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ORIGINAL ARTICLE

The Attentional Fields of Visual Search in Simultanagnosia and Healthy Individuals: How Object and Space Attention Interact

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Abstract

Simultanagnosia is a deficit in which patients are unable to perceive multiple objects simultaneously. To date, it remains disputed whether this deficit results from disrupted object or space perception. We asked both healthy participants as well as a patient with simultanagnosia to perform different visual search tasks of variable difficulty. We also modulated the number of objects (target and distracters) presented. For healthy participants, we found that each visual search task was performed with a specific "attentional field" depending on the difficulty of visual object processing but not on the number of objects falling within this "working space." This was demonstrated by measuring the cost in reaction times using different gaze-contingent visible window sizes. We found that bilateral damage to the superior parietal lobule impairs the spatial integration of separable features (within-object processing), shrinking the attentional field in which a target can be detected, but causing no deficit in processing multiple objects per se.

Key words: feature integration, parallel, posterior parietal cortex, serial, simultanagnosia

Introduction

Bálint (1909) described a reduced functional "field of view" (translation of Bálint's "psychic paralysis of gaze" from Husain and Stein 1988) in a patient who manifested no attention for visual events appearing outside central vision, having neither a visual field deficit nor oculomotor paralysis. This component of the Balint's triad, now called simultanagnosia (a term coined by Wolpert 1924), elucidates a distinction between the visual field and a functional "attentional field."

While the deficit of global visual processing is described in simultanagnosia, it remains to be determined whether it emerges from impaired multiple-"object" or "space" processing (Dalrymple et al. 2013) following bilateral damage to the superior parietal lobule (SPL). As an example, it has been proposed that these patients have difficulties judging whether a dot is within or outside a complex shape (Fig. 1A) because the necessary global perception of the visual display is prevented due to a shrinkage of peripheral spatial attention causing them to sample the visual information within an excessively restricted attentional window (Michel and Hénaff 2004). However, global perception might instead be prevented because of impaired parallel object processing, causing them see the dot or the shape but not both at the same time. The fact that these patients have trouble reporting all objects present in a visual scene even when the objects are superimposed within the same space (e.g., Fig. 1B) also suggests that there may be an additional impairment of object processing in particular when spatial integration of some lines (but not

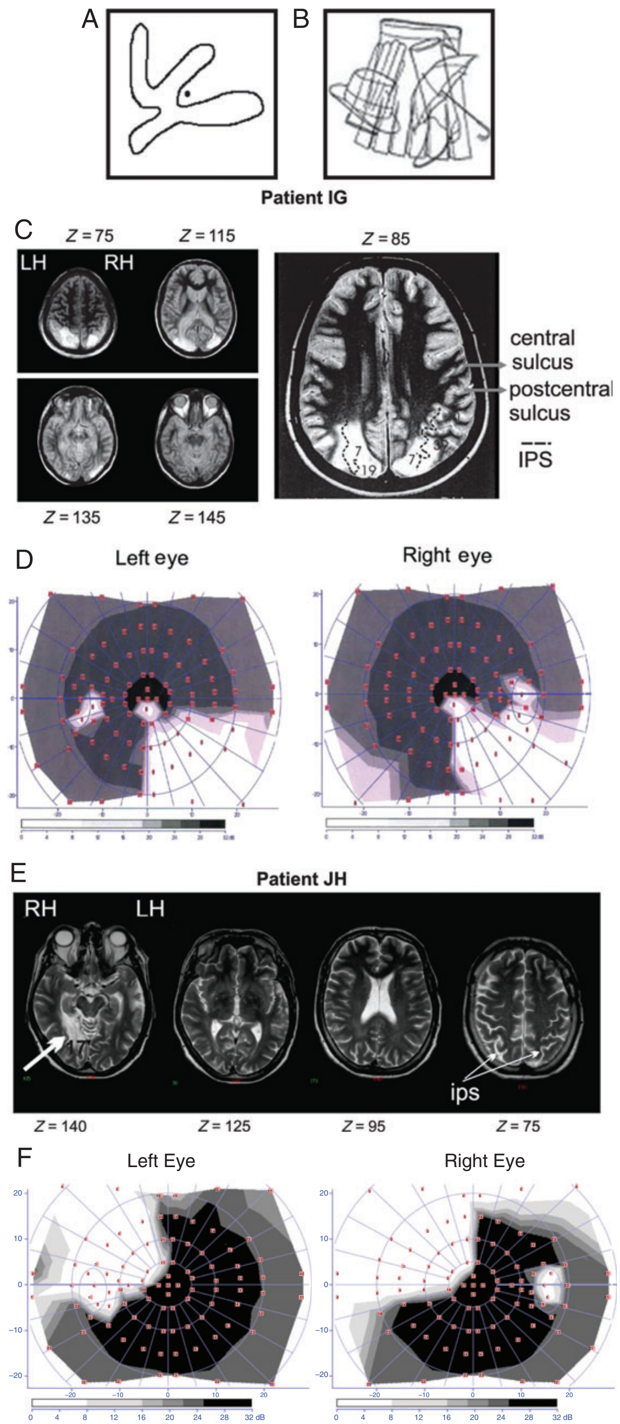

Figure 1. Example figures for testing simultanagnosia, MRIs, and visual field perimetry of patients IG and JH. (*A* and *B*) Figures typically used to test for simultanagnosia. In (*A*), the patient is asked to determine whether the dot is inside or outside of the object. In (*B*), the patient is asked to distinguish and name all the overlapping objects in the figure. (*C*) T_2-weighted magnetic resonance sections of patient IG's brain showing fairly symmetric bilateral lesions located at the upper and lateral occipito-parietal junction, cortically and subcortically, involving mainly the intraparietal and the parieto-occipital sulci with full damage to Brodmann's area 7 in the superior parietal lobule (SPL). Horizontal (axial) sections are shown with the corresponding z coordinates in standard Talairach space, from dorsal to ventral regions (Talairach and Tournoux 1988). The Z = 85 section is shown expanded on the right to delineate damaged brain areas more precisely. Brodmann's areas are numbered inside gray circles. The dotted lines outline the intraparietal sulcus (IPS). LH, left hemisphere, RH, right hemisphere. (*D*) Visual field perimetry for patient IG showing quadrantanopia in the right lower quadrant of the visual field of both eyes, due to the subcortical damage of the optical radiations below the PPC in the left hemisphere. (*E*) T_2-weighted magnetic resonance sections of patient JH's brain showing unilateral damage restricted to the optical radiations and the primary visual cortex (V1, Brodmann's area 17) in the right hemisphere. Horizontal (axial) sections are shown with the corresponding z coordinates in standard Talairach space, from dorsal to ventral regions (Talairach and Tournoux 1988) to attest that the posterior cerebral artery infarct fully spared the parietal cortex. (*F*) Visual field perimetry for patient JH shows quadrantanopia in the left upper quadrant of the visual field of both eyes.

others) is required to form a coherent visual object. Bálint's original report reflects this ambiguity: the perceptual consequence of bilateral posterior parietal damage was described as "an extreme restriction of visual attention, such that only one object is seen at a time" (Bálint 1909; Husain and Stein 1988). Based on the second part of Bálint's description, simultanagnosia (meaning "disorder of simultaneous perception," Luria 1959) is nowadays conceived as a deficit of parallel multiple object processing (Holmes and Horrax 1919; Coslett and Saffran 1991; Baylis et al. 1994; Rafal 1997, 2003; Rizzo and Vecera 2002; Moreaud 2003). Alternatively, other authors have instead highlighted the first part of Bálint's description proposing that the basic deficit of these patients lies at the global level of visual space processing (Kase et al. 1977; Karnath et al. 2000; Michel and Hénaff 2004; Clavagnier et al. 2006). This interpretation in terms of a deficit of "spatial" attention has been reinforced by neuroimaging data, confirming the involvement of the SPL in the covert orienting of attention toward peripheral locations (dorsal attentional network: Corbetta et al. 2000); thus, patients with simultanagnosia are left with only attention to central locations following bilateral SPL damage. Here, we aimed at testing whether there was such a peripheral shrinkage of spatial attention (Bay 1953; Tyler 1968; Thaiss and de Bleser 1992; Michel and Hénaff 2004; Shalev et al. 2004; Dalrymple et al. 2013) in a patient with simultanagnosia following bilateral SPL damage, and, if so, within which context.

Indeed, if simultanagnosia corresponds to a reduction of spatial attention (attentional field), then this pathological reduction may depend on the task and experimental condition. We know that stroke patients with chronic simultanagnosia detect targets regardless of their eccentricity during the assessment of their visual field by perimetry (where the visual scene is poor with only one very salient dot presented at a time apart from the central fixation cross) but fail to detect peripheral stimuli in natural visual scenes, suggesting that the attentional field size depends on the complexity of visual processing. A similar distinction between the visual field and the "perceptual span" or "region of effective vision" or "functional visual field" has been demonstrated in healthy subjects when they are engaged in difficult visual tasks (Geisler and Chou 1995; Motter and Simoni 2008), as has been demonstrated in reading using the gaze-contingent moving window paradigm (McConkie and Rayner 1975) or during visual search (Young and Hulleman 2013). Change blindness paradigms (Pashler 1988; O'Regan 1992; Rensink 2000; Simons 2000) have also shown that a large part of the visual field (particularly in peripheral vision) may not be attended, especially when the subjects are involved in a difficult visual search task. Lavie (1995) proposed that visual tasks that impose a high processing load require greater attentional resources, which may result in a smaller spatial attentional field. More specifically, there may be an interaction between the size of the attentional field and the allocation of attentional resources to other visual processing tasks such as the spatial integration of objects made of separable features (in feature-absent visual search displays), binding of object features (in conjunction visual searches), or parallel processing of multiple objects (Treisman and Gelade 1980; Wolfe and Horowitz 2004; Eckstein 2011). If Bálint's syndrome results from reduced spatial attentional resources, then one should observe variable spatial distributions of attention depending on the difficulty of the task for a simultanagnosic patient, as well as for healthy control participants. In order to determine the basic deficit causing simultanagnosia and to determine the fundamental contribution of the SPL in the multiple attentional processes, we investigated these interactions between allocation of attentional resources to space and to objects in healthy participants and in a patient with bilateral SPL lesions using visual search.

To this aim, we assessed the performance of the simultanagnosic patient IG in different visual search tasks (Fig. 2A–F) as well as the performance of healthy participants performing the same tasks with different sizes of gaze-contingent visible windows (Fig. 2G), a manipulation we hypothesize mimics the consequences of a peripheral reduction of the "attentional field" (Pomplun et al. 2001; Dalrymple et al. 2010, 2011, 2013; Young and Hulleman 2013). The principle is simple: if the visible window size is smaller than the attentional field usually deployed by the participant, there should be a reduction of performance with respect to the condition performed with full view, that is, without any masking of peripheral vision. Conversely, if the visible window size is larger than the participant's attentional window, then the visible window should not affect performance (reaction time [RT] to detect the target among distracters). Using this paradigm, we show that healthy participants work within a specific attentional window size for a given visual search task and that the cost in RT when forced to perform the task with a smaller visible window did not depend on the number of objects. The patient with bilateral SPL lesions showed search RT deficits only during search tasks that required the spatial integration of separable features, where she showed a similar pattern as the controls, with a variable (but shrunk) attentional window that depended on the visual search task but not the number of distracters.

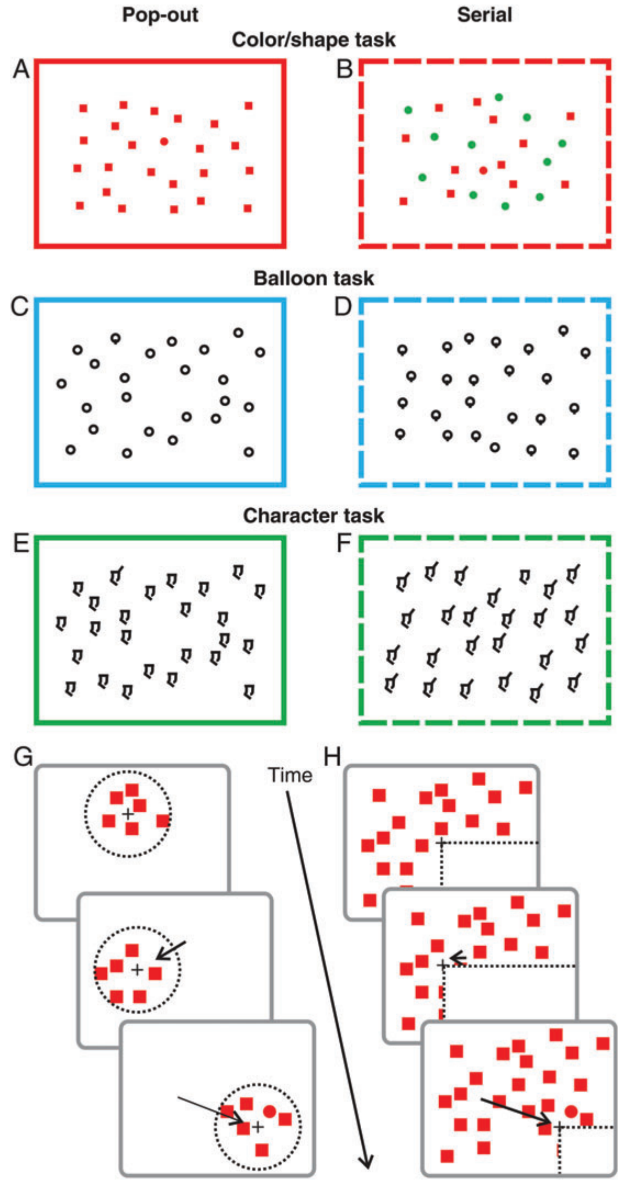

Figure 2. Visual search arrays and examples of gaze-contingent displays. (*A* and *B*) Color/shape task. In the pop-out condition (*A*), participants searched for a red circle among red squares. In the serial condition (*B*), participants searched for a red circle among green circles and red squares. (*C* and *D*) Balloon task. In the pop-out condition (*C*), participants searched for a lollipop shape among circles (feature-present), whereas in the serial condition (*D*), participants searched for a circle among lollipops (feature-absent). (*E* and *F*) Character task. Similar to the balloon task, in the pop-out condition (*E*), participants searched for an object with an additional feature (oriented bar on the top left of the object) among other objects without the feature, while the serial condition (*F*) required looking for the unique object without the additional feature. (*G*) Gaze-contingent display. Within the gaze-contingent condition, participants viewed the search arrays through different sized visible windows that were centered on the fovea and moved with gaze in real time. The area surround the visible window was white. The dotted circle shows the visible window and the cross depicts the current foveal location. The black arrows depict the direction of the saccade to current gaze. As the participants looks around, only a certain part of the array is visible at a given time. (*H*) Gaze-contingent mask mimicking quadrantanopia. Control participants also performed each task with a gaze-contingent mask that occluded the bottom-right visual quadrant relative to gaze position.

Materials and Methods

Participants

Patient IG was 37 at the time of this experiment. Ten years ago, she suffered from an ischemic stroke related to acute vasospastic angiopathy in the posterior cerebral arteries, established with an angiogram. Magnetic resonance imaging revealed a hyperintense signal on T2 sequencing that was fairly symmetrically located at the upper and lateral occipito-parietal junction, cortically and subcortically. Reconstruction of the lesion (Pisella et al. 2000) indicated that it involved mainly the intraparietal (IPS) and the parieto-occipital sulci with full damage to Brodmann's area 7 in the SPL, but there was also limited damage to the dorsal-lateral part of Brodmann's areas 19 and 18 and to the upper part of the angular gyrus (BA39) in the inferior parietal lobule (Fig. 1C). Patient IG presents with bilateral optic ataxia which remains chronic but never presented with either hemispatial neglect or oculomotor apraxia. Her eye movements were completely normal at clinical assessment, with latencies and amplitudes similar to controls within the functional saccadic range: Gaveau et al. (2008) found deficits only for very far eccentricities, for example, 20° or greater, saccade amplitudes which are almost never used in everyday life as they would normally be implemented with a head contribution. Patient IG has a quadrantanopia in the right bottom quadrant of the visual field of both eyes (Fig. 1D), due to subcortical damage of the optic radiations below the SPL in the left hemisphere. She also presents with mild chronic simultanagnosia. Initially, her simultanagnosia was so severe that it prevented her from perceiving two dots presented simultaneously, but this recovered quickly (see Pisella et al. 2000). During the acute phase, she reported that she could not clearly see more than one finger of her hand at once; she is now able to see "almost" all fingers simultaneously. At the time of testing, she could correctly distinguish all the objects in overlapping figures, but the skirt (the larger figure) was reported late and last (Fig. 1*A*). She also struggled more than control participants (she was successful but took more time) to determine whether the dot was inside or outside the figure (Fig. 1*B*). For the Navon test (Navon 1977), she did not show the classical global precedence effect of healthy controls: she was not slower in identifying the local letter when it was incongruent with the global letter (sH, hS) compared with when it was congruent (sS, hH). Note that for most simultanagnosic cases reported in the literature, patients tend to have larger lesions that are progressive (e.g., neurodegenerative disease such as posterior cortical atrophy), tend also to be older with ages of around 50 and up (Gilchrist et al. 1996; Clavagnier et al. 2006; Dalrymple et al. 2007; Huberle et al. 2010; Thomas et al. 2012) and therefore tend to have more severe symptoms (e.g., cannot report the global letter in the Navon test at all) including associated symptoms such as aphasia, alexia, neglect, constructional, or oculomotor apraxia.

We also included patient JH as a brain-damaged control for IG. He was 60 at the time of testing. Eleven years previously, he presented with a stroke in the vascular territory of the right posterior cerebral artery. Magnetic resonance T2 imaging sequence (Fig. 1*E*) attests that the damage specifically involved the primary visual area (Brodmann area 17) in the right occipital cortex and the optical radiations unilaterally, fully sparing Brodmann's area 19, the parietal cortex, the parieto-occipital, and IPS sulci. Patient JH presents with a pure quadrantanopia in the left upper quadrant of the visual field of both eyes (Fig. 1*F*).

In addition, different groups of neurologically intact controls participated in the different tasks. There were a total of 4 control participants ($M = 33.5$, age range = 23–39 years, all female) for the color/shape task, 4 control participants ($M = 37.8$, age range = 36–40 years, 3 female) for the balloon task and 4 ($M = 34.8$, age range = 28–39 years, all female) for the character task as well as for the control filled balloon task. The same controls performed all conditions within each task and some control subjects took part in multiple tasks.

Apparatus

Participants sat in a semidark room with their eyes at a distance of 57 cm from a high-speed CRT monitor (dimensions: 40 × 30 cm, refresh rate: 160 Hz), with their forehead and chin stabilized. Stimuli were presented on the screen using a real-time stimuli presentation (Visual Stimulus Generator ViSaGe, Cambridge Research System, Rochester, UK) along with custom-written code developed in the laboratory. Eye movements were recorded using a high-speed video Eyetracker (Cambridge Research System) at 1000 Hz. Subjects responded using a ViSaGe response box.

Stimuli and Procedure

Participants performed three different pairs of tasks in a randomized blocked order with pop-out and serial versions of each task (Wolfe 2001). One pair (Fig. 2*A*,*B*, color/shape task) consisted of finding a red disk among red squares (unique shape feature search) or among red squares and green disks (conjunction of shape and color features). Two pairs were unique feature-present and feature-absent tasks (Fig. 2*C*–*F*, balloon and character tasks). IG and controls also participated in an additional control task, the filled balloon task (Fig. 10*A*,*B*), which was identical to the balloon task except that the stimuli were not perceived being made up of separable features, as they were filled.

Each block of trials consisted of 60 target-present trials (3 repeats of 20 trials for each group of 11, 23, or 47 distracters, corresponding to 12, 24, and 48 objects) and 3 target-absent trials (1 repeat of 1 trial of each group of distracters) resulting in a total of 63 trials. Within each set of 20 target-present trials, the target appeared in each of 20 areas (the screen was divided into 5 equal columns by 4 equal rows). The distracters, depending on number, were then distributed randomly (with a certain minimum spacing between distracters) across the rest of the space.

Each trial began with a fixation dot at the center of the screen. Once fixation on the dot was detected, the dot was replaced by the stimulus array. Subjects were asked to press the right button on a response box as fast as possible with their right hand if they detected a target among distracters (target-present trials) and press the left button with their left hand if there was no target in the stimulus array (target-absent trials).

To determine the size of the attentional field, control groups performed each of the 3 pairs (pop-out/serial) of tasks with different gaze-contingent visible windows (Fig. 2*G*). For the color/shape task, the visible window diameters were 5°, 10°, 15°, 20°, and 30°. For the balloon and the character tasks, we used the same sized visible windows with the addition of a 12.5° one as we expected smaller attentional windows in the serial versions of these tasks and therefore planned to have a finer spatial resolution between 10 and 15°. In addition, all controls performed each task without a gaze-contingent window (full view condition).

Patient IG performed all tasks in the full view condition and in addition, she also performed the balloon feature-present (pop-out) task with a 15° and 20° visible window. In order to compare the performance of the controls to that of IG for the full view condition, we also had control participants perform each task with a gaze-contingent white mask that concealed stimuli located in the lower right visual field (relative to the current gaze position), mimicking IG's quadrantanopia (Fig. 2*H*).

Patient JH performed only the full view condition for the pop-out and serial versions of the balloon task (Fig. 7).

IG additionally performed the full view condition for both the pop-out and serial versions of the filled balloon task. Control subjects performed the same filled balloon tasks in full view condition and also the quadrantanopic gaze-contingent versions of the task (Fig. 10*B*).

All participants performed 2–4 blocks per condition.

Data Analysis

The total number of trials across the main group of experiments was 63 352 trials. Of those, 3100 were target-absent trials (which were not analyzed) and 60 252 were target-present trials. For the filled balloon task, there were 9154 total trials, of which 8719 were target-present trials. Patient JH performed 126 total trials, of which 120 were target-present trials. While there were much fewer target-absent than target-present trials (5% of total trials), there were very few errors made (where the target was absent but was reported as present) comprising only 3% of the total target-absent trials. Moreover, target-absent trials were randomly presented with the target-present trials. Thus, it is unlikely that the few number of target-absent trials biased the participants to automatically press the target-present button at every trial.

We analyzed only the target-present trials. Incorrect trials, where the target was present but was reported as absent comprised 1.7% of all trials. These were also removed from the analysis. RTs were calculated for correct button presses as the difference between the time of the button press and the stimulus array onset. In order to remove outliers that may bias the mean RTs, for each subject and each condition, we removed all RTs that were outside of the 2 standard deviations (SDs) of the mean, that is, outside of 95% of the distribution of RTs.

Repeated-measures *t*-tests were performed on RTs of controls to evaluate the effect of window sizes. All comparison groups were tested beforehand for assumptions of normality using the Shapiro–Wilks test and were found to be not significantly different from a normal distribution ($P > 0.05$) except for one (balloon serial with a mask of 12.5°, $P = 0.013$). To test for effects of object number for control participants, repeated-measures ANOVAs with window size and object number as factors were used.

IG's and JH's performance (RTs) was compared against the control group using modified *t*-tests (Crawford and Garthwaite 2002a, 2002b, 2007); these are designed specifically to test whether single subject's (patient) data fall within the range of control data, using the control group's mean and SD. They provide a robust comparison of a single data point against a small group of controls for single case studies. In addition, we directly compared RTs for IG and JH using single-case comparison statistics (Crawford et al. 2010).

To test for effects of object number for patient IG for the pop-out tasks, univariate ANOVAs were used in the full view condition with object number as a factor for each task. The total *N* (and thus df) were the number of trials for the full view condition for each task. For comparisons of IG's RTs in the pop-out balloon task between the 20° visible window and the full view condition as well as between the 15° visible window and full view condition, we used an ANOVA with window size and object number as factors. We also repeated this same analysis for each control subject for the 20° visible window. We also compared the difference in RTs between conditions for IG compared with controls using the standardized difference test of Crawford and Garthwaite (2005).

In control participants, we aimed at estimating the size of the attentional window with further accuracy using a model which assumes an inverse relationship between the attentional workspace (AW) and the search RTs, that is, the smaller the available AW, the longer the search RTs; search $\mathrm{RT} = a + b/\mathrm{AW}$, where a and b are model parameters; parameter a was the baseline search RT for the maximum window size (full view). We determined the available AW by assuming a Gaussian-shaped AW (e.g., see Intriligator and Cavanagh 2001) that could be cut off by the gaze-contingent viewing window (GCW). Thus $\mathrm{AW} = N(0,\sigma^2) \cap \mathrm{GCW}$. Parameters b (scaling parameter) and σ (SD) were calculated through nonlinear least-square fitting to the data. The size of the attentional window was determined to be 2 SD.

Results

Control subjects' Cost-per-Item Analysis

To establish that the search tasks we used (Fig. 2*A*–*F*) were typical search tasks that fell within the pop-out and serial categories, we calculated the cost per item (cpi) for each condition for the full view window. As can be seen in Figure 3, for all 3 pop-out tasks, the cpi varied from 0.6 to 2.5 ms per item. For the serial tasks, the cpi varied from 6.4 ms for the relatively easy color/shape conjunction task to 63 ms for the very difficult feature-absent character task. In the visual search literature, a delineation of 10 ms has often been suggested between efficient (pop-out) and inefficient (serial) searches; however, meta-analyses show no marked division (Wolfe and Horowitz 2004). Thus, the different search tasks fall well within a continuum from very efficient to very inefficient searches as has been suggested in the literature (Treisman and Gelade 1980; Wolfe and Horowitz 2004; Eckstein 2011; Young and Hulleman 2013).

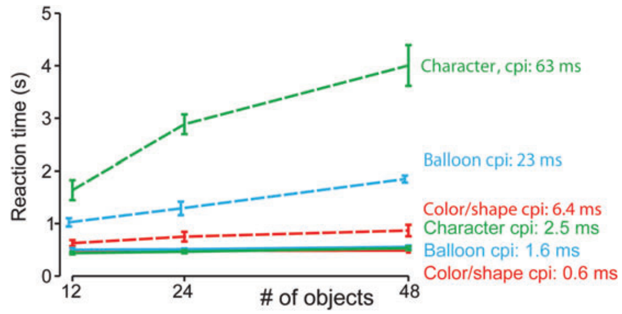

Figure 3. Cost per item across the different visual search tasks. Reaction times (RTs) for the controls are shown for different object numbers within each task. The color/shape tasks are shown in red, the balloon tasks in blue and the character tasks. Pop-out tasks are shown as solid lines and serial tasks are shown in dotted lines. Cost-per-item slopes are shown on the left with italics denoting serial tasks and were calculated using linear fits across the three object numbers. The standard errors are across subjects.

Control subjects' performance with variable visible windows.

We first determined the attentional window sizes for the control participants. Figure 4 shows mean performance for controls as a function of the visible window size for all the visual search tasks for window sizes of 10°, 12.5° (except for the color/shape task), 15°, 20°, 30°, and full view. As can be seen, overall RTs steadily increased as the visible window size decreased, but more or less depending on the task. We performed repeated-measures *t*-tests (Bonferroni corrected) comparing the RTs for different visible windows to the full view condition within each task to determine the point at which a visible window significantly increases RTs for each task. As mentioned earlier, we hypothesized that if there is an increase in RT with a certain visible window, this signifies that the attentional window is larger than the visible window, whereas no cost to RT suggests that the attentional window is smaller than the visible window used. In other words, even with the full view, the participant would not identify targets outside of their attentional window and thus would only perceive the target after moving gaze around the screen which increases RT. Thus having a visible window that is larger than the attentional window would make no difference. Across all the pop-out tasks (Fig. 4*A*,*C*,*E*), RTs were not significantly different for the 30° window compared with the full view condition (Bonferroni corrected paired *t*-tests, $P > 0.05$), suggesting that the attentional window was not bigger than 30°. However, RTs across all three pop-out tasks were significantly higher for the next visible window size, that is, 20° compared with the full view condition (color/shape, $t_{(3)} = 9.7$, $P < 0.002$, balloon, $t_{(3)} = 12.7$, $P < 0.001$, character, $t_{(3)} = 8.8$, $P < 0.01$; Bonferroni corrected, $P < 0.05$, shown by the * signs in Fig. 4, see figure legend), suggesting that the attentional window was bigger than 20°; according to our hypothesis, if the attentional window was smaller than 20°, then we would not have seen an increase in RTs. Thus, we averaged between the two and made a coarse estimate of 25° as the size of the attentional window (for all three pop-out tasks, dotted vertical lines).

For the serial tasks, RT performance varied across the different types of tasks (Fig. 4*B*,*D*,*F*). In contrast to the pop-out tasks,

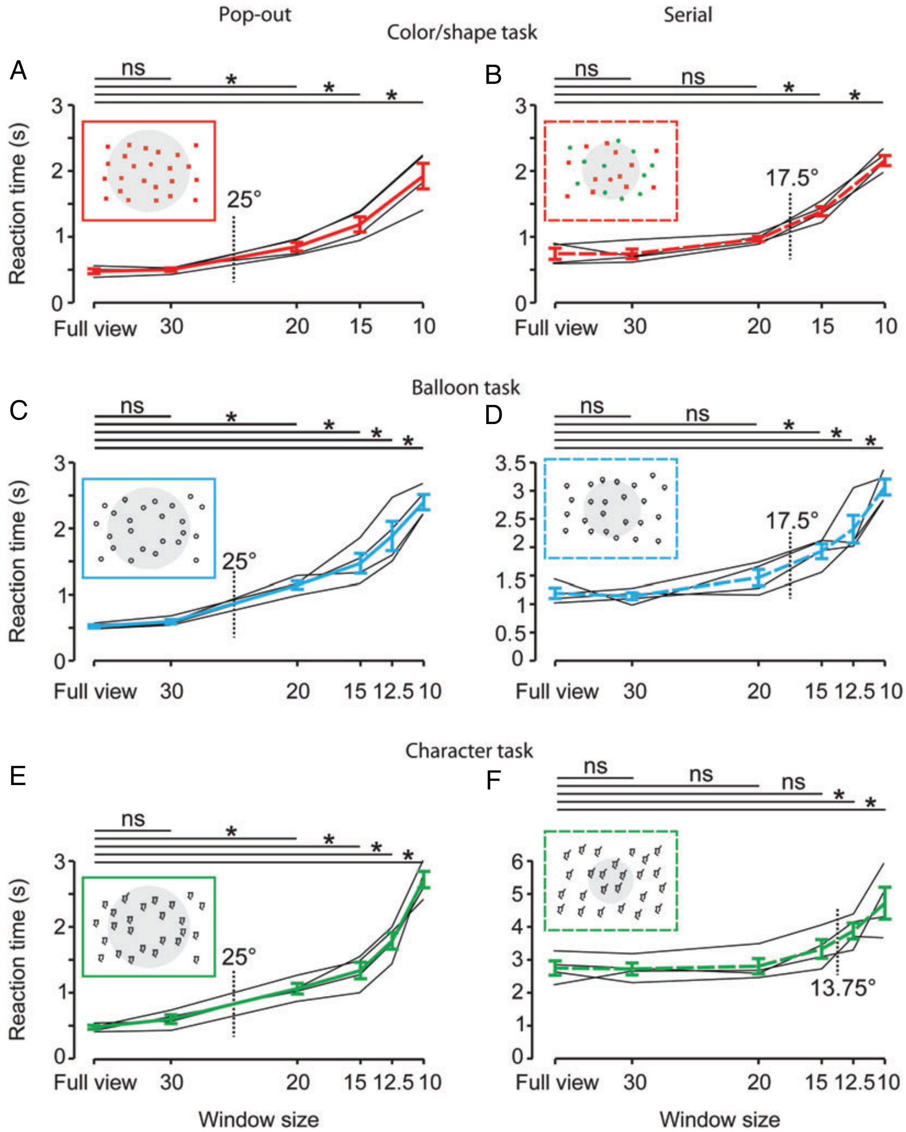

Figure 4. Reaction times for different visible windows. Mean reaction times are shown across controls within each task for the color/shape tasks in red (*A* and *B*), the balloon task in blue (*C* and *D*), and the character task in green (*E* and *F*). Individual reaction times are also shown for each participant (thin black lines). Pop-out tasks are shown in the left panel and the serial tasks are shown in the right panel. Note the difference in the ranges of reaction times in the y-axis. The horizontal lines above each figure depict each statistical comparison performed (multiple paired *t*-test, corrected using Bonferroni), ns, nonsignificant ($P > 0.05$, Bonferroni corrected), *$P < 0.05$, Bonferroni corrected). Window size is the diameter of the visible window centered on the current foveal location. The gray circles in the stimulus icons depict the estimated size of the attentional window based on the statistical comparisons.

RTs did not increase steadily depending on the visible window size, but rather varied depending on the task. In general, we found that the more difficult the search task in terms of longer RTs in the full view condition and higher cpi (Fig. 3), the shallower the increase in RT. For the color/shape conjunction task, RTs were significantly longer with a visible window of 15° ($t_{(3)} = 13.7$, $P < 0.01$, Bonferroni corrected = $P < 0.05$) but not 30° or 20° ($P > 0.05$); therefore, we estimated the attentional window size for this task to be 17.5°, that is, halfway between 15° and 20°. The findings were similar for the balloon task, RTs were not significantly different from the full view condition for neither the 30° nor the 20° windows ($t_{(3)} < 2.5$, $P > 0.05$), but were significantly different for the 15° window ($t_{(3)} = 6.3$, $P < 0.01$, Bonferroni corrected = $P < 0.05$), giving an estimate of an attentional window of 17.5°. For the most difficult task, that is, the character task, RTs did not significantly increase from the full view condition until the visible window size was 12.5° ($t_{(3)} = 21.7$, $P < 0.001$, Bonferroni corrected = $P < 0.05$), placing our estimate of the attentional window at 13.75°.

Finer Attentional Window Size Estimates and Relationship with cpi

In order to establish a more precise estimate of the size of the attentional window without the necessity of performing experiments with minute changes in the size of the visible window (e.g., 20° vs. 21° visible windows), we fit a Gaussian model to the RTs of each subject for each task (see Data Analysis section). The average attentional windows are delineated by the colored vertical dotted lines in Figure 5A. Figure 5A plots the normalized change in RTs relative to the full view condition for the different window sizes and allows a direct comparison of the increase in RTs across the different tasks. The attentional

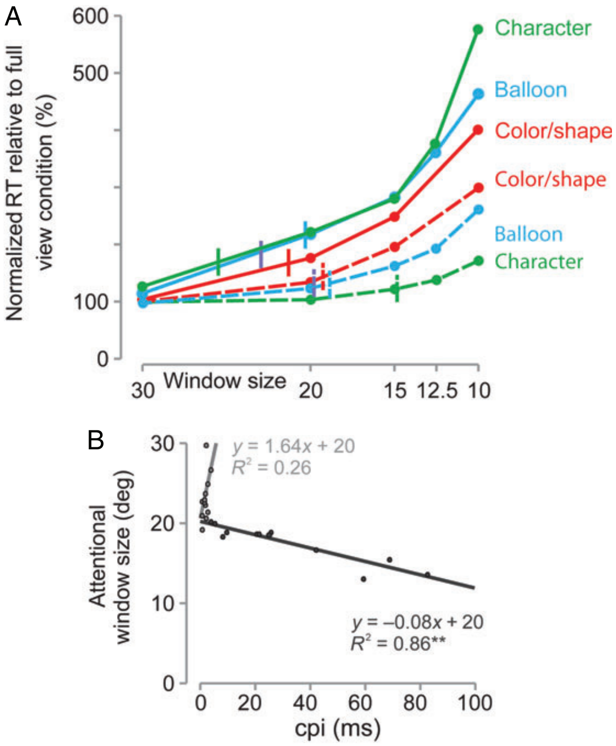

Figure 5. Normalized RTs, attentional window sizes, and the relationship to cost-per-item. (*A*) Normalized RTs across all conditions. The percentage increase relative to full view condition (in percentage) was calculated for each subject and each visible window by dividing the relevant RT for each visible window by the RT in the full view condition and converting this value into percentages, where 100% would be the same RT as the full view condition and 600% would be a 6-fold increase relative to the full view condition. Dots depict averages across subjects at each visible window, solid lines represent pop-out tasks, and dashed lines depict serial tasks. The color-coded vertical lines delineate the average attentional window for each task. (*B*) Relationship between attentional window size and cpi. Each data point represents a single subject within each task color coded for the pop-out (light gray dots) and the serial (dark gray dots). The linear fits are shown by the corresponding colors as are the slopes, intercepts, and R^2 values. **Significance at $P < 0.01$.

window fits were estimated to be 21.25°, 20.35°, and 25.5° for the color/shape, balloon, and character pop-out tasks and 19.33°, 18.86°, and 14.89° for the color/shape, balloon, and character serial tasks, respectively.

We investigated the relationship between cpi and attentional window size separately for the pop-out and serial tasks. In Figure 5B are plotted the pop-out (light gray) and serial (dark gray) individual subject data points as well as the linear fits from regression analyses. For the pop-out tasks, we did not find a significant relationship between cpi and attentional window size ($r_{(12)} = 0.51$, $P > 0.05$), likely because both the cpi and the attentional window size were very similar across the three tasks. In contrast, there was a strong significant relationship between cpi and attentional window size for the serial tasks ($r_{(12)} = -0.92$, $P < 0.001$).

Interaction Between Object Number and Window Size

We also tested whether there was an interaction between window size and object number for the control subjects, which would provide insight as to whether the attentional window was determined by spatial extent or the number of objects. Different sized visible windows would allow only a certain number of objects to be visible at one time (each gaze location), which vary depending on whether the search array was made up of 12, 24, or 48 objects. Thus, if the attentional window size varies depending on the number of objects, we would expect an interaction between number of objects and visible window size, because the cost in RT for a given visible window size would vary depending on the number of objects. In other words, the attentional window sizes would be different for the different number of objects in the search array. On the other hand, if the attentional window was determined by spatial extent only, then the differences in RTs across the different visible window sizes would be the same across the different number of objects, resulting in no interaction effect. Figure 6 plots RTs for each task for different visible window sizes and different number of objects. As can be seen, the different lines corresponding to RTs evolution with respect to the number of objects for different visible windows are mostly parallel to the same line in the full view condition, suggesting a similar cost of the reduction of the visible window size independent on the number of distracters falling within the window. Repeated-measures two-way ANOVAs with visible window size and object number as factors revealed no significant interaction effects for any of the tasks (color/shape pop-out, $F_{8,24} = 1.6$, $P > 0.05$; color/shape serial, $F_{8,24} = 0.5$, $P > 0.05$; balloon pop-out, $F_{10,30} = 0.8$, $P > 0.05$; balloon serial, $F_{10,30} = 0.6$, $P > 0.05$; character pop-out, $F_{10,30} = 0.9$, $P > 0.05$; character serial, $F_{10,30} = 1.9$, $P > 0.05$). This suggests that the attentional window size is spatial in nature as RTs change by the same amount regardless of the number of objects for each visible window.

IG's and JH's Performance

We asked patient IG to perform all 6 visual search tasks in the full view condition (Fig. 7). As can be seen, her RTs (light green lines) were close to the control full view condition (shown in black) for both the pop-out and serial color/shape tasks but were much longer for the other tasks. In order to be able to directly compare RTs between the patient and the controls, controls performed the different visual search tasks using a gaze-contingent mask that mimicked the patient IG's quadrantanopia (Figs 1D and 2H). Comparisons of RTs between IG and the control group with quadrantanopic mask (gray lines) within each task (Fig. 7) revealed nonsignificant differences in the color/shape task (pop-out, $t_{(3)} = 0.72$, $P > 0.05$; serial, $t_{(3)} = 1.04$, $P > 0.05$) but significantly higher RTs in all other tasks (balloon pop-out, $t_{(3)} = 6.2$, $P < 0.01$; balloon serial, $t_{(3)} = =11.03$, $P < 0.001$; character pop-out, $t_{(3)} = 12.6$, $P < 0.01$; character serial, $t_{(3)} = 16.63$, $P < 0.001$).

We tested an additional patient (JH, see Materials and Methods section) with lesions to the visual cortex and a quadrantanopia. He performed the pop-out and serial versions of the balloon task in the full view condition, to compare with IG, who is impaired in this task (Fig. 7). Comparisons of RTs between JH and the control group with a quadrantanopic mask (gray lines) revealed nonsignificant differences in either the pop-out ($t_{(3)} = 2.38$, $P > 0.05$) and serial ($t_{(3)} = 1.42$, $P > 0.05$) conditions (Fig. 7C,D). We also directly compared the RTs for patients JH and IG (Crawford et al. 2010) and found that IG's RTs were significantly higher than those of JH for both the pop-out ($t_{(3)} = 2.99$, $P < 0.05$) and serial ($t_{(3)} = 6.4$, $P < 0.001$). Thus, unlike patient IG, the deficit of patient JH can therefore be explained solely by his quadrantanopia (and perhaps his older age than the control group).

Based on these findings, we conclude that the IG's deficit lies in an inefficiency in integrating separable features into an object (required in the balloon and character but not in the color/shape task which required a conjunction of shape and color features),

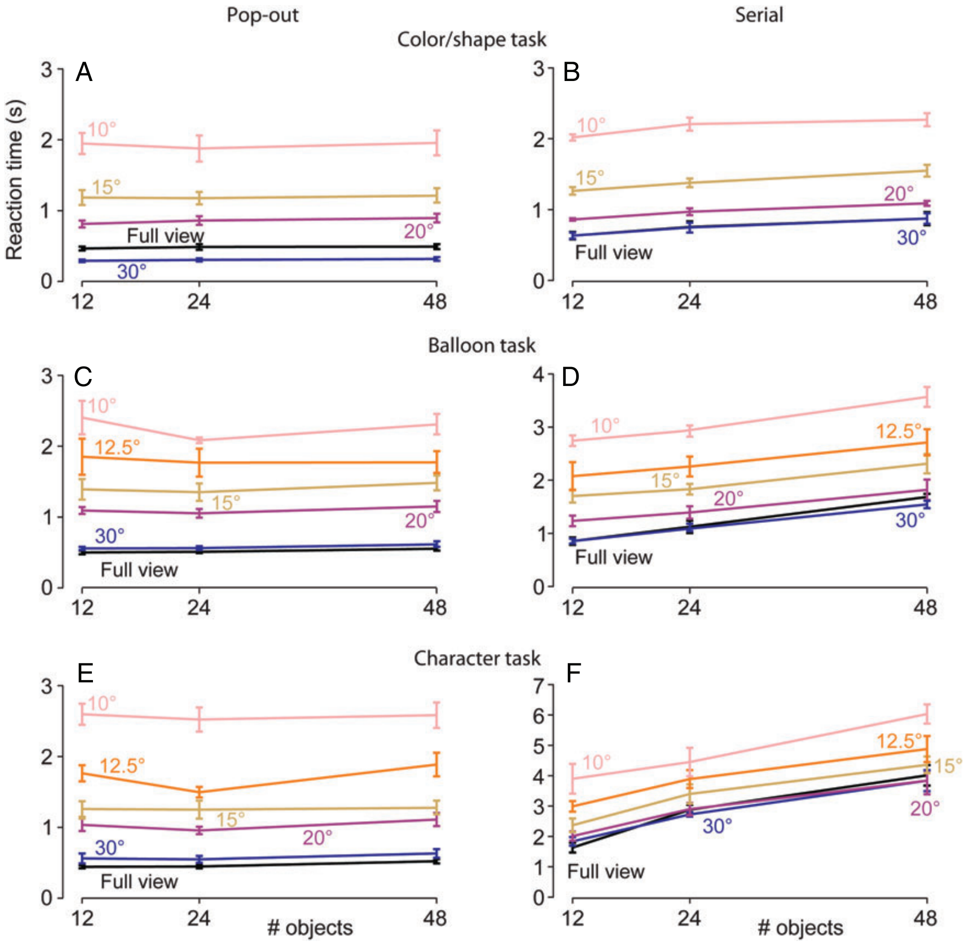

Figure 6. Visible window sizes versus number of objects. Reaction times for different visible windows are plotted as a function of number of objects for the color/shape tasks (*A* and *B*), the balloon tasks (*C* and *D*), and the character tasks (*E* and *F*). The pop-out tasks are in the left panel and the serial tasks are in the right panel. Visible windows are color coded and labeled in the figures.

in addition to her quadrantanopia. Task difficulty cannot explain the pattern of IG's results since according to the cpi analysis on controls (Fig. 3), the conjunction color/shape task is more difficult than both the pop-out balloon or character tasks, but patient IG is able to perform this task as efficiently as the controls. In addition, the increase in RTs for the IG in the pop-out tasks did not result from an impairment in parallel processing as can be seen in Figure 7C,E. For all pop-out tasks, the patient's performance was not significantly different across object numbers as shown by univariate ANOVAs with object numbers as a factor (color/shape, $F_{2,309} = 0.8$, $P > 0.05$, $N = 312$; balloon, $F_{2,307} = 1.5$, $P > 0.05$, $N = 310$; character, $F_{2,255} = 2.3$, $P > 0.05$, $N = 258$). Rather, the increase in RTs for IG in the balloon and character tasks was similar to the performance of the controls when performing the same tasks with restricted visible window sizes.

To compare IG's performance with that of the controls with restricted visible windows (for the balloon and character tasks), we removed trials where the target was in IGs blind quadrant when the stimulus array first appeared, that is, the lower right visual field. We calculated mean RTs for IG only for trials where the target was situated in the 3 other quadrants. For the pop-out balloon task, IG's RTs were significantly longer than controls with a visible window of 20° ($t_{(3)} = 27$, $P < 0.001$) and were significantly shorter than controls with a visible window of 12.5° ($t_{(3)} = 7.4$, $P < 0.01$) but were not significantly different from controls with a visible window of 15° (Fig. 8A, IG mean RT, 1.52 s; control mean RT, 1.47 s, $t_{(3)} = 1.4$, $P > 0.05$). For the character pop-out task, IG's RTs were significantly shorter than controls with a visible window of 10°($t_{(3)} = 5.1$, $P < 0.01$) and significantly longer than controls with a 30° visible window ($t_{(3)} = 4.8$, $P < 0.05$) but not significantly different from controls with a 12.5° (Fig. 8C, IG mean RT, 1.31 s; control mean RT, 1.34 s, $t_{(3)} = 1.7$, $P > 0.05$), a 15° visible window (control mean RT, 1.78 s, $t_{(3)} = 0.1$, $P > 0.05$) or a 20° window (control mean RT, 1.06 s, $t_{(3)} = 1.4$, $P < 0.05$).

For both the serial tasks, her RTs were significantly higher than the performance of controls with the smallest visible window tested, which was 10° (Fig. 8B, serial balloon, IG mean RT, 5.97 s, control mean RT, 3.07 s, $t_{(3)} = 92$, $P < 0.001$; Fig. 8C, serial character, IG mean RT, 13.06 s, control mean RT, 4.72 s, $t_{(3)} = 7.7$, $P < 0.01$).

In the pop-out balloon task, the comparison between controls with visible windows and IG suggested that IG's attentional window ranged between 12.5° and 20°. This was not as clear for the character pop-out task (wider range of possibilities) and for the serial tasks, the results suggest that her attentional window is smaller than 10°, but it is unknown what the possible range is. Based on these findings, we elected to have the patient perform the pop-out balloon task with selected gaze-contingent visible windows.

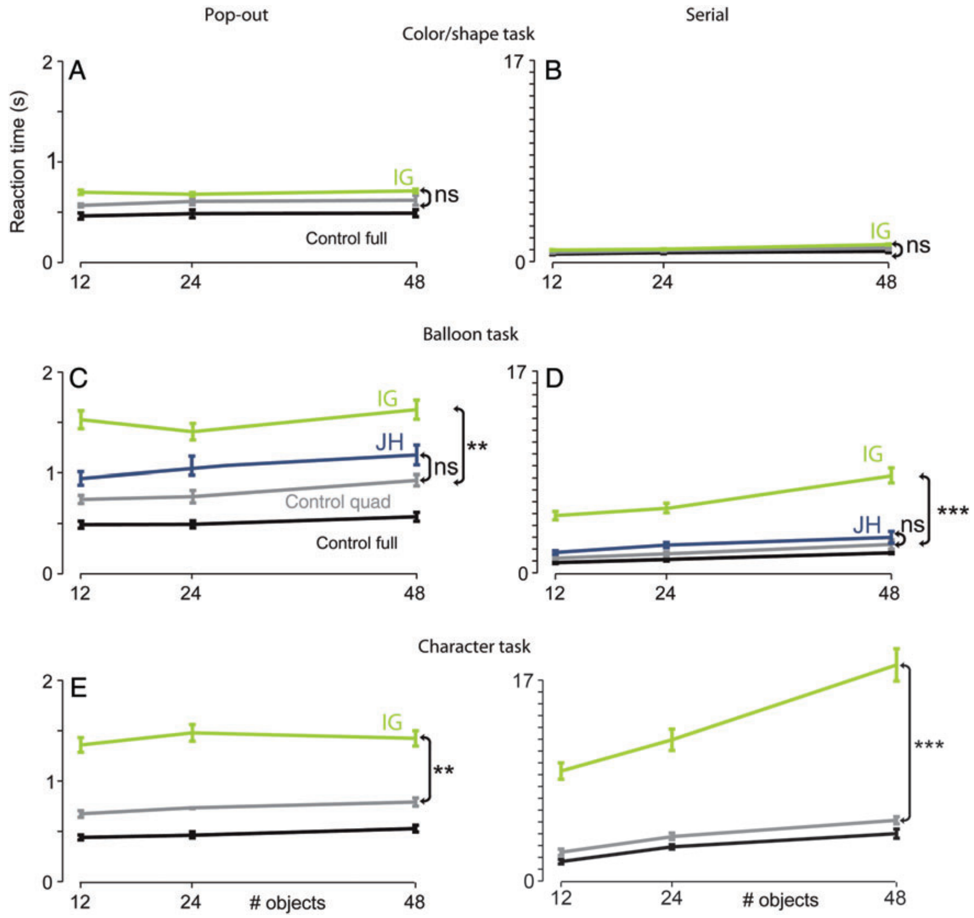

Figure 7. IG and JH's performance across the different tasks. IG's reaction times (light green lines) along with controls full view (black lines) and quadrantanopia (gray lines) conditions are shown as a function of the number of objects for the color/shape (A and B), the balloon (C and D) and the character (E and F) tasks. Mean RTs from control patient JH are also shown in C and D (in dark blue lines). The pop-out tasks are shown in the left panel (same y-axis range) and the serial tasks (same y-axis range) are shown in the right panel. The double arrows on the right of each figure show the comparisons made and the significance value (ns, nonsignificant, $^{**}P < 0.01$, $^{***}P < 0.001$). Modified t-tests comparing a single subject against a group were used (Crawford and Garthwaite 2002b, 2007). Error bars for controls are SEM across the group of controls whereas for IG and JH are SEM across individual RTs.

Demonstration of Smaller Attentional Window Size in Patient IG

Figure 9 depicts RTs as a function of object number for IG for the full view condition (green solid line) as well as with a 20° and a 15° visible window condition (bright green and khaki lines). As is evident, there was no difference in RTs for IG with a visible window of 20° compared with the full view condition (all quadrants, $F_{1,421} = 0.93$, $P > 0.05$), no effect of distracter number ($F_{2,421} = 0.67$, $P > 0.05$) and no interaction effect ($P > 0.05$). For comparison, we performed the same analysis on each of the control subjects. In contrast to IG, the RTs for the 20° visible window for all 4 subjects was significantly different from the full view condition ($F_{2,156\text{–}402} > 63$, $P < 0.001$, no distractor effect and no interaction effect).

In contrast to the findings of the 20° visible window, IG's RTs were significantly longer with a visible window of 15° than in the full view condition ($F_{1,430} = 6.7$, $P < 0.05$), but without any significant distracter or interaction effect ($P > 0.05$).

For the control subjects, a visible window of 30° did not affect performance suggesting that their attentional window was smaller than 30°. On the other hand, a visible window size of 20° resulted in significantly higher RTs compared with the full view condition (Fig. 6C), suggesting that their attentional window was larger than 20°, thus in between 20° and 30°. For IG, a visible window of 20° did not change her performance, suggesting that her attentional window was smaller than 20°. However, with a visible window size of 15°, her RTs significantly increased, suggesting that her attentional window was larger than 15°, thus in between 15° and 20°.

In addition, we compared the difference in RTs between visible window sizes as follows, 1) between controls and IG for the difference between the full view condition and the 20° visible window and 2) between the controls and IG for the difference between the 20° and the 15° windows. We found a significant difference between the full view condition and the 20° visible window between the controls and IG ($t_{(3)} = 7.9$, $P < 0.01$). This result confirms the results above that a 20° visible window increases RTs for the controls but not for IG. Thus, it shows that IG's attentional window is smaller than 20°. We did not find a significant difference between the controls and IG for the difference between the 15° and 20° window sizes ($t_{(3)} = 0.7$, $P > 0.05$). This confirms that the attentional window for IG is between 20° and 15° because reducing visible window between these sizes now produces a cost in IG as well as in controls.

Strikingly, the patient never "spotted" the restriction of her peripheral vision with these sized visible windows. The 20° visible window not only did not affect her performance but it was

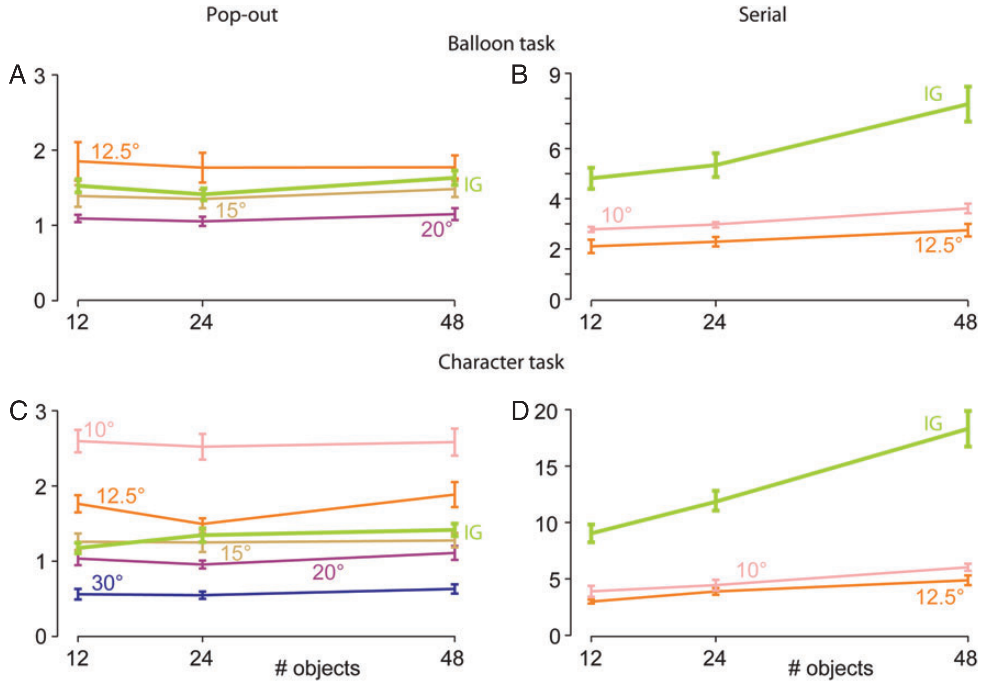

Figure 8. IG's performance compared with controls. IG's reaction times (light green lines) for targets that were in the three quadrants outside of the quadrantanopic field at central fixation are shown along with the closest control RTs for the balloon pop-out (*A*), the balloon serial (*B*), the character pop-out (*C*), and the character serial (*D*) tasks. RTs for the controls for different window sizes are color-coded as in Figure 6.

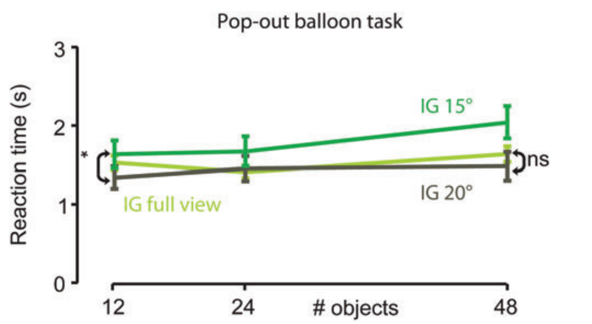

Figure 9. IGs performance in the pop-out balloon task with different visible windows. IGs search time is plotted against number of objects in the full view condition (light green line) and with a visible window of 15° (green line) and 20° (khaki line). Error bars are SEM across RTs. Ns, nonsignificant. *$P < 0.05$.

also not detected at all by the patient (no spontaneous report and also no report at specific verbal questioning after the experiment: we asked whether something was different in these sessions, the response was "nothing"). When we applied the 15° visible window and asked the same questions to her, the patient reported that "the screen was sometimes flickering" (probably due to the sporadic hiding of the items at the border of the window when it was moving left and right following the microsaccades during fixations), but her attention to the border of the visible window was not sufficient to provide her with an appropriate global understanding of what was happening. Note that in controls, even when a visible window is beyond the limits of the attentional field used for a specific task, it is consciously perceived, suggesting that healthy participants still keep some minimal attentional resources for peripheral vision outside their functional field of view for a given task, while it does not appear to be the case for patient IG.

Filled Balloon Control Experiment

In order to support our conclusion that patient IG's deficit lies in an inefficiency in integrating separable features into an object, we asked patient IG and 4 control subjects to perform an additional filled balloon task (Fig. 10). The visual stimuli were identical to those of the open balloon task except that the circles were filled (Fig. 10*A*,*B*) in order to be perceived as single objects rather than separable objects. This idea of replacing an empty space by a filled surface in order to "group" different parts into a single object was inspired by the experimental report of the simultanagnosic patient SL who could not make judgments about the triangular spatial relationship between 3 separate discs (Kanizsa illusory triangle), but could do so if the solitary triangle was made explicit by adding surface texture to the triangle (Barton et al. 2007). Similarly, our patient IG reported that she could not well see the line and the circle "at the same time," whereas she could do so when we filled the balloons. Patient IG performed the pop-out and serial versions of this filled balloons task, as did control subjects (both full view condition and with a quandrantanopic mask). For this task, patient IG performed no differently from control subjects for both the pop-out ($t_{(3)} = 1.43$, $P > 0.05$) and the serial ($t_{(3)} = 2.37$, $P > 0.05$) versions (Fig. 10*C*,*D*). These results demonstrate that IG did not show a restricted attentional window for objects that are perceived as a single object, even though their shapes are identical to the balloon stimuli. Thus, the restricted attentional window arises with objects with perceivable separate features.

Discussion

Visual search of a target among distracters involves the coordination between mechanisms that are required for object processing (feature-based attention) and mechanisms that govern the extent of space to be monitored (spatial attention). Here, we

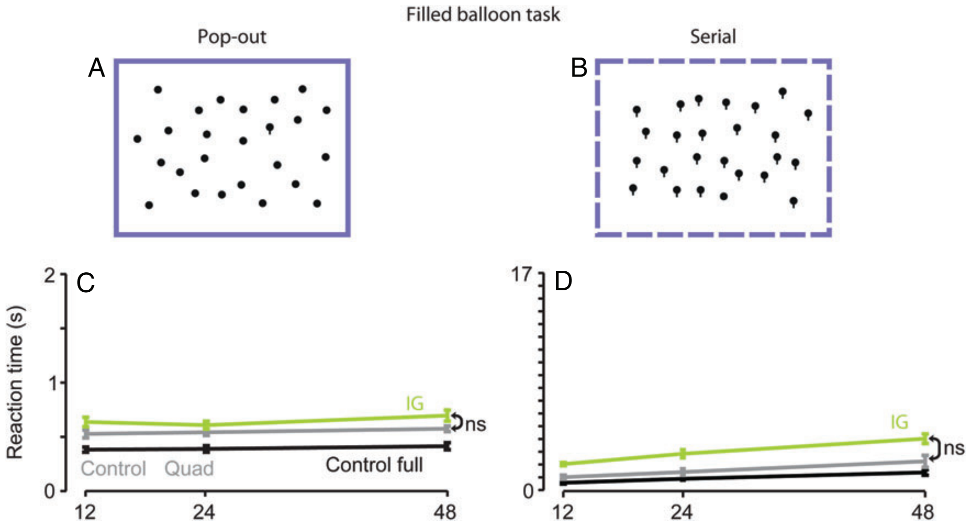

Figure 10. IG's performance in the filled balloon task. The visual search array is shown for the pop-out (*A*) and serial versions of the filled balloon (*B*) task. The arrays were identical to the balloon task except that the lollipops were filled. IG's reaction times (light green lines) along with controls full view (black lines) and quadrantanopia (gray lines) conditions are shown as a function of the number of objects (*C* and *D*) The pop-out tasks are shown in the left panel (same y-axis range as in Fig. 7) and the serial tasks (same y-axis range) are shown in the right panel. The double arrows on the right of each figure show the comparisons made and the significance value (ns, nonsignificant). Modified *t*-tests comparing a single subject against a group were used (Crawford and Garthwaite 2002b, 2007). Error bars for controls are SEM across the group of controls whereas for IG are SEM across her RTs.

identified how attention-for-object and attention-for-space interact in healthy subjects in two different "feature-present" (pop-out) and "feature-absent" (serial) searches, as well as in a shape unique-feature (pop-out) search versus a shape and color feature-conjunction (serial) search. By varying the size of a gaze-contingent window, we were able to determine that each visual search task was performed with a specific attentional window size: a spatial area around the fovea in which the target can be detected, irrespective of the number of objects falling in this window. Moreover, this attentional window size was remarkably consistent across the 4 healthy participants (Fig. 4). Indeed, we observed a cost in RTs for a gaze-contingent window size that varied according to the task but was independent of the number of distracters and similar across all participants. A significant increase in RT for a certain visible window size revealed that the respective visible window was smaller than the attentional "working space" set by the subject to perform the task. The attentional working space set by healthy subjects was similar in all 3 searches of unique features (pop-out tasks) but varied for the serial search conditions: it was larger in the object conjunction task than in the feature-absent tasks, and smaller in the feature-absent character task in which the difficulty of the spatial integration of separable features was higher. This suggests that all tasks require the sharing the attentional resources between object processing and space monitoring such that there is a continuum between easy object processing during which the target can be selected in the entire visual field (restricted by visual acuity) and more difficult object processing (here the necessary integration of separable features) which shrinks the "working space" in which target selection can occur, independently on the number of distracters within this attentional window.

Interestingly, our estimates of the task-specific attentional field sizes strongly correlated with the task-specific cpi, suggesting that they are 2 measures of the same phenomenon. It makes sense that the slope of RTs based on number of distracters (cpi measure) will be sharper if the attentional field in which multiple objects are processed in parallel is smaller. Moreover, a smaller attentional field will have to be displaced more often to cover the entire visual display size, in which the distracters are homogenously distributed.

The main purpose of this experiment was to study the consequences of bilateral lesions of the SPL on visual search by testing patient IG in the same visual search tasks. Patient IG was impaired only in feature-present and feature-absent conditions involving objects made of separable features, features, and not in the filled balloon tasks in which the equivalent stimuli were not made up of separable features. Moreover, in contrast to patient JH with a lesion to the occipital cortex, IG's deficit could not be solely explained by her quadrantanopia. The first conclusion is thus that the SPL, known to be involved in the covert allocation of attention in space (Kase et al. 1977), is also involved in object perception via processes of spatial integration of separable object features within objects. In contrast, IG did not demonstrate a deficit in the parallel processing of multiple objects, suggesting that damage to the SPL does not increase the attentional competition between-objects. For example, the patient's behavior was comparable with the controls in the object feature-conjunction task (color/shape, Fig. 7) across all distracter number conditions, that is, she does not show a deficit in the simultaneous perception of multiple objects. This is noteworthy as it also indicates that patient IG was not impaired in the processes of binding object features such as color and shape.

Together with this specific difficulty in integrating separable features, the consequence of the bilateral damage to the SPL on IG's performance in feature-absent and feature-present visual search tasks nicely mimicked the effects of applying gaze-contingent visible window sizes smaller than their attentional field on the performance of healthy subjects (Fig. 8). In other words, the performance of patient IG consisted of an offset of the line representing the RT performance of the healthy subjects in full view condition with respect to distracter number (a cost in RT independent of the number of distracters on the display, Fig. 7). Our interpretation of these results is that she demonstrated the same interaction between attention-for-object and attention-for-space as observed in controls but that an increased requirement of attentional resources for the spatial integration of separable features (within-object processing) shrinks the "attentional field" in which a target can be detected, independent on the number of objects falling within this attentional window. Taken together, these results fit with the hypothesis of a peripheral shrinkage of the attentional field, without an impairment of parallel processing (Michel and Hénaff 2004; Dalrymple et al. 2013): the target still pops-out but within a smaller attentional window. These results are also consistent with previous studies (Dalrymple et al. 2010, 2011) that showed that the performance of a patient with simultanagnosia in the identification of the global aspect of hierarchical letter stimuli and in viewing complex social scenes could be mimicked with a gaze-contingent restricted spatial area of visual processing in normal individuals, that is, without any additional impairment of visual processing.

In order to provide a direct demonstration that the patient actually deployed attention within a more restricted attentional window than controls, we applied gaze-contingent restricted windows to the patient and compared her performance with the full view condition with the same principle as for control participants: if the restricted window does not change IG's performance it means that her attentional window is smaller; otherwise, it means that it is larger than the visible window. We therefore asked the patient to perform the feature-present balloon condition with gaze-contingent windows of 20° and 15°, windows that produce a significant search RT cost in controls. The 15° gaze-contingent visible window did increase IG's search RT, demonstrating that her attentional window was larger than 15°. Note that the estimated size of the attentional window of simultanagnosic patient in previous reports was <4° (Tyler 1968; Dalrymple et al. 2010, 2007), probably because of the mild severity of simultanagnosia in our chronic patient (she was able to identify the global aspect of hierarchical stimuli but with longer RTs than healthy participants) and also because the attentional window size depends on the task, as demonstrated by the present experiments. Previous studies have also suggested that attentional window restrictions may reduce over time, that is, the attentional window may expand, due to recovery from simultanagnosia (Dalrymple et al. 2013). For the serial feature-absent tasks, the performance of patient IG was well below the performance of health controls with a visible window size of 10° (Fig. 8).

For the balloon feature-present task, with a restricted 20° gaze-contingent visible window, not only the patient not exhibit a cost in performance, showing that compared with the controls, she worked within a smaller attentional "working space," but also she was strikingly not aware of this peripheral mask enslaved to her eye position during the search (verbal report). This suggests that the stimuli lying outside this attentional window size available for the search (further than 20° of visual eccentricity) not only could not be detected as targets but was also unavailable to conscious perception: the conscious environment of the patient during the search was restricted to the attentional field in use during the search.

Taken together, this experiment elucidates how object-based attention and space-based attention may interact during ocular scanning of a visual scene, and how a restriction in the spatial extent of attention may arise from difficulties in processing complex objects. Indeed, the fact that the attentional window reduction in IG, reflected as a pathological cost in RTs, occurs only when separable features have to be integrated (in the open balloon and character tasks and not in the filled balloon and color/shape tasks) suggests that the spatial deficit is exacerbated by increased attentional demands necessary for separable features integration but not by the number of objects to process. This also demonstrates that the SPL, which corresponds to the dorsal visual stream (Milner and Goodale 1995, 2008) and the dorsal attentional system (Corbetta et al. 2000), is involved not only in space but also in object processing.

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Notes

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