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RESEARCH ARTICLE

Simulating simultanagnosia: spatially constricted vision mimics local capture and the global processing deficit

Kirsten A. Dalrymple · Walter F. Bischof · David Cameron · Jason J. S. Barton · Alan Kingstone

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Abstract Patients with simultanagnosia, which is a component of Bálint syndrome, have a restricted spatial window of visual attention and cannot see more than one object at a time. As a result, these patients see the world in a piecemeal fashion, seeing the local components of objects or scenes at the expense of the global picture. To directly test the relationship between the restriction of the attentional window in simultanagnosia and patients' difficulty with global-level processing, we used a gaze-contingent display to create a literal restriction of vision for healthy participants while they performed a global/local identification task. Participants in this viewing condition were instructed to identify the global and local aspects of hierarchical letter stimuli of different sizes and densities. They performed well at the local identification task, and their patterns of inaccuracies for the global level task were highly similar to the pattern of inaccuracies typically seen with simultanagnosic patients. This suggests that a restricted spatial area of visual processing, combined with normal limits to visual processing, can lead to difficulties with global-level perception.

Keywords Bálint syndrome · Simultanagnosia · Gaze-contingent · Hierarchical stimuli · Attention

K. A. Dalrymple (✉) · D. Cameron · J. J. S. Barton · A. Kingstone
Department of Psychology, University of British Columbia, Vancouver, BC, Canada
e-mail: kdalrymple@psych.ubc.ca

J. J. S. Barton
Division of Neurology, Department of Medicine, University of British Columbia, Vancouver, BC, Canada

J. J. S. Barton
Department of Ophthalmology and Visual Sciences, University of British Columbia, Vancouver, BC, Canada

W. F. Bischof
Department of Computing Science, University of Alberta, Edmonton, AB, Canada

Introduction

Bálint syndrome is a neurological disorder that typically results from bilateral lesions to the parieto-occipital junction (Bálint 1909). It is characterized by four primary symptoms: (1) dorsal simultanagnosia:[1] a restricted window of visual attention resulting in an inability to see more than a small perceptual area at one time; (2) spatial disorientation: an inability to locate objects in space; (3) optic ataxia: an inability to use visual information to guide accurate reaching toward objects; and (4) ocular apraxia: an inability to voluntarily execute accurate eye movements (Moreaud 2003; Rafal 2003; Rizzo and Vecera 2002).

In everyday life, patients with Bálint syndrome routinely describe scenes in a piecemeal fashion. This can be demonstrated in the laboratory by presenting patients with hierarchical stimuli, which are global shapes (such as letters) are made up of several local elements (e.g., other letters, see Fig. 1). When faced with such stimuli, patients

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[1] Patients with Bálint syndrome present with dorsal (as opposed to ventral) simultanagnosia (Farah 1990), which is an attentional limitation that prevents patients from seeing more than one object at a time. Thus, we define simultanagnosia in this context strictly as a reduction in attentional processing capacity that is in part reflected by a failure to process or maintain attention to a larger region of the visual field outside of the current focus of attention, as opposed to the more general definition offered by Wolpert (1924), which also includes difficulty with the interpretation of the global concept of a scene or a figure.

with Bálint syndrome are remarkably poor at identifying the global form despite normal accuracy for reporting the identity of the local elements (Karnath et al. 2000).

Simultanagnosia is understood to play a key role in this global processing deficit, but whether it can account for the global processing deficit entirely remains unclear. An alternate view posits that the restricted attentional window of simultanagnosia is insufficient for explaining the global processing deficit. While it is generally agreed that a restricted spatial area, or "window", of visual attention in simultanagnosia can preclude "normal" global processing, according to this position it should in theory be possible for an individual whose only limitation was a restricted window of visual attentional processing to reconstruct a global picture from the serial perception of local elements, i.e., with a restricted window of attention, it should still be possible to (1) *locate* local elements relative to each other, (2) *remember* their locations, and (3) *integrate* those elements into the global picture. If these processes are intact, patients with simultanagnosia should show longer reaction times but good accuracy for global report, making simultanagnosia alone insufficient for explaining the inability to derive global shape. However, simultanagnosic patients are unable to deduce the identity of global forms, even with unlimited viewing time. This has suggested to others that there may be an additional impairment underlying this inability to derive global shape, beyond a simple reduction of visual area (e.g., Farah 1990; Tyler 1968).

One candidate for an additional deficit is the inability to commit visual attention to each element in order to mark the local elements relative to each other. Tyler (1968) proposed precisely such a mechanism. He wrote that the "presence of small 'effective' fields combined with bilateral parietal 'attention' defects would seem to be the ideal substrate" (p. 168). Echoing this position, Farah (1990) conducted a thought experiment and proposed that if a healthy subject were seated in a dark room and saw a sequence of flashes on a screen, he/she should be able to "keep track of" their relative locations. "However," she argues, "this 'keeping track of' previous locations presumably involves allocating attention to them, something that dorsal simultanagnosics cannot do" (p. 44). Thus, these researchers suggest that there must be an additional attentional impairment, *beyond* the restricted attentional window, that contributes to the inability to derive global shape that is typically associated with simultanagnosia.

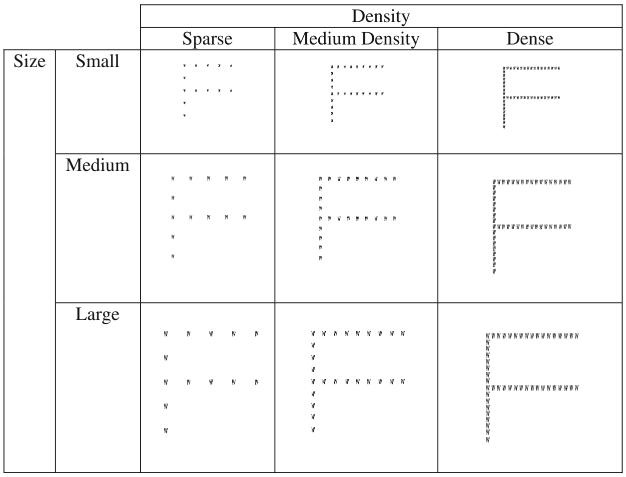

Fig. 1 Examples of the Navon hierarchical letters of each size and density used. Size refers to the dimensions of the global stimulus. Density refers to the degree to which the global letter is packed with local elements (more dense = more local elements and less inter-item space)

Despite this convincing reasoning, or perhaps because of it, no investigation to-date has tested whether this view of an additional attentional deficit beyond a restriction of the attentional window in simultanagnosia is accurate. The alternative possibility is that the restriction of the attentional window in simultanagnosia could on its own be sufficient to impair the ability to derive global shape. Clearly a restricted window of attention would impair the normal perception of global forms, but could it also impair the ability to piece together the global form from successive perception of local elements? The aim of the present study was to provide precisely this test. We tested healthy individuals with normal brains and normal visual perception on a global–local letter identification task under "simulated" conditions of simultanagnosia. This simulation was achieved by creating a gaze-contingent display to mimic a metaphorical "restricted window of attention" with a literal window of vision, as others have suggested (e.g., Bay 1953; Thaiss and de Bleser 1992; Tyler 1968).

The visual experience was created by use of an eye monitor and a gaze-contingent aperture on a computer screen (Fig. 2). Gaze-contingent displays have been used in the past with a variety of tasks, such as reading (McConkie and Rayner 1975), visual search (Pomplun et al. 2001), and scene exploration (Loschky et al. 2005). Critically, gaze-contingent displays reveal only a small portion of the stimulus at one time through a computer-created "window" that exposes only what the subject is looking at directly. Subjects can move the window by moving their eyes, and can explore the stimuli however they wish.

In the present experiment participants viewed hierarchical Navon letters (Navon 1977), stimuli which have been used in a number of investigations of patients with simultanagnosia (e.g., Clavagnier et al. 2006; Dalrymple et al. 2007; Karnath et al. 2000; Shalev et al. 2004). Their task was to identify the local, and, more importantly, the global letters. When simultanagnosic patients perform this hierarchical letter identification task under natural viewing conditions, they tend to do very well at identifying the local

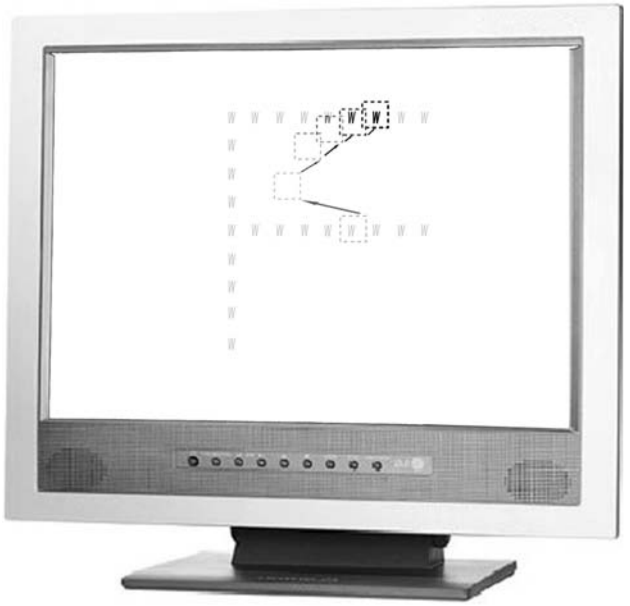

Fig. 2 Schematic of the gaze-contingent paradigm. *Dotted squares* represent the gaze-contingent window, which in reality had an invisible (*white* on *white*) border. For illustrative purposes the entire stimulus is visible (*light gray* items), but in practice only items falling within the window at a given time were visible to participants (*black items*). *Arrows* show hypothetical path of the window. *Darker elements* represent more recent window locations

letters, yet perform poorly at identifying the global letters when those letters are large and made of widely spaced local elements (Dalrymple et al. 2007). Their performance improves for small global letters that are made up of densely packed local elements.

According to Tyler's (1968) reasoning, and Farah's (1990) thought experiment, healthy participants, who do not have a deficit of visual attention, should keep track of individual local elements viewed through a narrowed window and successfully deduce the global letters. However, if the spatial constriction of visual processing associated with simultanagnosia is alone sufficient to impair global processing—even through serial perception of individual elements—narrowing the visual window of healthy participants should disrupt integration of local elements, yielding global-level processing deficits highly similar to those of a simultanagnosic patient.

Experiment

Method

Participants

Gaze-contingent group This group viewed hierarchical letters under conditions of limited visual information induced through a gaze-contingent display. Participants ($n = 24$, 12 males) were undergraduate students at the University of British Columbia who ranged in age from 18 to 42 years (mean = 20.7 years). All participants reported normal or corrected-to-normal vision and gave informed consent prior to participation in the experiments, which were performed in accordance with the ethical guidelines of the University of British Columbia.

Full-view control group This group viewed hierarchical letters under natural (unrestricted) viewing conditions. Full-view control participants ($n = 8$; 1 male) were undergraduate students at the University of British Columbia who ranged in age from 17 to 24 years (mean = 19.4 years). All participants reported normal or corrected-to-normal vision and gave informed consent prior to participation in the experiments, which were performed in accordance with the ethical guidelines of the University of British Columbia.

Patient SL Patient SL suffers from Bálint syndrome, which is characterized by ocular motor apraxia, optic ataxia, spatial disorientation, and dorsal simultanagnosia. She is a 48-year-old right-handed woman, with 12 years of education. She had idiopathic cerebral vasculitis resulting in bilateral parietal and lateral occipital infarcts (Fig. 3). Her visual exam showed Snellen acuity of 20/25 in each eye. Her neurological exam showed left hemi-neglect, left inferior quadrantanopia, and Bálint syndrome. Her dorsal simultanagnosia was evidenced through tests with four complex displays of visual scenes. For example, she could report elements of the Boston Cookie Theft picture (Goodglass and Kaplan 1983), but was unable to make sense of the whole scene. She initially reported seeing only "a boy's face… eyes," without reporting the mother on the right side of the display or the second child in the scene, nor did she describe the action in the scene. At the time of testing, several weeks after her stroke, she no longer showed left hemi-neglect or quadrantanopia, yet still showed optic ataxia when using the left hand to point to targets and she was still simultanagnosic. Patient SL and her data reported here have been discussed in a previous report (i.e., Dalrymple et al. 2007).

Stimuli and apparatus

Hierarchical letters (global letters made up of multiple repetitions of smaller, local letters) were produced dynamically by the computer, which used a series of screen coordinates to place repetitions of a local letter into the configuration of a given global letter. The screen coordinates for each global letter were determined by the experimenter, who designed the uppercase letters on a

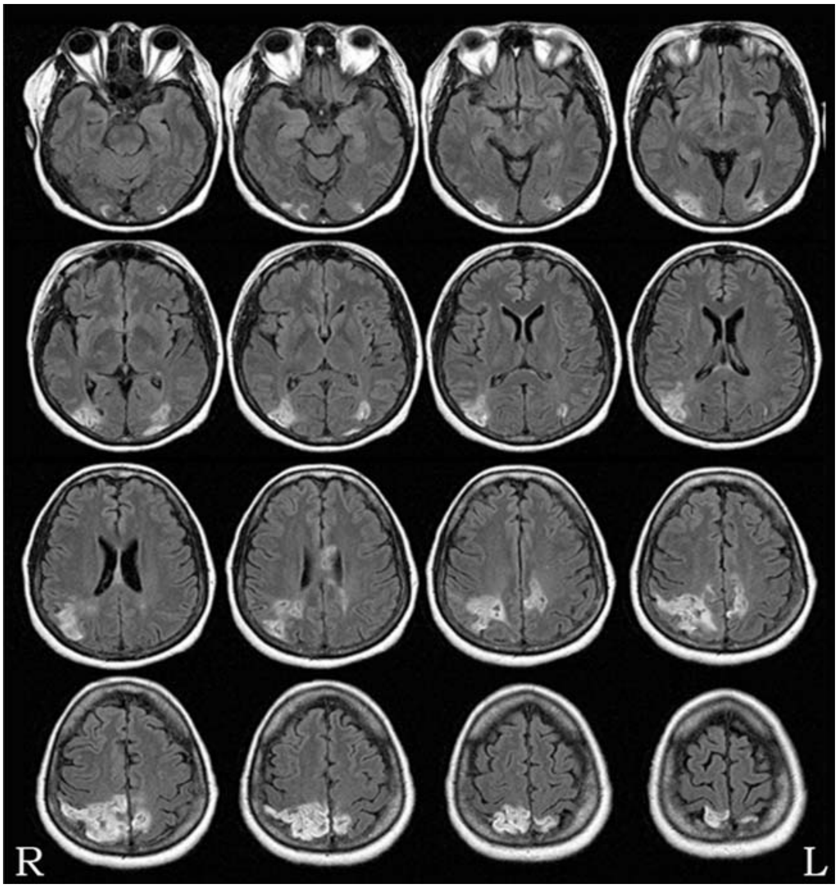

Fig. 3 Axial FLAIR sequences of MRI scans of patient SL within 1 month of testing. *White areas* indicate hypertense signal in damaged brain regions. *R* right, *L* left side of the brain

17 × 17 grid. Local letters were displayed in uppercase Times New Roman font and were black on a white background. All letters of the alphabet were eligible for use as global letters. Most letters of the alphabet were eligible for use as local letters, with the exception of letters M, O, and W, with which adjacent elements overlapped when stimuli were most densely packed. Note that this means that chance level accuracy for Global report is 3.8% (1/26), and 4.3% for Local report. Global and local letters were pseudo-randomly paired so that hierarchical letters were always incongruent. Global and local letters were sampled with replacement, such that letters could re-occur within the same block, preventing participants from deducing the identity of the letters based on which letters had already been displayed. Letters were created in three different sizes and densities, for a total of nine different size × density combinations (Fig. 1), identical to those used in our previous experiment (i.e., Dalrymple et al. 2007). Exact stimulus dimensions depended on which letters appeared at the Global and Local levels, as well as the size and density of the stimulus. Global letters were, on average, 17.4° × 15.3° for large stimuli, 8.9° × 7.0° for medium, and 5.9° × 4.7° for small stimuli. Local letters were, on average, 1.0° × 0.7° for large stimuli, 0.6° × 0.3° for medium, and 0.5° × 0.3° for small stimuli. Inter-element spacing ranged from 3.3° for large/sparse stimuli to 0.06° for small/dense stimuli, calculated by measuring the distance between the edges of adjacent local elements.

Full-view control participants and patient SL viewed these stimuli under natural (unrestricted) viewing conditions (simply looking at letters on the screen while their eye movements were monitored). For the gaze-contingent group, a 2°×2° (square) gaze-driven aperture was generated by the computer, and revealed the portion of the stimulus image at the gazed-at location only. This window size was chosen because, using similar stimuli with patient SL, we estimated the size of her attentional window to be 1.25° for threshold identification of global letters (Dalrymple et al. 2007), similar to estimates of 2–4° in other patients (Tyler 1968). The stimulus image consisted of the black letters on a white background. The non-gazed at area of the screen (area not covered by the moving aperture) was also white, matching the background color revealed by the aperture. Thus, the hard edges of the aperture were not perceptible. For the most part this created an effect of seeing one local element at a time, though partial elements could be visible when the aperture edges overlapped with the elements, and multiple elements could be visible when elements were densely packed and fell within the window.

For all participants, letters were displayed on a 33 × 24.5 cm screen corresponding to 36.5° × 27.5° at the viewing distance of 50 cm. Eye movements for the gaze-contingent and full-view groups, but not SL, were monitored using the EyeLink II eye tracking system (SR Research Ltd., http://www.eyelinkinfo.com). The on-line saccade detector of the eye tracker was set to detect saccades with an amplitude of at least 0.5°, using an acceleration threshold of $9{,}500°/s^2$ and a velocity threshold of 30°/s. A high-speed camera tracked the left eye, while a second camera tracked and compensated for head position by monitoring four infrared sensors placed on the corners of the display monitor. Cameras were mounted and held in place by a lightweight headband, which was placed and secured on the participants. Two computers were used in the experimental setup and were connected to each other via Ethernet, allowing for real-time transfer of saccade and gaze position data as well as response information. One computer collected the data from the eye tracker and displayed an image of the participant's eye and calibration information. The other computer displayed the stimuli and recorded keypress responses.

Procedure

Gaze-contingent group Prior to the set up of the apparatus, participants viewed a hierarchical digit (a global digit made up of repetitions of a local digit), and were asked to name the global and local digits to confirm that they understood the task. Digits were used as example and practice stimuli so that participants did not learn what the letters looked like before the experiment. Participants were informed that during the experiment they would be only seeing a small portion of the stimulus at one time, and that what was revealed was always contingent on where they were looking on the screen. Since many participants were unfamiliar with the concept of gaze-contingent displays, during the first practice trial the experimenter asked participants to follow her finger as she moved it across the screen, allowing participants to see how moving their eyes moved the gaze-contingent aperture (which moved along with the experimenter's finger in concert with the participant's eye movements).

Participants were seated 50 cm from the screen of the display computer with their chin supported by a chin rest. They were asked to remove any eyewear unless it was necessary for reading letters on a computer screen. The eye monitor was placed on the participant's head and securely fastened with a lightweight headband. Eye movements were recorded monocularly from the left eye. The experimenter verified that the camera did not obstruct the participant's view of the screen, and that the pupil was in view of the camera, even when the participant made eye movements to the far corners of the screen. The eye monitor was calibrated using a 9-dot array. Calibration was verified using the same procedure.

After successful calibration and verification, the experimenter initiated a short block of practice trials. This consisted of three trials of global digits made up of repetitions of a local digit. The stimuli for these practice trials consisted of global digits 1, 4, and 7, with any digit from 1–9 at the local level presented at randomly chosen sizes and densities. Practice trials were performed with the gaze-contingent aperture. Participants were asked to name the global digit to ensure that they were performing the task properly. Upon successful completion of the practice trials, the experiment began.

Each block started with the experimenter informing the participant of whether the task was to name the letters at the global or local level throughout the upcoming block. The participants then initiated the block by keypress. Each trial began with a fixation circle, which participants had to fixate accurately in order for the trial to proceed. When the participant accurately fixated the circle, they were able to initiate the stimulus onset by keypress. The fixation circle was removed for 500 ms at which point the stimulus appeared on the screen. Participants were given a maximum of 3 min per trial to identify the letter. When participants believed they knew the identity of the letter, they pressed space bar to terminate the trial. This led to a screen that prompted the participant to look down at the keyboard and to carefully enter their response. If they reached the time limit, the stimulus was replaced by a screen that informed them that they had run out of time and that they should enter a response based on what they thought the letter might have been. When the response was entered, a fixation circle appeared in preparation for the next trial. Participants were asked to press the space bar when they knew the identity of the letter to avoid recording eye movements as they searched the keyboard for their response. Participants did not receive feedback about their performance.

Trials were blocked by size × density configuration, and by level (global or local). Participants performed nine blocks during which they identified letters at the local level (one for each size × density combination) and three blocks during which they identified letters of one size at the global level. Participants were not asked to perform all nine blocks of the global trials because of anticipated participant fatigue. The size of the global letters was counterbalanced across participants. Participants saw global letters of all three densities, which were blocked and presented in random order. Each block consisted of 11 trials. Half of the participants performed the global identification blocks first, while the other half performed the local identification blocks first. The order of the blocks within a level was randomized, as well as the trials within each block.

Full-view control group All procedures were identical to the gaze-contingent group except that trials were performed under natural (unrestricted) viewing conditions and that participants performed the global level task for all sizes and densities (nine blocks). The eye monitor was used with this group to match the procedure used with the gaze-contingent group, but in this condition the eye monitor did not create a gaze-contingent window. There was no time limit for full-view control participants to respond, but participants never reached the 3-min maximum imposed on the gaze-contingent group.

Patient SL All procedures were identical to the gaze-contingent group except that trials were performed under natural (unrestricted) viewing conditions without an eye monitor, and that SL performed the global-level task for all sizes and densities (nine blocks). Also, there was no time limit for SL, who made verbal responses that were entered by keypress by the experimenter.

Analysis and results

We first performed a visual inspection of all eye movement plots for the gaze-contingent and full-view controls and removed any trials for which there was a clear shift of the eye movements indicative of poor drift correction for that trial. Accuracy[2] was calculated for all remaining trials by assigning a value of 0 to an incorrect response and 1 to a correct response. From this, a percent accuracy for each size × density condition was calculated (e.g., $8/11 = 0.727$ or 72.7%). We then compared the accuracy for the gaze-contingent group to the accuracy of the full-view control group in separate 3-way ANOVAs for global and local trials. The analysis of local trials included the between-subjects factor of group (gaze-contingent vs. full-view controls), and within-subjects factors of size (small, medium, and large) and density (sparse, medium density, and dense). Some participants from the gaze-contingent group did not complete all local conditions due to technical difficulties. Because participants in the gaze-contingent group performed global trials of one size only, the analysis of global trials included the between-subject factors of group (gaze-contingent vs. full-view controls) and size (small, medium, and large) and a within-subjects factor of density (sparse, medium density, and dense). Where appropriate, main effects and interactions were investigated with t tests.

SL's accuracy was calculated in the same way as it was for the gaze-contingent and full-view groups. To determine whether SL's accuracy was significantly different from these groups, we performed Bayesian standardized difference tests using SingleBayes (computer software, retrieved on September 10, 2009 from http://www.abdn.ac.uk/~psy086/dept/SingleCaseMethodsComputerPrograms.htm) (Crawford et al. 2009; Sokal and Rohlf 1995), comparing her accuracy to the accuracy of the gaze-contingent and full-view controls, respectively, for each size × density condition. All alpha levels were set to $P < 0.05$. To account for multiple comparisons, P values were also compared to a Bonferonni-corrected alpha, but results were unaffected. When performance was at ceiling, t tests could not be performed because of zero variance.

Local letter processing

Figure 4a illustrates the accuracy data for the full-view controls, the gaze-contingent group, and SL for naming the local letters in each size–density condition.

Gaze-contingent versus full-view controls

Accuracy was perfect or near perfect for both groups (gaze-contingent = 99.4%; full-view controls = 100%), and therefore there were no significant main effects of group, size, or density, and there were no interactions.

SL versus full-view controls

The full-view control group performed at ceiling for all local trials. SL also performed at ceiling for all but one condition (small-sparse = 90.9%).

SL versus gaze-contingent group

SL's accuracy was at ceiling for all conditions except small-sparse letters. In this condition, she performed significantly worse than the gaze-contingent group, SL = 90.9% versus gaze-contingent = 99.6%, $t(22) = -4.43$, $P < 0.001$. The gaze-contingent group was perfect or near-perfect for all conditions, and therefore did not differ from SL in any of the remaining conditions (all $P > 0.10$). Both SL and the gaze-contingent groups reached ceiling for small-dense and medium-medium density letters, and therefore did not differ from each other in these conditions either.

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[2] We do not to report reaction times (RTs) because patient SL's responses were entered by the experimenter and are therefore unreliable. The gaze-contingent group had long trial durations, whereas the full-view group responded almost instantly; hence, any differences in RTs for these groups are relatively uninformative.

Summary

The groups did not differ from each other in any way, except that SL performed worse than the normative groups on the small-sparse local letters.

Global letter processing

Figure 4b shows the accuracy for each group for identifying global letters.

Gaze-contingent versus full-view controls

There was a main effect of group, $F(1,26) = 62.86$, $P < 0.001$ (gaze-contingent = 66.4%; full-view controls = 99.4%), reflecting the fact that the full-view control group was significantly more accurate overall than the gaze-contingent group. There was a main effect of density, $F(2,51) = 47.41$, $P < 0.001$ (sparse = 69.1%; medium density = 88.0%; dense = 91.5%), reflecting the fact that, overall, participants performed worse in the sparse conditions, compared to the medium density or dense conditions: sparse versus medium density, $t(47) = -5.50$, $P < 0.001$; sparse versus dense, $t(47) = -6.13$, $P < 0.001$; medium density versus dense, $t(47) = -1.13$, $P = 0.264$. There was no main effect of size, $F(2,26) = 1.48$, $P = 0.247$ (small = 88.7%; medium = 81.1%; large = 79.7%). There was a group × density interaction, $F(2,51) = 39.29$, $P < 0.001$. No other interactions were significant. The group × density interaction was further explored by a series of paired *t* tests for each group as follows. These *t* tests were compared to a Bonferroni corrected alpha ($\alpha' = 0.017$) to account for multiple comparisons.

Full-view controls

The full-view control group showed no difference in accuracy for letters of different densities, sparse = 98.1%, medium = 100%, dense = 100%; sparse versus medium density, $t(23) = -2.00$, $P = 0.057$; sparse versus dense, $t(23) = -2.00$, $P = 0.057$; medium density versus dense (at ceiling).

Gaze-contingent

The accuracy of the gaze-contingent group was significantly worse for sparse letters compared to medium density and dense letters, sparse = 40.2%, medium density = 76.1%, dense = 83.2%; sparse versus medium density, $t(23) = -7.62$, $P < 0.001$; sparse versus dense,

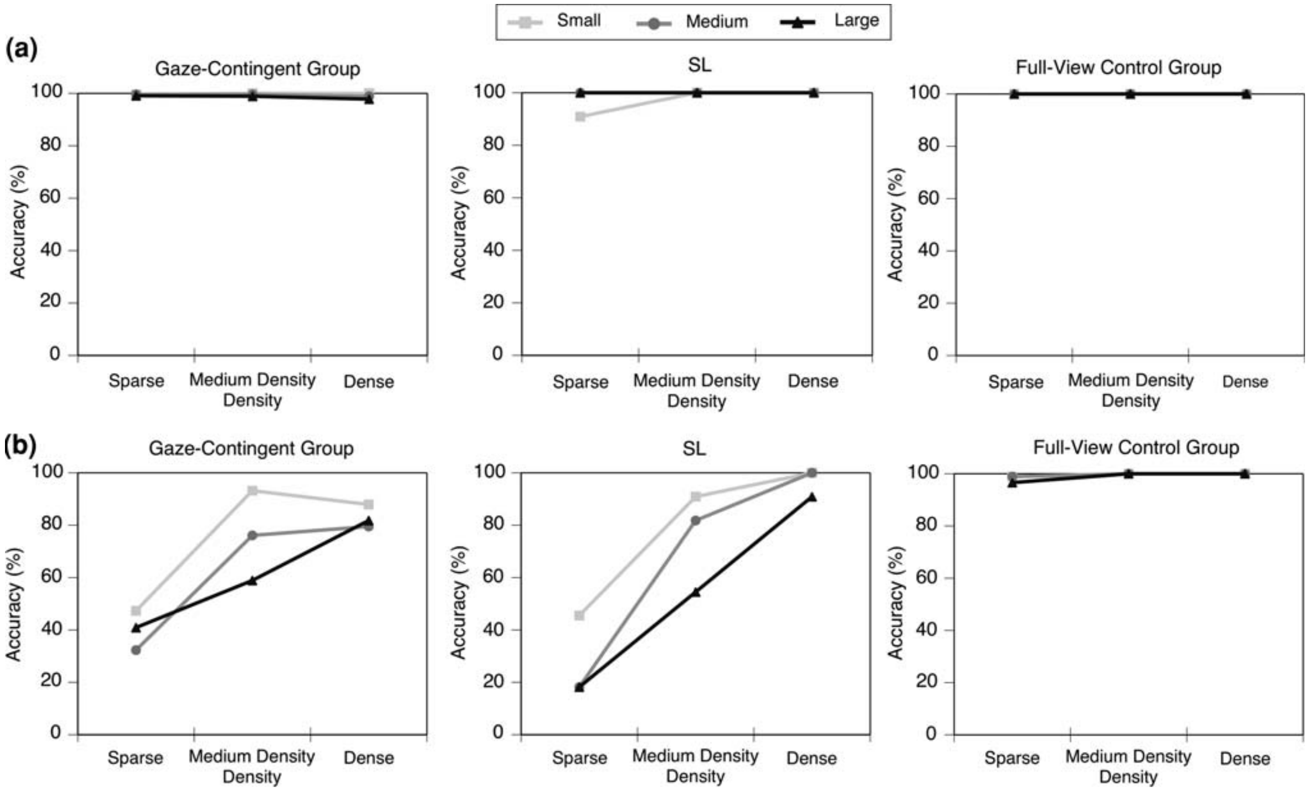

Fig. 4 Accuracy (%) for gaze-contingent group, full-view controls, and SL, for identifying **a** local letters and **b** global letters for each density × size condition

$t(23) = -10.28$, $P < 0.001$; medium density versus density, $t(23) = -1.13$, $P = 0.269$.

SL versus full-view controls

SL performed significantly worse than the full-view control group for all sparse letter conditions: small-sparse, $t(8) = -15.74$, $P < 0.001$; medium-sparse, $t(8) = -23.77$, $P < 0.001$; large-sparse, $t(8) = -10.87$, $P < 0.001$, and while the full-view control group was at ceiling for all other conditions, SL was not.

SL versus gaze-contingent group

SL's accuracy did not differ from the gaze-contingent group's accuracy in any condition (all $P > 0.10$).

Summary

The full-view control group performed better than the gaze-contingent group overall. Although the full-view control group was unaffected by the density of the letters, performing at ceiling, or near-ceiling, the gaze-contingent group was affected by stimulus density, performing worse on sparse letters than medium density or dense letters. SL did not differ from the gaze-contingent group in any of the conditions.

Discussion

Our results show that when restricted to seeing only a small portion of a stimulus at one time, healthy individuals are impaired at piecing together the global identity of hierarchical stimuli. In contrast to previous predictions in the literature, subjects were unable to keep track of the locations of previously viewed elements, as evidenced by their impaired ability to identify global letters, particularly when those letters are large and made up of widely spaced local elements. Furthermore, healthy participants under restricted viewing conditions show accuracy patterns that are remarkably similar to those of a patient with Bálint syndrome performing the same task under natural viewing conditions, suggesting that the global level impairment in Bálint syndrome is not due to an additional attentional deficit unique to the disorder, but may instead be the result of the narrowed attentional window, combined with *normal limits* to visual attention.

Our gaze-contingent paradigm was designed to test whether the constriction of the spatial area of visual processing in simultanagnosia is alone sufficient to impair global level processing, including the ability to synthesize global shape by the serial perception of individual local elements. The ability to keep track of the relative location of stimuli relies on visual attention and working memory (Farah 1990). Since visual attention is impaired in simultanagnosics but intact in healthy participants, one might expect that healthy participants would have little difficulty keeping track of the relative location of stimuli that are exposed over time by movement of the window across the letters. In contrast to this prediction, we found that even with normal visual attention, healthy participants viewing hierarchical letters through a restricted viewing window are unable to keep track of local elements in order to derive the identity of the global letter, suggesting that there are normal limitations on the use of visual working memory and attention to integrate global information under such viewing conditions.

Not only did our gaze-contingent window manipulation mimic SL's overall accuracy at the global task, but it also produced similar patterns of performance across different stimulus densities. Previously, we suggested that inter-element spacing, rather than stimulus size per se, is key for determining global level performance in patients with Bálint syndrome (Dalrymple et al. 2007). Like SL, our gaze-contingent group was most impaired at identifying global stimuli with large inter-element spacing, stimuli that would allow fewer local elements to fall in a narrowed viewing window compared to stimuli with local elements that are more densely packed.

Our findings support the growing body of evidence that suggests that visual short term memory (VSTM) is normal in simultanagnosia (e.g., Duncan et al. 2003; Huberle and Karnath 2006). The finding that simultanagnosics struggle with large-sparse letter stimuli, which have large inter-element spacing and which may therefore increase the VSTM load by increasing time between the perception of successive elements, suggests the possibility that a global processing deficit can be linked to a VSTM impairment. However, it has been argued that if simultanagnosia is linked to a limitation of VSTM, the addition of more elements (and therefore VSTM load) would lead to further decrements in performance, a prediction that is contradicted by the improvement that is seen when patients view hierarchical letters made up of several, densely packed elements compared to a few, sparse elements (Huberle and Karnath 2006). The present findings support this notion because participants in our gaze-contingent group, who have normal VSTM, had similar inaccuracies with global report to our simultanagnosic patient SL. Furthermore, based on Budensen's Theory of Visual Attention, others have suggested that rather than reduced VSTM capacity, the primary deficit in simultanagnosia is a limitation of processing capacity (Duncan et al. 2003). Our findings with healthy participants support this idea and suggest that the inability to derive global shape in simultanagnosia may reflect a restricted window of visual processing combined with normal limits in general visual processing capacity that allows integration of visual information across time.

The visual deficits in Bálint syndrome were identified early on as being attentional in nature. Holmes and Horrax (1919) described the disorder as one of visual attention rather than blindness because their patient had variable perception of objects that fell on fully functioning retinas. "The essential feature was his inability to direct his attention to, and take cognizance of, two or more objects that threw their images on the seeing portion of his retinae. As this occurred no matter on what parts of his retinae the images fell, it must be attributed to a special disturbance or limitation of attention…" (Holmes and Horrax 1919, p. 390). The global processing deficits in simultanagnosia have been hypothesized to be related to "local capture", i.e., patients being "locked" on the local elements of an object at the expense of the global whole (Karnath et al. 2000), perhaps due to an inability to disengage attention from those local elements (Farah 1990). However, more recent evidence shows that despite poor report of the global level hierarchical stimuli, patients scan these stimuli extensively, arguing against an inability to disengage from individual parts of the stimulus (Clavagnier et al. 2006; Dalrymple et al. 2009). In those reports, eye movements were not predictive of the success at global level report in these patients.

Others have described the attentional limitation in Bálint syndrome as being related to a restricted window of visual processing (e.g., Bay 1953; Shalev and Humphreys 2002; Shalev et al. 2004, 2007; Thaiss and de Bleser 1992; Tyler 1968). Bay described it as a "peripheral constriction", not unlike "viewing [a] picture through a diaphragm" (p. 545, 546). Thaiss and de Bleser (1992) suggested that their patient may suffer from a rigid reduction of the spatial extent of the visual "spotlight". Tyler (1968) (p. 166) referred to the visual deficit in his patient as "shaft vision", yet implied some flexibility. When Tyler measured his patient's effective visual fields he concluded that they were quite variable. While items were consistently perceived within 2° of fixation, perception could also occur for items at up to 20° eccentricity, though this more peripheral processing quickly fatigued, within 10–30 s.

More recently, the flexibility of the restricted window of attention has been tested empirically with hierarchical stimuli. The ability to expand the window of attention from local to more global stimuli is partly determined by the stimulus itself. For example, patients viewing hierarchical letters made up of unfamiliar local elements (Hebrew letters) showed good performance for naming the global letters compared to when local items were familiar (English letters) (Shalev et al. 2007). Similarly, priming the global level of a hierarchical letter with a solid letter that is of the same size as the global level of the stimulus can improve global-level report in simultanagnosia (Shalev et al. 2004), in theory by expanding the window of attention prior to the presentation of the target stimulus. Finally, when viewing "globally biased" stimuli (hierarchical faces) patients actually show a type of "global capture", in that they see only the global level of the stimulus without awareness of the local level (Dalrymple et al. 2007). Based on these and other findings, some have suggested that the primary deficit in simultanagnosia could specifically involve an inability to expand a restricted window of attention (Shalev and Humphreys 2002) with the default state being a relatively small area of useful visual field (e.g., global capture seems to occur less commonly than local capture in simultanagnosia). With global capture of hierarchical faces, the expansion of the window may occur at the expense of attentional acuity. Patients can see the global face, but not the individual elements that make up the face.

It is possible that SL's successful global-level report in this task reflects successful expansion of her restricted window of attention. However, the fact that participants in our gaze-contingent group who had a rigid restriction of vision show the same accuracy patterns as SL suggests instead that her attentional window remained fixed in this task. Indeed, one of the strengths of our model is its parsimony in that it models the simultanagnosic behaviors with a simple restriction of the visual window. This provides strong support for the idea that the restriction of attention in simultanagnosia is alone sufficient to explain the global processing deficit, regardless of how the restriction itself is manifested.

The idea of a *restricted* window of attention as a mechanism for simultanagnosia is consistent with the present results that a literal restriction of vision is sufficient to cause Bálint-like global processing deficits in healthy participants viewing hierarchical letters. However, although the size of the gaze-contingent window in our experiment appears to be an appropriate choice for mimicking patient behavior with hierarchical letter stimuli, these results do not mean that this window size will replicate simultanagnosic performance with all stimuli, given the data showing that the attentional window varies with factors like priming at the global level and salience at the local level. For example, we do not anticipate that a *rigid* restricted window would lead to global capture behavior in healthy participants viewing hierarchical face stimuli (Dalrymple et al. 2007). However, it may be possible to design paradigms to simulate other hypothesized properties of the simultanagnosic window of attention with different stimuli. For example, the global capture effects patients experience with hierarchical faces may be simulated in healthy subjects by use of a gaze-contingent window that is small, but expandable, but with limited processing capacity mimicked by decreasing the spatial resolution within this larger window, limiting the processing of local elements. Our paradigm is primarily designed as a starting point in testing concepts related to the restricted window of attention in simultanagnosia, and provides multiple avenues for future studies of the properties of the visual attention window in simultanagnosia.

In contrast to a restricted window of attention, one alternate explanation for the global perceptual deficits in simultanagnosia is that they result from damage to the right hemisphere, which has been implicated in playing a role in global processing, while the left hemisphere has been implicated in local processing (e.g., Delis et al. 1986; Robertson et al. 1988; van Kleeck 1989). While damage to the right hemisphere could be related to the global processing deficit in simultanagnosia, simultanagnosia results from bilateral damage, leaving no a priori reason to predict preferential processing of one stimulus level over the other. Furthermore, we have shown with patient SL that "global capture" can occur with globally biased stimuli (i.e., hierarchical faces; Dalrymple et al. 2007), demonstrating that simultanagnosia is not characterized by a local preference per se, as may be the case with right hemisphere damage alone. Rather than a selective global deficit from right hemisphere damage, we suggest that patients have preference for the local elements of hierarchical letters because these elements fit into a narrowed window of visual attention. This explanation is consistent with the improvement in global-level report seen with patients, and with our gaze-contingent group, for global letters that are smaller and more densely packed. These stimuli allow for more of the global stimulus to occupy the narrowed window of vision at one time and therefore lead to better global-level report.

We thank an anonymous reviewer for suggesting an alternative explanation for SL's impaired global report, that it is the result of poor ocular motor control from the other deficits of Bálint syndrome. SL indeed shows evidence of difficulties with the accurate execution of voluntary eye movements (ocular motor apraxia). However, Clavagnier et al. (2006) monitored the eye movements of two simultanagnosic patients while they identified the global and local levels of hierarchical letter stimuli and found that the patients' eye movements were abnormal but not predictive of performance on the letter identification task. We recently performed a comparable experiment with SL and similarly found that her eye movements were not predictive of her accuracy at identifying global or local letter stimuli (Dalrymple et al. 2009). Rather, we found that SL's abnormal eye movements were the *consequence* rather than the cause of her difficulties with global-level report suggesting that her ocular motor apraxia was not to blame. Our current findings with healthy participants in the gaze-contingent paradigm are again consistent with this conclusion. These participants do not have ocular motor deficiencies, yet showed global-level report difficulties similar to SL's. This further supports the idea that seeing only a small portion of the stimulus at one time, rather than disordered eye movements, is crucial to difficulties with global-level report.

Having demonstrated that our manipulation was successful in creating Bálint-like accuracy patterns for this particular two-dimensional task, it might be possible to extend this effect to other domains. Patients with Bálint syndrome suffer from other visual-spatial deficits, such as spatial disorientation, optic ataxia, and ocular apraxia (Holmes and Horrax 1919). While some have considered the possibility that simultanagnosia is also responsible for these other deficits (Luria et al. 1962), others argue that each deficit is dissociable from the others (Cummings et al. 1986; Hecaen and de Ajuriaguerra 1954; Luria et al. 1962), and modern neuroimaging suggests that the anatomic substrates of each differ. Nevertheless, it remains possible that simultanagnosic limitations of processing in two and three dimensions may affect visual reaching and saccadic targeting. For instance, it is possible that participants placed in a three-dimensional environment where they were restricted to seeing a single object at one time would have difficulties reaching for the objects, akin to optic ataxia. Extending our simulation to a three-dimensional environment may allow us to determine the contribution of limited windows of processing to reaching and ocular motor deficits in Bálint syndrome.

In summary, we have shown that when restricted to seeing only a small portion of a display at one time, healthy participants show difficulties with global level perception of hierarchical stimuli. This behavior is well documented in patients with simultanagnosia, who suffer from a constriction of the spatial extent of their visual window of attention. Even with protracted viewing times, our participants, like simultanagnosics, were unable to correctly derive the global level of hierarchical stimuli, suggesting a difficulty keeping track of the relative locations of the individual elements viewed through serial fixations. Our findings suggest that the constriction of the spatial area of visual processing in simultanagnosia may itself contribute to this difficulty, rather than some additional impairment of visual attention resulting from parietal damage. We propose that parietal damage may cause a restriction of the spatial extent of the attentional window that limits the amount of visual information that can be processed at one time, and this restriction of visual information, combined with normal limits to visual processing, affects the ability to keep track of the relative position of the elements of a scene leading to a piecemeal view of the world.

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