on the MoCA compares to SWM– patients, suggesting that SWM+ patients had more severe cognitive impairments. They also differed regarding the Barthel Index score, $U = 374.50$, $z = -3.65$, $p < .001$. On average, SWM+ patients scored 5.45 points lower on the Barthel Index compared to SWM– patients, which indicated that SWM+ patients had a lower functional independence compared to SWM– patients. The SWM+ and SWM– group were comparable regarding SAN score, U = 656.50, z = -1.10, p = .272, indicating that there were no differences in the severity of communication deficits. Lastly, there were differences between the SWM+ and SWM– patients regarding the Motricity Index Arm, U = 511.00, z = -2.45, p = .014, and Motricity Index Leg, U = 469.50, z = -2.76, p = .006. This indicated that SWM+ patients had more motor problems than SWM– patients.

Table 1

Median Scores, Percentage and Interquartile range (IQR) of Demographical and Clinical Data

Variables	SWM–			SWM+			Control		
	n	%		n	%		n	%	
Gender, % male	85	32.94		31	48.39		28	53.58	
Hemisphere of stroke, % left	68	52.94		27	37.04		-	-	
	n	median	IQR	n	median	IQR	n	median	IQR
Median age, in years	85	58	15	31	57	13	28	53	18.5
Days post-stroke onset	79	19	9	29	24.5	19			
MoCA (range = 0 - 30)	57	22	5	18	19	9			
Barthel index (range = 0 - 20)	55	18	8	27	9.5	14			
SAN score (range = 1 - 7)	59	6	2	26	6	3			
Motricity index Arm (range = 0 - 100)	58	99	34	26	68.5	99			
Motricity index Leg (range = 0 - 100)	57	99	31	26	75	57			

Note. IQR = Interquartile Range; MoCA = Montreal Cognitive Assessment; SAN = Stichting Afasie Nederland.

Search Organization

Perseverations: The mean scores and standard deviations of the measures of search organization are shown in Table 2. The average number of perseverations in the visible and invisible condition, split by group, is depicted in Figure 1. There was a significant main effect of Group, $F(1) = 20.884$, $p < .001$, $\eta^2 = .084$. Specifically, SWM+ patients made more perseverations compared to the SWM– patients. In addition, there was a significant main effect of Visibility, $F(1) = 39.906$, $p < .001$, $\eta^2 = .149$. This indicates that more perseverations were made in the invisible condition compared to the visible condition. There was an interaction effect between Group * Visibility on the number of perseverations, $F(1, 228) = 5.745$, $p = .017$, $\eta^2 = .025$. Simple main effects analysis showed that both the SWM– patients, $p < .001$ and SWM+ patients, $p < .001$, made more perseverations in the invisible condition compared to the visible condition. It also showed that the SWM+ patients made more perseverations compared to the SWM– patients in the invisible condition, $p < .001$, but groups did not differ in the visible condition, $p = .126$.

To summarize, both groups (i.e. SWM– and SWM+) made more perseverations in the invisible compared to the visible condition. The SWM+ group was most affected by the lack of marks, as more perseverations were made in the SWM+ group compared to the SWM– group in the invisible condition, whereas no group differences were observed in the invisible condition.

Table 2

Mean Scores and Standard Deviations of Measures of Search Organization

Search organization measures	SWM+ (n = 31)	SWM– (n = 85)
Visible		
Perseverations	3.45 (10.03)	0.28 (0.59)
Intersection rate	0.20 (0.25)	0.10 (0.12)
Best *r*	0.68 (0.26)	0.78 (0.19)
Invisible		
Perseverations	16.16 (21.55)	6.00 (7.76)
Intersection rate	0.11 (0.12)	0.04 (0.05)
Best *r*	0.73 (0.30)	0.88 (0.17)

Note. SWM = spatial working memory.

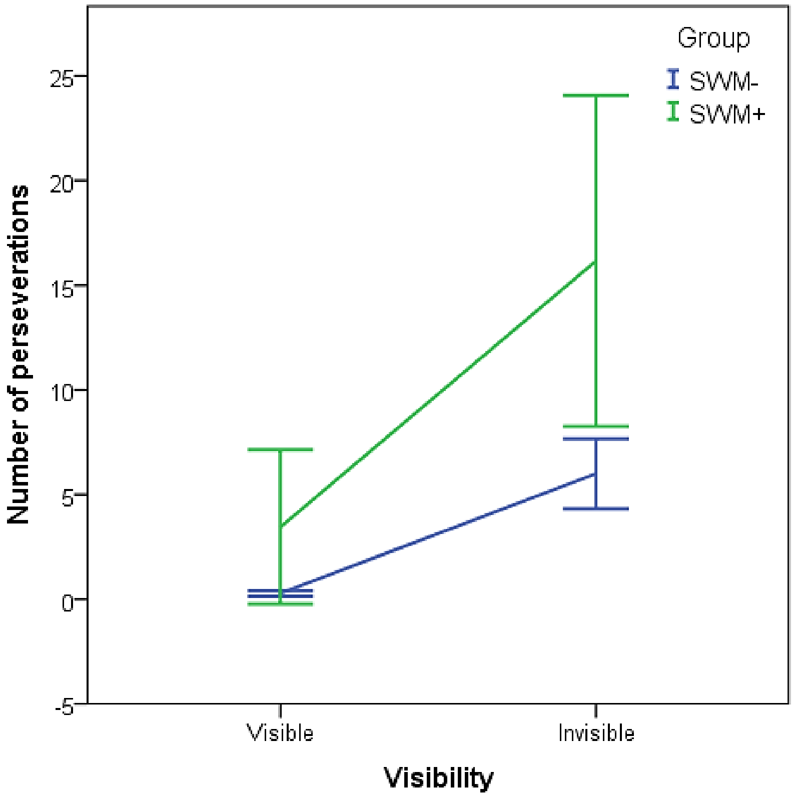

Figure 1. Delayed perseverations of the SWM– and SWM+ group for the visible and invisible condition. Error bars indicate the 95% confidence interval.

Intersection rate: The intersection rate of both stroke groups for the visible and invisible condition is depicted in Figure 2. There was a significant main effect of Group, $F(1) = 18.433$, $p < .001$, $\eta^2 = .075$. Specifically, the SWM+ group made more intersections than the SWM– group, indicating less organized search. In addition, there was a main effect of Visibility, $F(1) = 14.143$, $p < .001$, $\eta^2 = .058$. The intersection rate was higher in the visible condition compared to the invisible condition, indicating less organized search in the visible condition. There was no interaction for Group * Visibility, $F(1, 228) = 1.158$, $p = .283$, $\eta^2 = .005$.

To summarize, patients in the SWM– group searched more organized compared to patients in the SWM+ group. Patients in both groups searched more organized in the invisible condition compared to the visible condition.

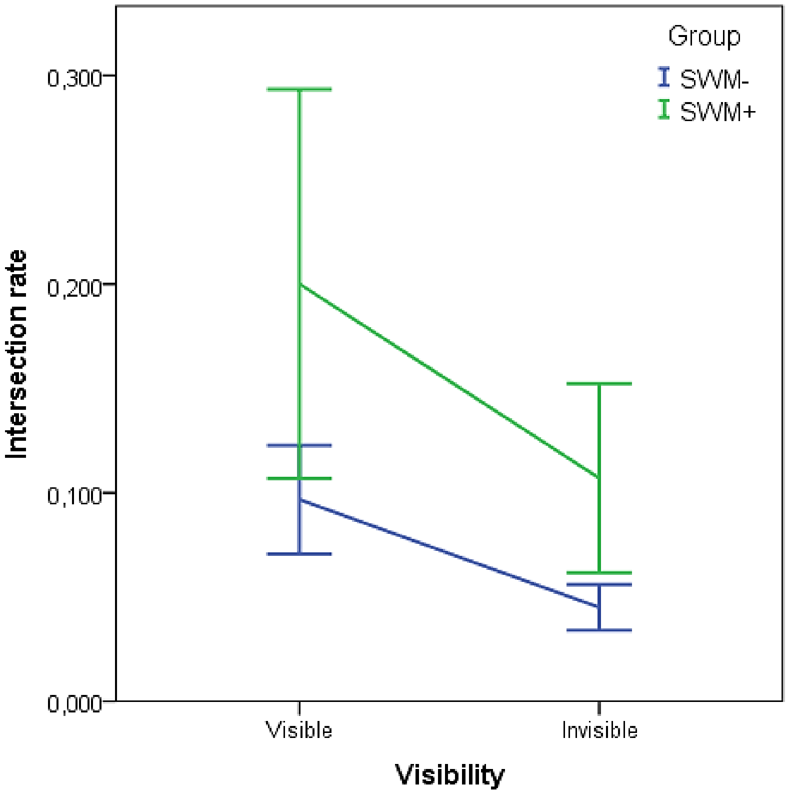

Figure 2. Intersection rate of the SWM– and SWM+ group for the visible and invisible condition. Error bars indicate the 95% confidence interval.

Consistency of search direction: The consistency of search direction (best *r*) of both stroke groups for the visible and invisible condition is depicted in Figure 3. There was a significant main effect of Group, $F(1) = 16.537$, $p < .001$, $\eta^2 = .068$. Specifically, the SWM+ group searched less consistent than the SWM– group. Furthermore, there was a significant main effect of Visibility, $F(1) = 5.695$, $p = .018$, $\eta^2 = .024$. The search consistency was lower in the visible condition compared to the invisible condition, indicating a more organized search in the invisible condition. There was no interaction between the effects of Group * Visibility regarding consistency of search direction, $F(1, 228) = 0.452$, $p = .502$, $\eta^2 = .002$.

To summarize, patients in the SWM– group searched more consistent compared to SWM+ patients. Furthermore, all patients searched on average more consistent in the invisible condition than in the visible condition.

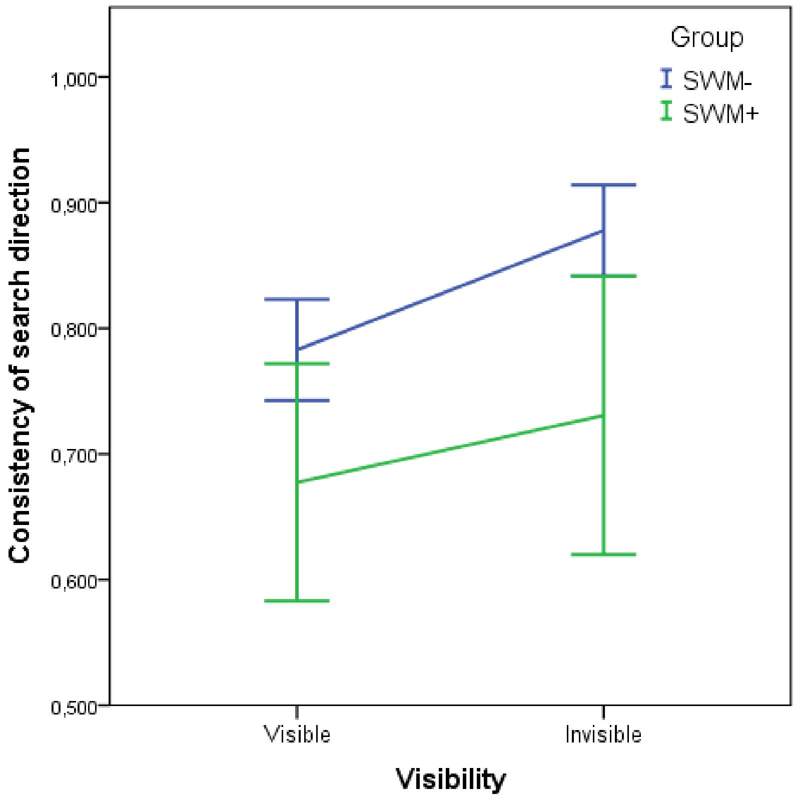

Figure 3. Consistency of search direction of the SWM– and SWM+ group for the visible and invisible condition. Error bars indicate the 95% confidence interval.

Correlations

Visible condition: In Table 3 the correlations between SWM threshold and the measures of organization are depicted. We found no correlation between the SWM threshold and the number of perseverations in the visible condition, $\rho = 0.15$, $p = .108$. There was a small positive correlation between the intersection rate and the SWM threshold, $\rho = 0.26$, $p = .004$, indicating that stroke patients with a more impaired SWM made more intersections. We also found a small negative correlation between consistency of search direction (best *r*) and the SWM threshold, $\rho = -0.19$, $p = .037$, which indicated that patients with a more impaired SWM searched less consistent.

Invisible condition: We found a small positive correlation between the amount of perseverations and SWM threshold, $\rho = 0.28$, $p = .003$. This indicates that stroke patients with a more impaired SWM perseverated more. Furthermore, we found a small positive correlation between the intersection rate and the SWM threshold, $\rho = 0.26$, $p = .004$, which indicates that stroke patients with a more impaired SWM made more intersections. We also found a small negative correlation between consistency of search direction (best *r*) and the SWM threshold, ρ = -0.29, *p* = .001, which indicated that patients with a more impaired SWM searched less consistent.

To summarize, a larger SWM deficit relates to more perseverations in the invisible condition, to more intersections in both conditions, and to a lower search consistency in both conditions. A larger SWM deficit thus relates to less organized and consistent search.

Table 3

Correlations Between SWM Threshold and Measures of Search Organization

Search organization measures	SWM threshold
Visible	
Perseverations	0.15
Intersection rate	0.26**
Best *r*	-0.19*
Invisible	
Perseverations	0.28**
Intersection rate	0.26**
Best *r*	-0.29**

Note. SWM = spatial working memory.
* $p < .05$; ** $p < .01$.
Test of significance: two-tailed.

Discussion

In this study, we aimed to investigate whether organized visual search is related to SWM capacity. We found that stroke patients with an SWM deficit searched less organized than stroke patients without this deficit. This shows that visual search is related to SWM capacity, which is in line with many of the theories discussing visual search that propose that working memory plays an important role in the visual search process (Treisman, 1988; Wojciulik et al., 2001; 2004; Woodman & Luck, 2004). Specifically, the spatial subsystem of working memory is thought to create a general systematics in visual search (e.g. top-down, left-right) and a deficit in SWM would thus result in a less efficient visual search (Woodman & Luck, 2004). Furthermore, it is assumed that visual search and spatial change detection (an important task of SWM) both require access to a shared, limited capacity process in the brain (Oh & Kim, 2004;

Striemer, Ferber, & Danckert, 2013; Woodman & Luck, 2004). Specifically, Woodman & Luck found that an increased SWM load impaired visual search efficiency, which thus shows that SWM and visual search are related through the shared process in the brain. Furthermore, when looking at the brain analogy of SWM and visual search, bilateral parietal lesions could lead to both spatial impairments and impairments in visual search tasks (e.g. Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997), which is another indication of the relation between SWM and visual search.

Next to our first aim, we investigated whether visual search is affected by the absence of marks during cancellation, and whether patients with an SWM deficit are affected differently by the absence of marks than patients without an SWM deficit. We found that in the visible condition, stroke patients made more intersections and searched less consistent compared to the invisible condition. This indicates that stroke patients searched *less* organized in the visible compared to the invisible condition. This is consistent with the notion that when marks are not apparent, a different search strategy is used compared to when marks are apparent (Wojciulik et al., 2001). Namely, when no marks are present, it becomes essential to use a strategy in order to mark all targets, as it is nearly impossible to remember which targets already have been marked and which not.

Contrary, stroke patients made more perseverations in the invisible condition compared to the visible condition. They thus performed worse in the invisible condition regarding perseverations, which is in contrast with the better performance in the invisible condition regarding the organization and consistency of search. An explanation for the deviating perseveration score is that patients had to remember which targets were marked in the invisible condition, as no marks appeared on the screen. Since the targets had similar shapes, the locations of the marked targets had to be remembered (i.e. relying on SWM). Although a more systematic search was applied in general (i.e. more consistent and organized search), it appeared that patients could not remember all the cancelled locations, and erroneously cancelled some targets again. Our result that patients with SWM problems scored lower on every outcome measure in the invisible condition compared to patients without SWM problems can also be explained by the fact that when no marks are apparent, all locations have to be remembered with SWM. This means that the invisible condition of the star cancellation test is more prone to deficits in SWM. When a goal is to minimize the SWM component in a cancellation task, the visible condition of the star cancellation should be used instead of the invisible condition.

Our third aim was to investigate whether a relation existed between the severity of the SWM deficit and the degree of search organization. We found small relations between search organization and SWM on both the visible and invisible condition (only perseverations in the visible condition was not related to the SWM threshold). This indicates that the higher the severity of SWM, the lower the visual search organization is based on perseverations, intersection rate and consistency. Abnormal search patterns on cancellation tests could thus possibly be expected to occur in patients with impaired SWM. However, since perseverations in the visible conditions are not related to severity of an SWM deficit (i.e. perseverations are not affected by an increasingly impaired SWM), this measure of search organization can therefore be used to assess visual search in all stroke patients without the need to control for SWM problems.

We employed an SWM test in which target locations were arranged in a non-lateralized array to measure SWM capacity in stroke patients, whom may or may not have a lateralized attentional deficit, the core deficit of visuospatial neglect. This test was similar to the test used by Malhotra and colleagues (2004; 2005). In typical SWM tests (e.g. Corsi Block Tapping), targets are located on the left and right side of the hemifield. As patients with a lateralized attentional deficit have less attention for targets at their contralesional side, SWM cannot reliably being assessed (Husain & Rorden, 2003). Since in the current task all stimuli were presented vertically, the results of this test could not be accounted for by a lateralized attentional deficit. However, attentional differences between the upper and lower part of the stimulus field were not tested, so it is not possible to rule out that altitudinal neglect played a role (Rapcsak, Cimino, & Heilman, 1988). However, Malhotra and colleagues (2005) found no significant difference in performance between stimuli presented above or below the horizontal middle. Finally, in the test used by Malhotra et al. (2004; 2005), some of the patients could only respond accurately to a single location per trial. Therefore, we used a simplified SWM test in which only two locations had to be remembered per trial, making it less demanding.

We compared the stroke groups on clinical data to check the comparability of the groups and, among other results, we found that the SWM+ and SWM– group were comparable regarding hemisphere of stroke. This was not expected, since multiple studies (e.g. De Renzi, Faglioni, & Previdi, 1977; Malhotra et al., 2005) found that damage to the right parietal and insula region is associated with SWM deficits. We therefore expected that the SWM+ group consisted of more right hemisphere patients. This deviation from previously found results could be due to the fact that the hemisphere of stroke information was not noted for every patient (information missed for 7 patients in the SWM– group and 3 patients in the SWM+ group).

Furthermore, SWM+ patients were tested later after stroke, had more severe cognitive impairments, motor impairments and lower functional independence compared to SWM–

patients. Possibly, patients in the SWM+ group were more severely affected and therefore transferred later to the revalidation center compared to the patients in the SWM– group.

Strengths and Limitations

One of the strengths of this study was the large number of included patients compared to other studies in which stroke patients where investigated (e.g. Malhotra et al., 2004; 2005). Due to the large number of included patients, two groups of at least 30 patients could be formed. Therefore, our sample has a high power, by limiting the impact of outliers or extreme results (Patel, Doku, & Tennakoon, 2003). A second strength was the employment of the non-lateralized SWM test, as already discussed.

However, our study did have some limitations. First, we included patients who were admitted for inpatient rehabilitation care (10–15% of total stroke population; Van Mierlo et al., 2015). This is a relatively young (i.e. elderly patients are less likely to be transferred to a rehabilitation center), moderate affected stroke population with potential for improvement. Therefore, it is not sure whether our results generalize to all stroke patients. Second, we cannot exclude the possibility that some of the patients deliberately re-marked targets for several reasons (e.g. aesthetic, overcompensation), which would still count as perseverations and would thus increase the total number of perseverations. However, we have no reason to assume that there is a difference between the two groups regarding deliberately re-marked perseverations, since patients in both groups may have shown this behaviour. The comparison between the groups is thus still relevant.

Third, the invisible condition of star cancellation test could have suffered from a learning effect, since it was assessed after the visible condition. However, in patients without neglect, good to excellent test repeatability was found (Baily, Riddoch, and Crome 2004). Conversely, it was also found that patients with severe neglect are likely to show an increased performance on repeated testing due to a larger possibility of improvement. Possibly, more neglect patients were present in the SWM+ group, as SWM deficits have been related to neglect (Malhotra et al., 2005). This means that there is a possibility that the SWM+ group had a (larger) learning effect than the SWM– group, which would lead to *better* performance in the invisible condition for the SWM+ patients. However, contrary results were found, as SWM+ patients searched *less* organized compared to the SWM– patients in the invisible condition. But this good to excellent test repeatability found by Baily, Riddoch, and Crome concerned only omissions, which were not a part of the search organization measures we used in this study. However, there has not been a study that compared the test-retest comparability of the star cancellation test regarding the search strategy measures. Further research should look at this relation.

Lastly, the position of the SWM test in the screening (last) could have played an interfering role in terms of fatigue. It was found that fatigue resulted in more errors and sub-optimal performance (Van der Linden, Frese, & Meijman, 2003), which could have possibly resulted in a higher SWM threshold due to errors. Future studies should randomly assign the SWM test and the two conditions of the star cancellation test as the first test in the screening to control for fatigue effects.

Conclusion

Until now, cancellation test are used mostly to assess spatial inattention (Mark et al., 2004). In contrast, few studies have evaluated disruptions in visual search organization. Our study was the first to evaluate visual search organization during cancellation in relation to SWM. Our results show that organized visual search is related to a better SWM capacity. Thus, stroke patients with an SWM deficit search less organized than patients without an SWM deficit. They make more perseverations, have a higher intersection rate, and a lower consistency of search direction. Therefore, in patients with impaired SWM, distinct search patterns on cancellation tests could be expected to occur, in both conditions. Furthermore, it would be interesting to include the search organization measures, next to the omission difference score, in the evaluation of the score of the patient on the test. Namely, next to the determination of the presence of neglect, it would provide us with additional information about the patients cognitive performance, namely SWM.

Next to this, our findings presented here emphasize that when no marks are apparent, the SWM component in the test is increased compared to when marks are apparent. Namely, the score difference of the SWM+ and SWM- groups in both conditions shows that the SWM component is more apparent in the invisible condition. For example, perseverations did not differ between the groups in the visible condition, only in the invisible condition. So, the visible condition of the star cancellation should be used when only neglect is of interest, and the invisible condition should be used when additional information is needed.

Future studies could look into more cognitive components that influence search organization, and differences between the invisible and visible condition of the star cancellation test.

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