Abstract

The current study investigated the size and flexible control of visual span among patients with schizophrenia during visual search performance. Visual span is the region of the visual field from which one extracts information during a single eye fixation, and a larger visual span size is linked to more efficient search performance. Therefore, a reduced visual span may explain patients’ impaired performance on search tasks. The gaze-contingent moving window paradigm was used to estimate the visual span size of patients and healthy participants while they performed two different search tasks. In addition, changes in visual span size were measured as a function of two manipulations of task difficulty: target–distractor similarity and stimulus familiarity. Patients with schizophrenia searched more slowly across both tasks and conditions. Patients also demonstrated smaller visual span sizes on the easier search condition in each task. Moreover, healthy controls’ visual span size increased as target discriminability or distractor familiarity increased. This modulation of visual span size, however, was reduced or not observed among patients. The implications of the present findings, with regard to previously reported visual search deficits, and other functional and structural abnormalities associated with schizophrenia, are discussed.

1. Introduction

The terms visual span, perceptual span, span of effective vision, and useful or functional field of view all refer to the area of the visual field from which information is extracted during each eye fixation (Rayner, 1998). A larger visual span size has been linked to more efficient performance on visual search tasks where one searches for a target among a number of non-target items (e.g., Bertera & Rayner, 2000; Rayner & Fisher, 1987; Reingold, Charness, Pomplun, & Stampe, 2001). In the presence of a wider visual span, more visual information is processed during each eye fixation and fewer fixations are required to complete the search.

Patients with schizophrenia (SCZ) are impaired on visual search tasks; that is, they are less efficient in detecting a target, especially when it is presented in a crowded display (e.g., Elahipanah, Christensen, & Reingold, 2010; Fuller et al., 2006; Lieb, Merklin, Rieth, Schüttler, & Hess, 1994; Mori et al., 1996). Patients are also known to have restricted attentional resources (e.g., Granholm, 1992; Granholm, Morris, Sarkin, Asarnow, & Jeste, 1997; Nuechterlein & Dawson, 1984); a deficit that impedes their performance on a wide variety of tasks requiring attention (e.g., Span of Apprehension Task; Continuous Performance Test). Given that research with healthy participants has shown that experimental manipulations that decrease the availability of attentional resources (e.g., divided attention conditions) cause a reduction in visual span size (e.g., Pomplun, Reingold, & Shen, 2001; Wood et al., 2006), we hypothesized that limited attentional resources among patients with SCZ serve to produce a smaller visual span resulting in impaired visual search performance. In a previous study (Elahipanah et al., 2010), it was found that patients’ visual search impairment was accentuated as a function of target eccentricity. Given that participants were instructed to fixate a central fixation cross at the onset of each search display, this finding is consistent with the hypothesis that patients with SCZ may have a smaller visual span and are, therefore, less likely to detect a peripheral target prior to executing the first saccade. However, in the aforementioned study, visual span size was inferred from the pattern of response times (RTs) and, consequently, it was not possible to rule out other explanations for patients’ disproportionate impairment in detecting more peripheral targets, such as different search strategies or eye movement patterns.

The current experiment aimed to investigate this hypothesis more directly by employing eye-tracking technology and a variant of the gaze-contingent moving window paradigm.
In the present study, we measured patients’ visual span size compared to healthy participants on two different visual search tasks and as a function of two different manipulations of task difficulty. As outlined below, both these manipulations have been shown to influence visual span size in healthy participants. We reasoned that the emergence of a consistent pattern of results across both tasks and conditions would more likely reflect a stable between-group difference rather than a finding that is restricted to a specific search condition. This issue is especially pertinent given prior demonstrations of the task-dependent nature of visual span.

The first search task in the present study (similarity task) employed two different levels of target–distractor similarity (T–D similarity). Decreasing the similarity between the target and distractors results in greater target discriminability, a more efficient visual search (Duncan & Humphreys, 1989), and larger visual spans (e.g., Rayner & Fisher, 1987) among healthy participants. The second task (familiarity task) contrasted search for an unfamiliar target among familiar distractors (U–F condition) with search for a familiar target among unfamiliar distractors (F–U condition). Among healthy participants, the former condition has been shown to produce a more efficient search than the latter condition; that is, a familiarity-based search asymmetry is observed (e.g., Frith, 1974; Richards & Reicher, 1978; Shen & Reingold, 2001). In addition, a U–F search is associated with larger visual spans than an F–U search (Greene & Rayner, 2001). It has been found that familiarity with distractors is the main determinant of search efficiency in the U–F search condition (Shen & Reingold, 2001). This familiarity effect is hypothesized to occur because unfamiliar distractors require extra processing, which results in a narrowing of the visual span so that fewer items are processed during each eye fixation (Greene & Rayner, 2001).

Thus, the main goal of the present study was to compare visual span size between patients and healthy participants on both the similarity and familiarity visual search tasks. In addition, the secondary goal of our study was to ascertain whether patients...
with SCZ can flexibly modulate their visual span across task conditions.

2. Methods

2.1. Participants

Thirty-two patients diagnosed with SCZ or Schizoaffective Disorder according to the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association [DSM-IV-TR], 2000) and 26 healthy control participants completed task 1; twenty-six patients and 24 healthy controls completed task 2.\(^1\) Patients were recruited at the Centre for Addiction and Mental Health (CAMH) and their diagnosis was confirmed using the Structured Clinical Interview for Diagnosis of DSM-IV Axis I Disorders Patient Edition (SCID-P; First, Spitzer, Gibbon, & Williams, 2001a). All SCZ participants were clinically stable and were receiving a single second-generation antipsychotic medication. Patients receiving medications with known cognitive effects (i.e., benzodiazepines, tricyclic antidepressants, anticonvulsants, analgesics, anticholinergics) were excluded from the study. Healthy control participants were recruited from the community via newspaper advertisements and were matched to the patient participants based on age and sex. They were confirmed as free of Axis I psychiatric disorders using the SCID Non-Patient Edition (SCID-N/P; First, Spitzer, Gibbon, & Williams, 2001b). In addition, individuals who reported a lifetime history of any other medical condition known to have cognitive effects (e.g., severe heart or pulmonary disease, insulin-dependent diabetes, thyroid disease. Demographic and clinical characteristics of the sample are shown in Table 1.

2.2. Experimental apparatus

The experiment was constructed and presented using the Experiment Builder Software (SR Research Ltd.). Stimuli were presented on a 22″ (20″ viewable) Viewsonic Professional Series P225fb monitor. A chin-rest was used to keep the participants’ viewing distance fixed at 60 cm from the monitor. An EyeLink 1000 eyetracker was used to record participants’ eye movements and RT, and implement the gaze-contingent moving window paradigm.

2.3. Stimuli and design

2.3.1. Similarity task

A total of five different stimuli were used (see Fig. 1A). The target was always the only circle (○) in the display and the distractors were an equal mixture of stimuli (△, □, and ×) in the low T–D similarity search condition, and an equal mixture of stimuli (○, □, and ×) in the high T–D similarity search condition. There were a total of 49 items in each search display. To eliminate response bias and reduce the possibility of a speed-accuracy trade-off, the search displays always contained a target, either on the right or the left half of the display and participants were asked to respond to target location via a forced-choice format. Participants started each trial by pressing a button while fixating a central dot and indicated target location by pressing a right or left button. Trials were terminated by participants’ response. Correct responses were signaled via a bell and errors via a buzzer. There were two types of trials in the task: baseline trials (during which the whole display was visible to the participant) and window-present trials (during which a circular window linked to the participant’s gaze was present and the display outside this window was masked). Each participant received 16 practice trials – i.e., 2 practice trials for each possible combination of trial type (no window vs. window-present), T–D similarity and target location. After the practice trials, 32 baseline trials (16 trials in each T–D similarity condition) were presented, and the normative RT of each participant in each search condition was calculated as the third quartile of the baseline RT distribution (Pomplun et al., 2001; Reingold et al., 2001). Following the baseline

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\(^1\) Sample size differs across tasks because the familiarity task was modified after the first 8 participants, rendering data for these subjects unusable for the analysis.
trials, 12 blocks of window-present trials were presented. Each block included 16 randomly-presented trials (8 trials in each of the T–D similarity conditions). In the first block, the diameter of the window was set to 8◦ for both search conditions. The median RT in each block was compared to the normative RT to determine the size of the gaze-contingent window in the next block. The window size was increased if the median RT was lower than 98% of the normative RT and decreased if it was shorter than 98% of the normative RT. The first adjustment was an increase or decrease of 1.28◦ in the window diameter, and each successive adjustment was 11% smaller than the preceding one. Window sizes for the two T–D similarity conditions were adjusted separately. To account for any changes in RT due to fatigue or practice, normative RT was updated by introducing a block of 16 baseline trials (8 trials in each T–D similarity condition) after every 3 blocks of window-present trials. These trials replaced the 16 earliest baseline trials, and normative RT was recalculated.

2.3.2. Familiarity task

A total of two different stimuli were used: familiar (amiliar) and unfamiliar (unfamiliar) (see Fig. 2A), described to the participants as “the number four” and “the mirror image of the number four” (Shen & Rensgolz, 2001). There were a total of 25 items in each search display and the target was the unique item in each display (i.e., an odd-man-out visual search). In the U–F condition, participants searched for the unfamiliar (unfamiliar) stimulus among familiar (familiar) distractors. In the F–U condition, participants searched for the familiar (familiar) stimulus among unfamiliar (unfamiliar) distractors. A target was present in each search display and participants were asked to indicate target location (right/left). As in the similarity task, the gaze-contingent moving window paradigm and iterative algorithm were used to measure each participant’s visual span size across search conditions. Each participant received 16 practice trials (i.e., 2 practice trials for each combination of trial type, distractor familiarity and target location). Then to determine the normative RT of each participant in each of the search conditions, 48 baseline trials were presented (24 in each familiarity condition). Next, 12 window-present blocks were presented, each with 24 randomly presented trials (12 trials in each of the familiarity conditions), and the window size was adjusted over blocks using the same algorithm as described for the similarity task. Normalized RT in each condition was updated by introducing a block of 24 baseline trials after every 3 blocks of window-present trials.

2.4. Procedure

After acquiring written consent and general demographic/clinical information, participants’ vision was tested using a Snellen acuity chart. Next, participants were interviewed using the SCID, after which they completed the visual search tasks. Both groups were again highly accurate (above 98% across both conditions). After removal of incorrect responses and outliers from the baseline trials, median RT was obtained for each person in each familiarity condition and baseline search performance was evaluated with a 2(familiarity) × 2(group) mixed models ANOVA with T–D similarity as the within-subject factor and group as the between-subjects factor. The results of this ANOVA showed a main effect of T–D similarity, F(1,56) = 437.55, p < .001, η2 = .89; and group, F(1,56) = 5.78, p = .02, η2 = .09, indicating slower search among distractors with greater similarity to the target, and by the patient group. A significant T–D similarity × group interaction effect was not observed, F(1,56) = 0.99, p = .77, η2 = .002, suggesting that the groups were similarly faster in the low T–D similarity condition.

To obtain an estimate of each person's visual span size, the mean of the last three window sizes in each of the T–D similarity conditions was calculated (Pomplun et al., 2001). A 2(T–D similarity) × 2(group) mixed models ANOVA was performed with visual span size as the dependent variable, T–D similarity as the within-subject factor and group as the between-subjects factor. The results of this ANOVA showed a main effect of T–D similarity, F(1,56) = 191.57, p < .001, η2 = .77; and a significant T–D similarity × group interaction, F(1,56) = 5.85, p = .02, η2 = .10, indicating smaller visual span sizes in the high T–D similarity condition and a differential effect of T–D similarity on the two groups' visual spans. Patients' visual span size was on average 1.22 (degrees visual angle) smaller than that of healthy control participants in the low T–D similarity condition, t(56) = 2.28, p = .03, Cohen's d = 0.60. However, there was not a significant between-group difference in visual span size in the high T–D similarity condition, t(56) = 0.6, p = .55, Cohen's d = 0.16. Moreover, while healthy participants' visual span was on average 5.2° larger in the low T–D similarity condition than in the high T–D similarity condition, t(31) = 11.18, p < .001, Cohen's d = 2.20, patients modulated their visual span size by an average of only 3.6° across the two conditions, t(25) = 11.18, p < .001, Cohen's d = 1.49 (see Fig. 1B).

3.2. Familiarity task

Both groups were again highly accurate (above 98% across both conditions). After removal of incorrect responses and outliers from the baseline trials, median RT was obtained for each person in each familiarity condition and baseline search performance was evaluated with a 2(familiarity) × 2(group) mixed models ANOVA with RT as the dependent variable, familiarity as the within-subject factor and group as the between-subjects factor. The results of this ANOVA showed a main effect of familiarity, F(1,48) = 13.70, p = .001, η2 = .22; and group, F(1,48) = 16.38, p < .001, η2 = .25, indicating slower search among unfamiliar distractors, and by the patient group. A significant familiarity × group interaction effect was not observed, F(1,48) = 1.47, p = .23, η2 = .03, suggesting that the groups were similarly faster when the distractors were familiar.

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PANS = Positive and Negative Syndrome Scale; WAIS-III = Wechsler Adult Intelligence Scale–Third Edition; WRAT = Wide Range Achievement Test.

* p < .05.
To obtain an estimate of each participant's visual span size, the mean of the last three window sizes in each of the familiarity conditions was calculated. A 2(familiarity) × 2(group) mixed models ANOVA was performed with visual span size as the dependent variable, distractor familiarity as the within-subject factor and group as the between-subjects factor. The results of this ANOVA showed a main effect of group, $F(1,48) = 8.60, p = .005, \eta^2_g = .15$; and a significant familiarity × group interaction, $F(1,48) = 7.34, p = .009, \eta^2_g = .13$, indicating smaller visual span sizes among patients with SCZ and a differential effect of distractor familiarity on the two groups' visual spans. A comparison of the groups' visual span sizes in the two search conditions indicated that patients' visual span size was on average 3.4° (visual angle) narrower than that of healthy controls in the U–F search condition, $t(48) = 4.37, p = .001$, Cohen's $d = 1.24$; patients' visual span size was also on average 1° (visual angle) narrower than that of healthy controls on the F–U condition; however, this difference was not statistically significant, $t(48) = 1.04, p = .31$, Cohen's $d = 0.29$. Moreover, healthy participants' visual span in the U–F condition was on average 1.8° larger than in the F–U condition, $t(23) = 2.94, p = .007$, Cohen's $d = 0.60$; while there was not a significant visual span difference among patients between the two conditions, $t(25) = 0.96, p = .35$, Cohen's $d = 0.20$ (see Fig. 2B).

4. Discussion

Patients in the current study demonstrated slower search across all search conditions. This finding is consistent with previous reports of impaired visual search performance among patients with SCZ (e.g., Elahipanah et al., 2010; Elahipanah, Christensen, & Reingold, 2011; Fuller et al., 2006; Mori et al., 1996). The central hypothesis of the current study, however, was that patients with SCZ have a narrower visual span; that is, they process information from a smaller area of their visual field during each eye fixation. The current data support this hypothesis; specifically, in both tasks patients demonstrated smaller visual spans in the easier search condition. The hypothesis of a smaller visual span among patients with SCZ has, to our knowledge, never before been directly investigated; however, our results are consistent with a related finding by Cegalis and Deptula (1981) of impaired peripheral signal detection by patients during the execution of a foveal task, and our previous finding of patients' disproportionate impairment in detecting peripheral targets in a visual search task (Elahipanah et al., 2010). A smaller visual span among SCZ patients is also consistent with normative data of visual span reduction as a function of decreased task difficulty. Healthy individuals adjust their visual span size according to task demands, which has been reported previously (e.g., Rayner & Fisher, 1987). Patients with SCZ, on the other hand, demonstrated less flexibility in the adjustment of their visual span across task conditions. Thus, it appears that patients with SCZ are impaired in their ability to flexibly modulate the size of their visual span in order to optimally allocate their visual attention in accordance with task demands.

As noted above, visual span size has been linked to more efficient performance on visual search tasks (e.g., Bertera & Rayner, 2000; Rayner & Fisher, 1987; Reingold et al., 2001). Therefore, the current finding of a narrower visual span among SCZ patients describes one possible mechanism underlying patients' impaired search for targets in visual scenes. Visual span size is also highly correlated with reading speed (Legge et al., 2007). Therefore, a smaller visual span size may lead to reading impairments among patients with SCZ. Reading ability has not been widely investigated among SCZ patients; however, Revheim et al. (2006) have reported significant impairment in reading rate, comprehension, and phonological awareness among SCZ patients. Neural models suggest that top–down adjustment of attentional focus is implemented by frontal and parietal cortical areas through modulation of visual cortex activity (Corbetta & Shulman, 2002). More specifically, the frontal eye field (FEF) and the posterior inferior frontal gyrus (IFG) send top-down signals to suppress activity in portions of visual cortex corresponding to unattended locations, and enhance activity in areas corresponding to attended locations, and this modulation changes as a function of stimulus discriminability; that is, anticipation of low – as opposed to high – contrast stimuli is associated with greater FEF and IFG activity, and less visual cortex activity at the unattended locations (Sylvester, Jack, Corbetta, & Shulman, 2008). The dorsal fronto-parietal network is also modulated by bottom–up factors, such as the distinctiveness of objects in a visual scene (e.g., Bichot & Schall, 1999; Thompson, Bichot, & Schall, 2001), and is, therefore, a likely neural substrate for the adjustment of attentional focus or visual span according to task demands. This notion is consistent with the findings of Scalf et al. (2007), who reported increases in the activation of the FEF and inferior frontal gyrus subsequent to practice designed to improve the functional field of view (i.e., visual span) of older adults. The observed changes in brain activity were associated with improvements in participants' performance across a number of task conditions that required visual attention and perception, suggesting a common neural network underlying the control of the visual span and visual attention. Collectively, these data suggest that the SCZ-related visual span impairment observed in the current data may be related to previously reported structural and functional abnormalities in the FEF and inferior frontal gyrus among SCZ patients (e.g., Camchong, Dyckman, Austin, Clementz, & McDowell, 2008; Jeong, Wible, Hashimoto, & Kubicki, 2009; Yoon et al., 2008).

Impairment in the allocation and adjustment of attentional focus may also be related to patients' deficits in the magnocellular or dorsal visual system. The magnocellular pathway projects predominantly to the dorsal visual stream and mediates the perception of motion and spatial relationships while the parvocellular projections to the ventral stream are mainly involved in perception and discrimination of the colour and form of objects (Mergian & Maunsell, 1993; Ungerleider & Mishkin, 1982). In addition, and of particular relevance to the current investigation, the anatomic connectivity of the dorsal and ventral visual systems points to a functional division whereby peripheral visual processing is preferentially supported by the dorsal pathway (Pandya & Yeterian, 1990; Yeterian & Pandya, 2010). It is also hypothesized that the faster processing of visual stimuli by the magnocellular system in the dorsal stream is important in guiding the spotlight of attention; consequently, deficits in the dorsal pathway may result in visual search impairments or dyslexia (Vidyasagar, 1999). Moreover, several studies have demonstrated deficits in the magnocellular/dorsal visual system among SCZ patients (e.g., Butler et al., 2001; Butler & Javitt, 2005; Chen et al., 1999; King, Christensen, & Westwood, 2008; Martínez et al., 2008; O'Donnell et al., 2006). Collectively, these data suggest that patients' magnocellular/dorsal visual system deficit may result in impairments in the allocation of the spotlight of attention and, consequently, visual search and reading impairments. Interestingly, Revheim et al. (2006) found that SCZ patients' reading impairments were correlated with their magnocellular deficits. Future research can determine whether the relationship of magnocellular deficits and reading impairments among SCZ patients is mediated through a smaller visual span size. One of the distinct advantages of the visual span measure is that it provides additional information over and above the results from
gradient or variable-resolution gaze-contingent displays (Reingold, 2000). Distractibility of the gaze-contingent border, for example, by using differences in visual span size. As such, methods that reduce the impact of distractor familiarity on search efficiency was quantitatively similar across populations, it may be executed via qualitatively different mechanisms. Further studies are required to investigate this intriguing possibility.

Similarly, in the present study, impaired modulation of visual span was not associated with disproportionate impairment across the task conditions as measured by RT. Thus, the current data demonstrate that deficits in visual span modulation exist even in the absence of concurrent RT effects. The above discrepancies between the RT and span size measures are likely due to the fact that although span size clearly impacts global search efficiency as measured by RT, it is but one of several variables that influence search efficiency.

Some limitations of the current study must also be noted. First, the gaze-contingent moving window paradigm can be considered a valid tool for the measurement of visual span size inasmuch as certain assumptions are valid. One important assumption is that restricting one’s effective field of view disrupts their visual performance. While this is an empirically valid assumption among healthy individuals, it may not hold among patients with SCZ. More specifically, if patients have difficulty allocating their attention to the area of the visual field that can be efficiently processed for current task purposes, the introduction of the restricting window may initially improve their performance by eliminating peripheral noise; patients’ performance may then deteriorate only when the window size is further reduced. Although this hypothesis is important, it cannot be sufficiently investigated in the current data and awaits examination in future studies. Second, patients with SCZ may be distracted and slowed down to a greater degree by the presence of the gaze-contingent window. If so, the current algorithm would overestimate the visual span size for patients compared to healthy controls. Given the direction of between-group differences in the current study, this possibility does not invalidate our results, but rather might cause an underestimation of the between-group differences in visual span size. As such, methods that reduce the distractibility of the gaze-contingent border, for example, by using gradual or variable-resolution gaze-contingent displays (Reingold, Loschky, McConkie, & Stampe, 2003) might be more suitable for visual span studies in clinical populations. Third, the size of the attentional window might also be adjusted according to one’s expectation of the next search display (e.g., Nakayama & Joseph, 1998). Therefore, it is possible that arranging the search conditions in separate blocks might have yielded different results, as it would have allowed patients to adjust their visual span size over the entire block. Therefore, contrasting span size across blocked versus randomized presentation of easy and difficult search conditions among both patients and controls would be an interesting follow-up to the present investigation.

In conclusion, the current data provide evidence of a smaller visual span among patients with SCZ. Moreover, they suggest an attenuated modulation of visual span size as a function of task demands among patients with SCZ that should also be considered when comparing visual span size between patients and healthy individuals. These differences in the distribution and flexible modulation of visual attention might – at least partially – explain patients’ impaired performance on experimental and daily tasks that depend on the visual processing of information.

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