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Research report

Opening a window on attention: Documenting and simulating recovery from simultanagnosia

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ABSTRACT

Simultanagnosia is a disorder of visual attention: the inability to see more than one object at one time. Some hypothesize that this is due to a constriction of the visual "window" of attention. Little is known about how simultanagnosics explore complex stimuli and how their behaviour changes with recovery. We monitored the eye movements of simultanagnosic patient SL to see how she scans social scenes shortly after onset of simultanagnosia (Time 1) and after some recovery (Time 2). At Time 1 SL had an abnormally low proportion of fixations to the eyes of the people in the scenes. She made a significantly larger proportion of fixations to the eyes at Time 2. We hypothesized that this change was related to an expansion of her restricted window of attention. Previously we simulated SL's behaviour in healthy subjects by having them view stimuli through a restricted viewing window. We used this simulation paradigm here to test our expanding window hypothesis. Subjects viewing social scenes through a larger window allocated more fixations to the eyes of people in the scenes than subjects viewing scenes through a smaller window, supporting our hypothesis. Recovery in simultanagnosia may be related to the expansion of the restricted attentional window that characterizes the disorder.

1. Introduction

Simultanagnosia is an inability to see more than one object at a time resulting from bilateral lesions to the parieto-occipital junction (Bálint, 1909; Holmes and Horrax, 1919; Riddoch et al., 2010; Rizzo and Vecera, 2002). It can be so severe that patients appear "functionally blind" (Kim and Robertson, 2001), with little or no understanding of the fragmented world they perceive. Although appearing functionally blind, simultanagnosia has been identified as a disorder of visual attention, rather than blindness (Holmes and Horrax, 1919): "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

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attention…" (Holmes and Horrax, 1919, p. 390). Since then, a notion of simultanagnosia as resulting from a *restricted window* of attention has become increasingly apparent in the literature. Bay (1953) suggested that his patient's simultanagnosia could be accounted for by "shaft vision", which prevented the patient from seeing the whole picture. He described it as a "peripheral contraction", not unlike "viewing [a] picture through a diaphragm" (p. 545, 546). Similarly, Thaiss and de Bleser (1992) suggested that their patient, TK, may suffer from a rigid reduction of the spatial extent of the visual spotlight.

Previously, we conducted an experiment to test this idea of a restricted window of attention by "simulating" simultanagnosia by applying a literal restriction of vision to healthy participants while they identified hierarchical letter stimuli (Dalrymple et al., 2010). When viewing hierarchical letters (large global letters made up of several repetitions of smaller local letters, e.g., a large letter K made up of small letter D's), patients with simultanagnosia tend to report the local letters, and are unable to identify the larger, global letters (Clavagnier et al., 2006; Dalrymple et al., 2007; Huberle and Karnath, 2006; Karnath et al., 2000; Shalev et al., 2004). Interestingly, healthy participants viewing hierarchical letters through a gaze-contingent window (a small window of vision that allows them to see only a small portion of the stimulus at once) showed similar accuracy patterns for identifying hierarchical letters to what is typically seen with patients with simultanagnosia. That is, they showed good accuracy for identifying the small, local letters, but were impaired at identifying the large, global letters. We interpreted this as evidence that a narrowed window of vision leads to perceptual phenomena that are similar to those seen in simultanagnosia, suggesting that a literal restriction of vision may be a good model of the restriction of attention in simultanagnosia.

In support of this conclusion, we found similar effects with our restricted window paradigm when we applied it to more complex stimuli (Dalrymple et al., submitted for publication). We examined how simultanagnosic patients scan social scenes, with an interest in determining how their scanning behaviour relates to the concept of a restricted window of attention. We tested this by applying the restricted window paradigm to healthy subjects while they scanned social scenes. It is well established that healthy participants scanning social scenes under unrestricted viewing conditions tend to allocate a large proportion of fixations to the eyes of the people in the scenes (Birmingham et al., 2007, 2008a, 2008b; Smilek et al., 2006). This is a highly replicable, robust finding, which seems to occur in a variety of tasks (e.g., describe the scene, look at the scene, remember the scene, etc.). In our experiment, we found that patients with simultanagnosia show reduced fixations to the eye region of the social scenes compared to healthy controls. Remarkably, healthy participants viewing the scenes through the restricted window also showed reduced fixations to the eyes of the people in the scenes. This behaviour occurred regardless of how participants controlled the movement of the window: whether using their eyes (gaze-contingent window) or using a computer mouse (mouse-contingent window). This further solidified the idea that it is the restricted viewing window itself that is key to this behaviour. Again we concluded that a literal restriction of vision may be a good model of the restriction of attention in Bálint syndrome.

Although our *rigid* window of vision successfully simulated both simple and more complex Bálint behaviours in these experiments, a careful inspection of the literature suggests that the restricted window of attention in simultanagnosia may not be rigid, but may instead be flexible in size. Like Thaiss and de Bleser's (1992) description of patient TK, Tyler (1968) referred to the visual deficit in his patient as "shaft vision" (p. 166), yet Tyler's description clearly implies some flexibility. When he measured his patient's effective visual fields he concluded that they were quite variable: consistent perception occurred within 2° of fixation, and could occur at up to 20°, though this larger window of effective vision quickly fatigued (within 10–30 sec). Tyler's description, therefore, suggests a type of shaft vision, with a flexible spatial extent that may widen or shrink. It appears as though the size of the window is outside of the patient's control: the window is restricted at rest and expanding the window is a demanding process that is easily fatigued.

Shalev et al. (2004) found direct evidence for a flexible window of attention in simultanagnosia. Specifically, through testing with hierarchical letters they found that first presenting patients with a large solid letter that takes up the same spatial extent as the global aspect of a hierarchical letter improved the patient's ability to name the global level of that hierarchical letter. These authors interpreted this finding to indicate that the "default" restricted window of attention was temporarily widened by the prime, allowing for explicit processing of the global hierarchical letter.

The idea of an expanding attentional window leads to some interesting questions about patient recovery. Little is known about how perception in simultanagnosia changes with recovery. Nyffeler et al. (2005) documented the scanning behaviour of a simultanagnosic patient at 8, 14, and 37 weeks after injury, while she explored simple line drawing (e.g., objects, schematic clock). This patient showed improved performance over time (e.g., better object naming, increased exploration of the stimuli), which Nyffeler et al. concluded reflected an enlargement of a restricted attentional field. Is it possible that the "default" size of the restricted attentional window increases over the course of patient recovery? Finding the answer to this question was the primary aim of this study. This expansion of a patient's window of attention would be reflected in a recovery of normal behaviours. Therefore, applied to the scanning of social scenes, we hypothesized that a patient who initially showed reduced proportions of fixations on the eyes of people in social scenes may show increased fixations on the eyes in the scenes after some recovery. This was tested in Experiment 1 of this study.

Return of more normal behaviours is a natural and expected consequence of recovery and may not necessarily reflect an expansion of the attentional window over time. However, if our hypothesis is supported in Experiment 1 and patients do allocate more fixations to the eyes in scenes after some recovery, we can determine whether this behaviour is related to a change in the size of the window of attention by changing the size of the restricted window in our paradigm with healthy participants. If changes in patient scanning behaviour are related to an expansion of the window of

attention over time, a similar change in behaviour should occur with healthy participants viewing scenes through windows of different sizes (Small *vs* Large). We tested this window expansion hypothesis in Experiment 2 by asking two groups of healthy participants to describe the social scenes while exploring them with a mouse-contingent aperture[1] of two different sizes. If the recovery of normal behaviour in simultanagnosia is related to an expansion of a narrowed window of attention, this should be reflected in similar changes in behaviour through manipulations of the size of the mouse-contingent display. Similarly, this would provide further evidence of a flexible, rather than rigid, window of attention in simultanagnosia. Importantly, this would further link the simultanagnosic deficits to an underlying mechanism (a restricted window of attention), and provide direct evidence for how that mechanism evolves over the course of patient recovery.

It is important to emphasize that the visual deficits in simultanagnosia are known to be *attentional* in nature (Holmes and Horrax, 1919). These patients have fully functioning retinas (Holmes and Horrax, 1919), and can see objects of different sizes (Rafal, 2001). What is *not* known is how that disorder of attention manifests itself. The current experiments apply the concepts of the disordered visual attention in simultanagnosia that are arising in the literature. Concepts such as "shaft vision" (Bay, 1953; Tyler, 1968) and "viewing [a] picture through a diaphragm" (Bay, 1953, p. 545, 546) imply a spatial context to the restriction of attention. Our aim is to test the validity of these concepts by testing whether they adequately capture the true nature of the attentional deficit. The chosen method for testing this is through modeling the attentional disorder in healthy individuals.

There are obvious difficulties in experimentally creating a restricted attentional window in healthy individuals. As an alternative, and inspired by the literature, a simulation of the *attentional* disorder in simultanagnosia was created through a literal restriction of *vision* in healthy individuals. This literal restriction of vision aims to create a representation of the visual experience of the patients, but also limits what can be attended by the individuals. That is, by limiting the spatial extent of what can be seen, this model limits what can be attended to, i.e., attention is restricted to what is visible in the window. Therefore, in both patients and healthy individuals, we have a scenario of reduced visual information: in patients, this *results from* a neurological restriction of the *attentional window*; in healthy subjects this is *created through* an artificial restriction of the *visual window*. To reflect this important distinction, specific terminology will be used throughout this paper: when discussing patients, the limitation will be described as a restricted or limited window of visual *attention*; when discussing healthy individuals in the model groups, the limitation will be described as a restricted or limited window of *vision*.

[1] We used the mouse-contingent manipulation because in Dalrymple et al. (submitted for publication) participants complained of discomfort (e.g., nausea) when using the gaze-contingent procedure, and because the results of the gaze- and mouse-contingent methods were virtually identical.

2. Methods

2.1. *Case report: patient SL*

2.1.1. *Time 1: June 2005*

Patient SL is a right-handed woman, with 12 years of education. She had idiopathic cerebral vasculitis resulting in bilateral parietal and lateral occipital infarcts (Fig. 1). She had been treated with cyclophosphamide and prednisone for her vasculitis, but had completed these 4 months prior to her testing. She was on carbamazepine for a single seizure suffered several months prior. She presented with left hemi-neglect, as assessed with the Sunnybrook Neglect Assessment Battery (Leibovitch et al., 1998), left inferior quadrantanopia, and Bálint syndrome, with ocular motor apraxia, optic ataxia, and simultanagnosia, though her acuity was 20/25 in both eyes. Her optic ataxia was evident in that she often mis-reached for objects, and failed to orient her grasp correctly to the axes of objects such as pencils. This was evident despite normal motor and sensory function on her neurological examination, which also showed accurate reaching to her own body parts. Her 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. Neuropsychological evaluation showed normal attention, language, and verbal memory functions. Her reading was in the borderline impaired range and she tended to guess words based on the first or last letters. She was successful at recognizing simple line drawings of objects and could correctly identify colours and simple shapes. After her discharge to home, she continued to note difficulties. Her reading was slow but she could read menus and signs. She had trouble with photographs in books or newspapers, in that she often missed elements in them. She bumped into objects on either side when walking, and because of her navigational problems traveled in a wheelchair for some months. She had some minor difficulties using kitchen utensils with her left hand mainly, but this improved quickly.

Magnetic resonance imaging (MRI) showed bilateral lesions in the lateral occipital cortex, at the junction of Brodmann areas 19 and 37, extending more dorsally through inferior and superior parietal cortex laterally, in Brodmann areas 39 and 40, with some minimal involvement of medial area 31 superiorly (Fig. 1). These lesions are typical of those seen in other patients with dorsal simultanagnosia (Riddoch et al., 2010). Although a ventral form of simultanagnosia purportedly can result from lesions of the left occipital cortex, such patients tend to present mainly with alexia and right hemianopia, without the navigational problems and optic ataxia seen in SL (Kinsbourne and Warrington, 1962, 1963). Also, modern neuroimaging implicates the left fusiform gyrus in patients with letter-by-letter reading and alexia (Leff et al., 2006), which was spared in SL. Thus, on the basis of neuroimaging and behavioural evidence, it is probable that SL had simultanagnosia as a consequence of bilateral 'dorsal' lesions of parietal and lateral occipital cortex.

At the time of initial testing, SL was 48 years old and no longer showed left hemi-neglect or quadrantanopia and had no defects in saccadic targeting and generation, as was confirmed by her rapid and accurate saccades during the calibration of the

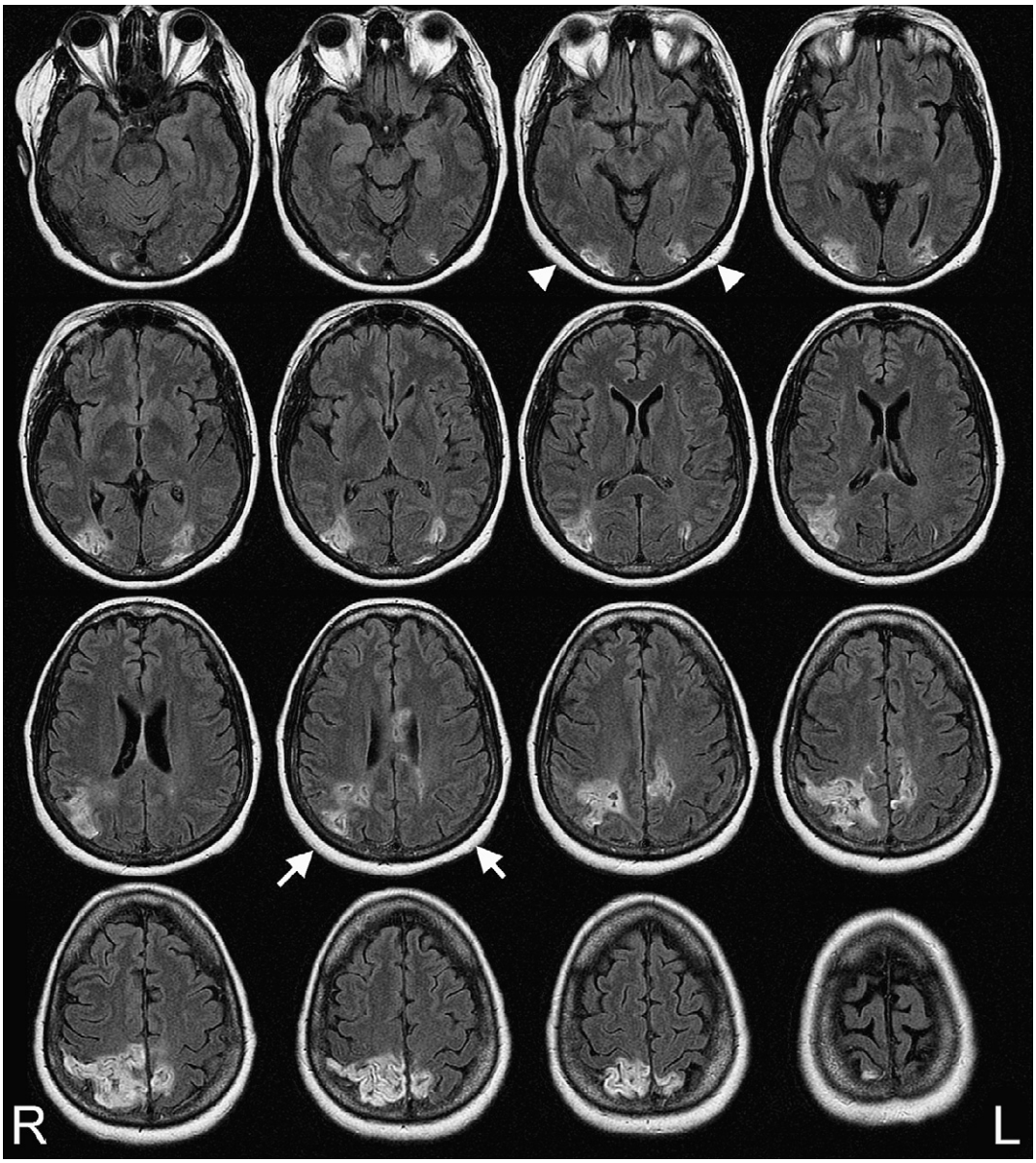

Fig. 1 – Axial fluid-attenuated inversion recovery (FLAIR) sequences of MRI scans for patient SL. R = Right, L = Left side of the brain. Arrowheads indicate the junction of Brodmann areas 19 and 37, while arrows indicate the junction between areas 39 and 40.

eye monitor. However she still showed optic ataxia when using the left hand to point to targets. This was a specific sensorimotor transformation for the contralateral hand, and therefore not due to a general difficulty with perceptual localization (which would affect both hands). She also showed evidence of topographical difficulties, being unable to navigate through her environment without substantial assistance.

2.1.2. *Time 2: November 2008*

SL was 52 years old at the time of testing. She had no new neurologic events, or seizures since her original trauma. Her acuity correction at far was 20/40-2 ou, 20/30-1 ou with pinhole. Her fixation and smooth pursuit showed distractibility, yet her saccades were quick and accurate, without delay in initiation to command and she showed no nystagmus. She was alert and attentive with normal language and speech. She named more elements on the Boston Cookie Theft picture than at Time 1 and described each of these elements fully. She could read short sentences well, with only slight hesitation with longer words or when finding the next line. She made randomly distributed errors of omission and commission on an object cancellation task. She still met the diagnostic criteria for Bálint syndrome, and had a left inferior quadrantic scotoma, secondary to her cerebral vasculitis. SL had no new neurological incidents between the time of this scan and the time of testing.

2.2. *Stimuli and apparatus*

Scenes were chosen from those used in prior studies of visual attention in healthy subjects (Birmingham et al., 2007, 2008a,

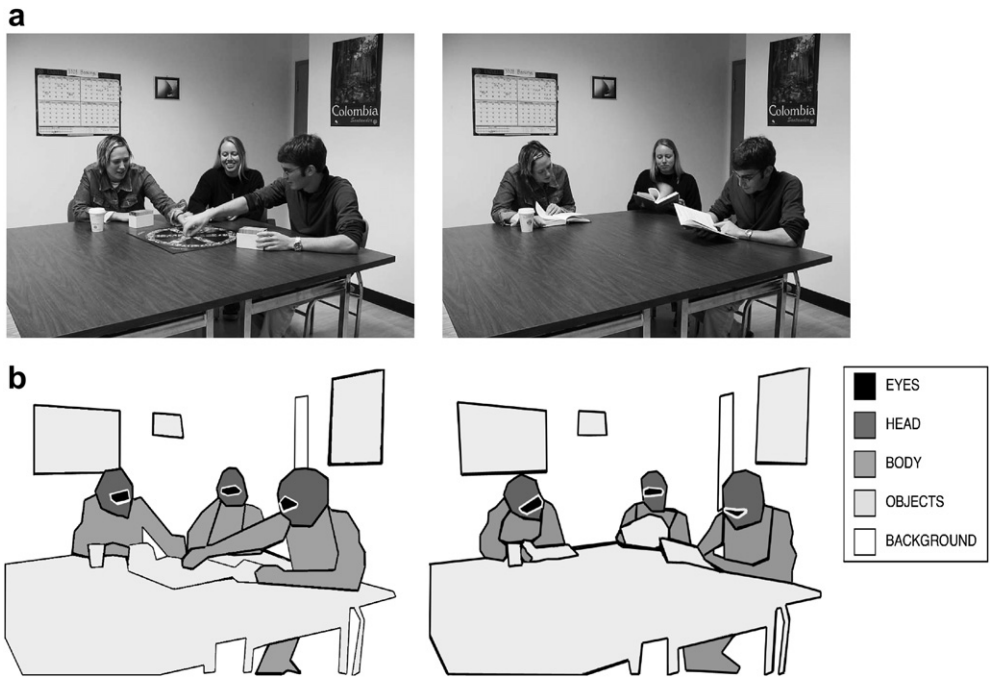

Fig. 2 – Example of scene stimuli (a) and regions of interest (b). "Interactive" scenes appear on the left, "Non-interactive" scenes on the right.

2008b). These full colour images were originally taken with a digital camera in different rooms in the Psychology building at the University of British Columbia. Image size was 36.5 × 27.5 cm corresponding to 40.1° × 30.8° at the viewing distance of 50 cm, and image resolution was 800 × 600 pixels. Eight scenes were used in the present experiment. Each scene contained 3 persons in either "interactive" or "non-interactive" state. All scenes were comparable in terms of their basic layout: each room had a table, chairs, objects, and background items (e.g., see Fig. 2a).

Eye movements were monitored using the EyeLink II eye tracking system for SL at Time 1 and the mouse-contingent group who viewed the scenes through the large aperture. The EyeLink 1000 eye tracking system was used for SL at Time 2 and the mouse-contingent group who viewed the scenes through a small aperture (SR Research Ltd., www.eyelinkinfo.com).[2] The Eyelink II has a temporal resolution of 4 msec (sampling rate 250 Hz) and a spatial resolution of .5°. The EyeLink system records sample data indicating the location of gaze, in pixel coordinates. Before any analysis was carried out, these samples were parsed into fixation and saccade events (and blinks) using the EyeLink software. The event parser identifies epochs in the data file where a saccade is occurring by calculating the distance between gaze position in different samples and implementing motion, velocity and acceleration thresholds. The on-line saccade detector of the eye tracker was set to detect saccades with an amplitude of at least .5°, using an acceleration threshold of 9500°/sec^2 and a velocity threshold of 30°/sec. A fixation is defined as any event that was not a saccade or a blink. One 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 subjects. The Eyelink 1000 differs in that it has a temporal resolution of 1 msec (sampling rate 1000 Hz) and mounts the cameras on the desktop, rather than on a headband. The on-line saccade detector was set to detect saccades with an amplitude of at least .15°, using an acceleration threshold of 8000°/sec^2 and a velocity threshold of 30°/sec. 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. The experimenter computer collected the data from the eye tracker and displayed an image of the participant's eye and calibration information. The display computer displayed the stimuli and recorded keypresses.

2.3. *Procedure*

Subjects were seated 50 cm from the screen of the display computer with their chin supported by a chin rest. Eye movements were recorded monocularly from the left eye. The eye monitor was calibrated using a 9-dot array. Calibration was validated using the same procedure.

After successful calibration and validation, subjects were asked to fixate a dot at centre-screen in order to correct for

[2] The Eyelink 1000 was used for SL at Time 2 and the Small window mouse-contingent group because of equipment upgrades that took place in the 3.5 years after initial testing. Both Eyelink systems have the same .5° Gaze Accuracy, and the difference between the Eyelink II and Eyelink 1000 sampling rates does not affect the analysis of fixation frequencies, therefore the use of two different systems should not impact our results.

drift in gaze position. Once the dot was fixated, the experimenter initiated the onset of the scene image by keypress. Scenes were presented in random order. Subjects were asked to verbally describe each scene while a digital voice recorder recorded their descriptions. SL had unlimited time to describe the scene, and indicated that her description was complete by informing the experimenter that she was ready for the next picture. At this point, the experimenter initiated the next trial by keypress. Healthy subjects viewed the scenes through a square mouse-contingent window of one of two sizes ("Small" $1^\circ \times 1^\circ$ or "Large" $2^\circ \times 2^\circ$). They terminated their trials by keypress, initiating the next trial. All subjects viewed 8 social scenes.

3. Experiment 1: SL

The purpose of this experiment was to determine if and how patient SL's scanning of social scenes changed over the course of her recovery. We predicted that SL would scan social scenes more like healthy participants as she recovered from her deficits. Specifically, we predicted that she would allocate more fixations to the eyes of the people in the social scenes at Time 2 compared to Time 1. SL's Time 1 data was taken from our previous report, Dalrymple et al. (submitted for publication), while her Time 2 data was collected for the present study.

3.1. Analysis

For each image, an outline was drawn around each region of interest (e.g., "eyes") and each region's pixel coordinates and area were recorded. We defined the following regions: Eye, Head (excluding eyes), Body (including arms, torso and legs), foreground Objects (e.g., tables, chairs, objects on the table) and Background (e.g., walls, shelves, items on the walls). Fig. 2b illustrates these regions for two scenes. To compensate for the different sizes of these regions, we computed area-normalized fixation proportions (Birmingham et al., 2008a; Smilek et al., 2006), by first dividing the number of fixations in each region by the area of the region, separately for each image and each participant, and then computing proportions based on these normalized data.

To determine where SL fixated, we analyzed the fixation proportion data with a series of paired two-tailed *t*-tests comparing the different regions of interest (Eye, Head, Body, Objects, and Background) to each other for SL at Time 1 and at Time 2, respectively. To compare SL's fixation proportions at Time 1 to her fixation proportions at Time 2, we performed two-tailed paired *t*-tests on the fixation proportions for each region. Time 1 data was paired with Time 2 data based on scene viewed. We also computed SL's mean fixation durations, number of fixations per trial, and trial duration (Fig. 4) and compared her data at Time 1 and Time 2 for each of these measures using a paired two-tailed *t*-test. All *p* values were compared to $\alpha = .05$.

Finally, to determine how SL's fixations are allocated over time, we plotted her cumulative proportions of fixations to the Eye region (our primary region of interest) at 5, 15, 30, 45, and 60 sec (Fig. 3b). We chose these intervals because most control subjects do not exceed trial durations of 60 sec. We also compared SL's Time 1 versus Time 2 cumulative proportions of fixations on the Eye region at the earliest time intervals (5 sec and 10 sec) using paired two-tailed *t*-tests (*p* value compared to $\alpha = .05$). This was done to determine when during the trial SL's fixation allocation to the eyes at Time 2 diverged from that at Time 1.

3.2. Results

Results from Experiment 1 and Experiment 2 are presented in Figs. 3 and 4. For visual comparison, these figures also include data from healthy control subjects from Dalrymple et al. (submitted for publication), who viewed scenes in unrestricted viewing conditions.

3.2.1. SL Time 1

SL's highest proportion of fixations was on the Head region (.34). This proportion was significantly larger than those for Object (.11), $t(7) = -4.64$, $p = .002$, and Background (.08), $t(7) = 6.14$, $p < .001$, regions. SL also had a greater proportion of fixations on the Body region (.32) than the Object, $t(7) = -5.35$, $p = .001$, and Background region, $t(7) = 5.27$, $p = .010$. No other Regions differed from each other.

3.2.2. SL Time 2

SL's highest proportion of fixations was on the Eye region (.43). This proportion was significantly larger than those for Body (.12), $t(7) = 6.34$, $p < .001$, Background (.07), $t(7) = 7.69$, $p < .001$, and Object (.06), $t(7) = -10.38$, $p < .001$, regions. SL also had a greater proportion of fixations on the Head region (.32) than the Body, $t(7) = -10.61$, $p < .001$ Background, $t(7) = -12.19$, $p < .001$, and Object, $t(7) = -8.99$, $p < .001$, regions, though her proportion of fixations to the Head region did not differ significantly from her proportion of fixations to the Eye region. The proportions of fixations to the Body, differed from those of the Background, $t(7) = 4.53$, $p = .003$, and Object, $t(7) = -3.68$, $p = .007$, regions, though these later regions did not differ from each other.

3.2.3. SL Time 1 versus Time 2

SL had a significantly higher proportion of fixations on the Eye region at Time 2 compared to Time 1, $t(7) = -3.79$, $p = .007$, and a significantly lower proportion of fixations to the Body region, $t(7) = 4.37$, $p = .003$, at Time 2. Her fixation proportions to the other regions remained unchanged: Head, $t(7) = .65$, $p = .534$; Object, $t(7) = 2.31$, $p = .054$, Background, $t(7) = .37$, $p = .722$. SL's fixations were significantly shorter, $t(7) = 3.27$, $p = .014$, she made more fixations $t(7) = -6.29$, $p < .001$, and took longer to describe the scenes, $t(7) = -4.98$, $p = .002$, at Time 2 compared to Time 1.

3.2.4. Interval analysis

Having established that SL fixates the Eye region more at Time 2 than at Time 1, we compared her Time 2 versus Time 1 fixations on the Eye region at the earliest viewing intervals to determine at what point within a trial, on average, her fixation proportions on the eyes increased as a result of recovery. SL's increase in fixations to the eyes at Time 2 relative to Time 1 was apparent as early as 5 sec into the trials, as indicated by

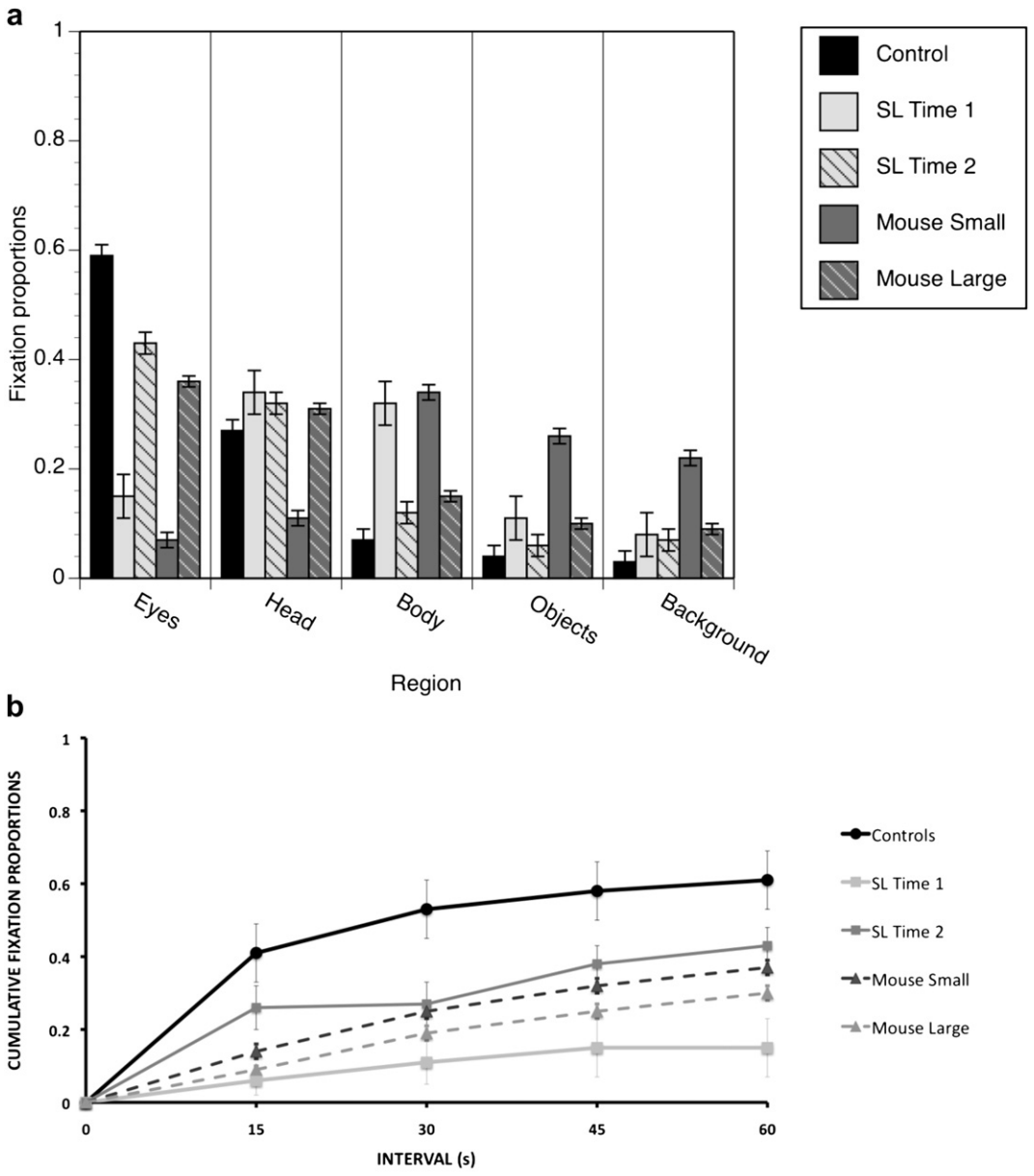

Fig. 3 – (a) Fixation proportions for patient SL at Time 1 and Time 2, and for participants who viewed scenes through Small and Large mouse-contingent windows. Fixation proportions are normalized for the size of the region. (b) Cumulative proportions of fixations on the Eye region over the first 60 sec of viewing for SL at Time 1, and Time 2, and for participants who viewed scenes through Small and Large mouse-contingent windows. Also included in both (a) and (b) are control data from Dalrymple et al. (submitted for publication) for visual comparison. Error bars represent standard error.

a trend to significance in the comparison, $t(7) = -2.30$, $p = .055$. By 10 sec into the trials, SL was making significantly more fixations on the eyes at Time 2 compared Time 1, $t(7) = -3.41$, $p = .011$.

3.2.5. *Summary*

SL fixated the eyes in the social scenes more at Time 2 than at Time 1. These extra fixations were accompanied by a corresponding decrease in fixations to the bodies in the scenes, while fixations to the other regions remained constant. Another notable effect was that SL's fixations decreased in duration, but increased in number from Time 1 to Time 2. Her trial durations also increased from Time 1 to Time 2. One might be concerned that SL's increased fixations to the eyes at Time 2 may have been due to the fact that she explored the images for longer, giving her more of an opportunity to find the Eye regions. However, as can be seen in Fig. 3b, and confirmed by comparison of SL's cumulative fixations at Time 2 versus Time 1, SL's increased fixations on the eyes at Time 2 relative to Time 1 were evident as early as 5 sec into the trial. This strongly suggests that her increased fixations on the eyes at Time 2 are not related to her increased trial duration.

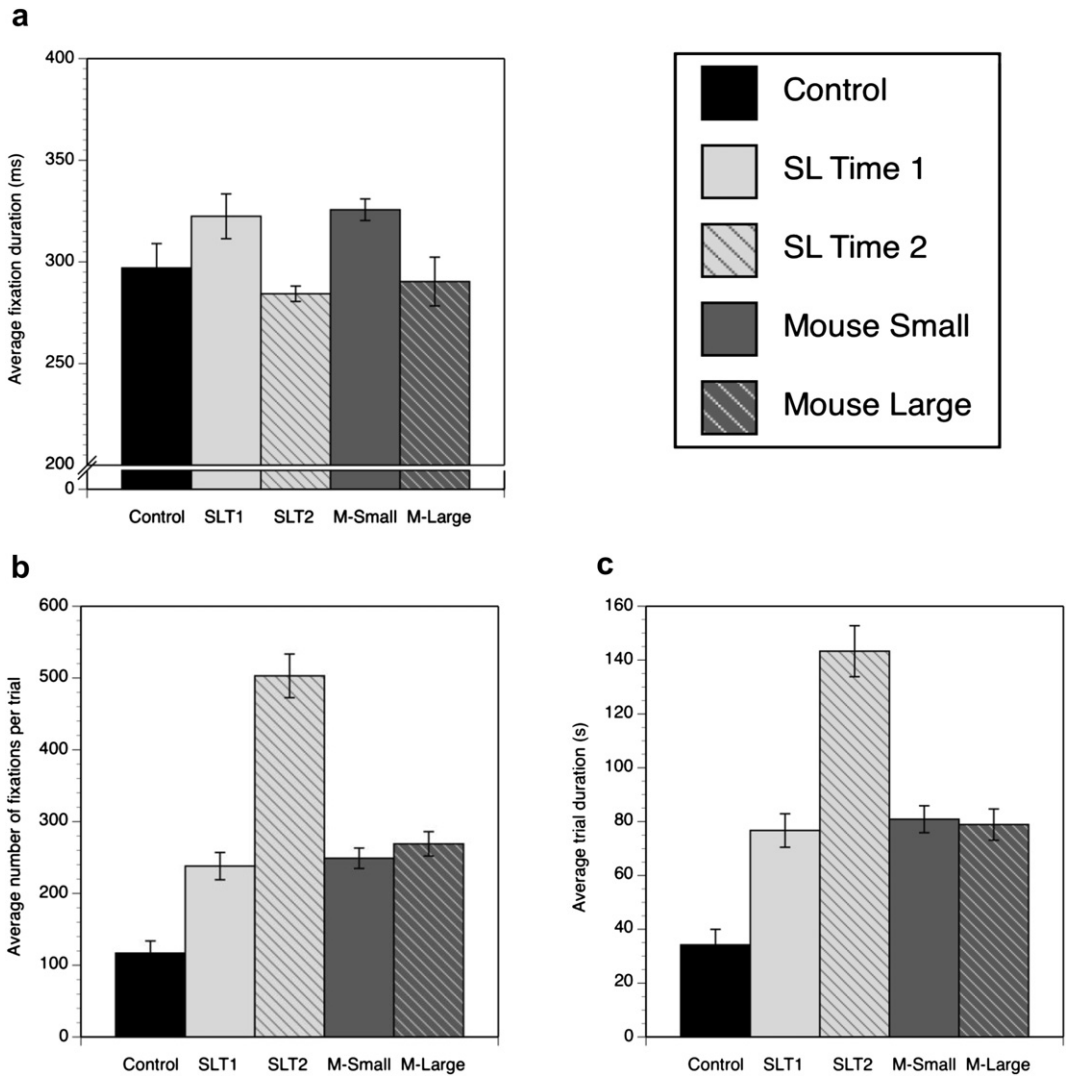

Fig. 4 – (a) Average fixation durations (in msec) (b) Mean number of fixations per trial, and (c) mean trial duration (in sec), for patient SL at Time 1 and Time 2 and for participants who viewed scenes through Small and Large mouse-contingent windows. Also included are control data from Dalrymple et al. (submitted for publication) for visual comparison. Error bars represent standard error.

4. Experiment 2: mouse-contingent windows

The purpose of Experiment 2 was to test the hypothesis that SL's increased fixations on the eyes of the social scenes at Time 2 compared to Time 1 are related to an expansion of the size of her window of visual attention. To test this hypothesis, we compared our mouse-contingent group from our previous study (Dalrymple et al., submitted for publication) to a new mouse-contingent group who viewed the scenes with a window of a different, smaller, size than our initial group. If SL's changes in behaviour reflect an increase in the size of her attentional window, we should see similar differences in the behaviour of participants viewing the scenes through Small versus Large sized windows. In other words, participants viewing scenes through a larger window should look at the eyes more than participants with a smaller window.

4.1. *Method*

4.1.1. *Participants*

4.1.1.1. Window Size: Small. Participants ($n = 13$, 3 males) were undergraduate students at the University of British Columbia who ranged in age from 19 to 29 years (mean = 21years). 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. The data from one participant was excluded from the analyses due to shift of the eye monitor during the task.

4.1.1.2. Window Size: Large. Participants ($n = 17$, 7 males) were undergraduate students at the University of British Columbia who ranged in age from 17 to 23 years (mean = 19 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.

4.1.1.3. Stimuli, apparatus and procedure. The stimuli and procedure for Experiment 2 were the same as Experiment 1, except that participants viewed the scenes through a mouse-contingent aperture. The computer generated a square aperture centered on the mouse coordinates. This 'window' revealed a portion of the stimulus, with the screen outside the window being white. The aperture moved as participants moved the mouse across the screen. SL's attentional window was previously estimated to be approximately 1.25° based on her threshold for identifying the global level of hierarchical letter stimuli (Dalrymple et al., 2007), thus the window sizes chosen for the present experiment were on the lower and upper side of that estimate: the "Small" window was $1^\circ \times 1^\circ$ while the "Large" window was $2^\circ \times 2^\circ$ in size.[3] Participants were able to freely explore the screen with the window and their eyes were tracked according to the methodology used in Experiment 1. Eye fixations were defined as in Experiment 1. Data from the Large window group was previously reported in Dalrymple et al. (submitted for publication), whereas the Small window group data was collected for the purpose of the present study.

Participants first underwent a practice trial using the mouse-contingent window. They were instructed to start from a circle at centre-screen labeled "Start" and follow a line from that circle until they reached a second circle labeled "End". This was designed to familiarize them with, and teach them how to control, the mouse-contingent aperture. They were then instructed to freely search the screen for a hidden object. Once they located the hidden object and felt comfortable with the apparatus, the main experiment began. Like SL, participants were asked to verbally describe social scenes while a digital voice recorder recorded their descriptions. Participants initiated the trials on their own, which were limited to 3 min. Participants rarely used the full 3 min to perform the task.

4.1.2. *Analysis*

One participant from the Small aperture group was excluded due to shift of the eye monitor during the task. To determine where the mouse-contingent groups fixated, and if and how they differed, we analyzed the fixation proportion data with a two-way mixed design analysis of variance (ANOVA) with between-subjects factors of Window Size (Small *vs* Large) and within-subjects factor of Region (Eye, Head, Body, Objects, and Background). Interactions were followed up with one-way ANOVAs to compare the groups for each Region. We also computed average fixation durations, number of fixations per trial, and trial durations (Fig. 4), and compared the Small and Large aperture groups on this measure using one-way repeated measures ANOVAs with between-subjects factor of Window Size (Small *vs* Large). All p values were compared to $\alpha = .05$.

Finally, we conducted a two-way mixed ANOVA with between-subjects factor of Group (Small *vs* Large window) and within-subjects factor of time interval (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 sec) to determine if the Small and Large window groups differ in their allocation of fixations on the Eye region (our primary region of interest) over time. We plotted each group's proportions of fixations to this region at 15, 30, 45, and 60 sec, to illustrate how their fixations are allocated over time (see Fig. 3b).

4.2. *Results*

4.2.1. *Mouse-contingent windows: Small versus Large*

4.2.1.1. Omnibus ANOVA. There was a main effect of Region $F(4,27) = 13.78$, $p < .001$, and a significant Window Size × Region interaction, $F(4,108) = 151.87$, $p < .001$, but no main effect of Window Size $F(1,27) = .23$, $p = .635$.

4.2.1.2. One-way ANOVAs and t-tests. There was a main effect of Window Size for each Region, indicating that the Small aperture group differed from the Large window group in terms of proportions of fixations on each of the Regions. The Large window group had a higher proportion of fixations on the Eye region compared to the Small window group, $F(1,27) = 132.71$, $p < .001$, and the Small window group had a higher proportion of fixations to all other regions compared to the Large window group: Head, $F(1,27) = 224.59$, $p < .001$; Body, $F(1,27) = 166.10$, $p < .001$; Objects, $F(1,27) = 203.90$, $p < .001$; Background, $F(1,27) = 95.94$, $p < .001$. The average duration of fixations for the Large window group was significantly shorter than that of the Small window group, $F(1,27) = 6.46$, $p = .017$, but these groups did not differ in terms of mean number of fixations per trial, $F(1,27) = .25$, $p = .622$, or mean trial duration, $F(1,27) = .02$, $p = .879$.

4.2.1.3. Mouse-contingent window: Small. There was a main effect of Region, $F(4,44) = 100.24$, $p < .001$. The Small window group's highest proportion of fixations landed on the Body region (.34), followed by Objects (.26), Background (.22), Head (.11), and Eye (.07). They had a significantly higher proportion of fixations to the Body than any other region. Their proportions of fixations to the Object and Background regions did not differ, though these proportions were significantly higher than the fixation proportions to the Head and Eye regions, which did not differ from each other.

4.2.1.4. Mouse-contingent window: Large. There was a main effect of Region, $F(4,64) = 88.41$, $p < .001$. The Large window group's highest proportion of fixations landed on the Eye region (.36), followed by Head (.31), Body (.15), Objects (.10), and Background (.09). They had a significantly higher proportion of fixations to the Eye and Head region compared to all other regions, and a higher proportion of fixations to the Body region compared to the Background region. No other regions differed from each other.

4.2.1.5. Interval analysis. There was a main effect of Interval $F(11,27) = 104.67$, $p < .001$, indicating that both the Small and

[3] Note that the "Large" window size was used in Dalrymple et al. (submitted for publication), while the "Small" window size is new to this experiment. The "Large" window group in Dalrymple et al. had larger proportions of fixations on the eyes than SL at Time 1. Thus, in the present experiment, we are "working backwards" to simulate her Time 1 behaviour with the new, smaller window, while seeing if the original "Large" window better approximates her Time 2 behaviour.

Large window groups showed an increase in their fixations on the eyes over time. There was no main effect of Group, $F(1,27) = 2.97$, $p = .097$, or Group × Interval interaction, $F(11,27) = .62$, $p = .811$, indicating that the groups did not differ in terms of proportions of fixations on the eyes and that both groups increased their fixations on the eyes at the same rate.

4.2.1.6. Summary. The Large window group allocated a significantly greater proportion of fixations to the eyes in the scenes than did the Small window group. They also made significantly shorter fixations than the Small window group. Although these groups did not differ significantly in terms of the number of fixations made per trial, the Large window group made slightly more fixations per trial than the Small window group. Combined with shorter fixations, this leads to no difference in the average time spent describing each scene. As can be seen in Fig. 3b, both groups show consistent increases in the proportions of fixations on the eyes over time. Although the Small window group allocated a greater proportion of fixations to the eyes than the Large window group in the first 60 sec of the trial, this difference was not significant. While the Small window group then fixated elsewhere in the scenes, reducing their overall proportion of fixations on the eyes relative to other regions, the Large window group continued to allocate more fixations to this region after the 60 sec mark, resulting in a much larger overall proportion of fixations on the eyes compared to the Small window group.

5. Discussion

Previously we reported that simultanagnosic patient SL showed reduced fixations on the eyes in social scenes compared to healthy controls (Dalrymple et al., submitted for publication). We hypothesized that, with recovery, SL would allocate more fixations to the eyes in social scenes, behaving more like normal controls. Furthermore, we hypothesized that this behavioural change would be related to an expansion of the restricted window of attention that characterizes simultanagnosia, and that this expansion could be simulated in healthy subjects through the use of restricted viewing windows of different sizes.

Our first hypothesis was supported by the results of Experiment 1, which indicate that SL did allocate more fixations to the Eye region of social scenes after 3.5 years of recovery than she did when she was first tested. Our second hypothesis was supported by the results of Experiment 2, which indicate that healthy participants viewing social scenes through a larger mouse-contingent viewing window allocate more fixations to the eyes in social scenes than participants viewing scenes through a smaller mouse-contingent window. Furthermore, participants viewing the scenes through a smaller window show similar proportions of fixations on the eyes as SL at Time 1, while participants viewing the scenes through a larger window show similar proportions of fixations on the eyes as SL at Time 2. In addition, SL's fixation durations at Time 1 were more similar to the fixation durations of participants viewing the scenes through a small window (i.e., both groups had relatively long fixation durations), while her fixation durations at Time 2 were more similar to the fixation durations of participants viewing the scenes through a larger window (i.e., both groups had relatively short fixation durations). All groups show consistent allocations of fixations to the different regions over time.

Participants' descriptions of the scenes, though subjective in nature, are also informative about the similarities between SL and the window groups. Upon examination of these descriptions, we observed that both window groups and SL at Time 1 and Time 2 appear to determine the main action in the scene (e.g., people reading, see Fig. 2a, right), but do so by describing details. As the trial times for SL and the window groups suggest, they spend longer collecting sufficient details to feel satisfied with their description of each scene. Interestingly, at Time 1, SL miscounts the number of people in one scene, counting one individual twice, without realizing that she had done so. This suggests that SL has poor spatial memory for where objects (or in this case, individuals) appear in the scene.

One change in SL's behaviour that is not captured by the change in Window Size is that SL spent more time describing the scenes at Time 2 compared to Time 1. We speculate that this is not related to SL's recovery, but to her motivation and stamina at Time 2. That is, at Time 2, the healthier SL may have had more stamina been particularly motivated to describe the scenes to the best of her ability (which to her may have been as thoroughly as possible). Perhaps she was proud of her recovery and wanted to demonstrate her improved abilities. Motivation would not be a changing factor with the window groups and therefore time spent describing the scene would not change from small to large window sizes.

How does SL compare to other simultanagnosics reported in the literature? We (Dalrymple et al., 2007) previously reported that SL shows the classic global processing deficits documented in other simultanagnosic patients (e.g., Clavagnier et al., 2006; Karnath et al., 2000; Shalev et al., 2004, 2007). SL had difficulty naming the global level of hierarchical letters, particularly when they were large and made up of widely spaced local elements. SL's recovery was documented with these hierarchical stimuli. We tested her shortly after injury and then after some recovery and found that, like with the social scenes in the present study, her behaviour approaches, but does not reach, normal. That is, SL's ability to name the global level of the hierarchical letter stimuli improved from her initial testing reported in Dalrymple et al. (2007), but is not yet at normal (perfect) levels. It is difficult to compare the magnitude of SL's improvement on the letters versus the social scenes, but the fact that she shows partial improvement on the well-established letters task supports the results of partial improvement in the current scenes study.

The results from these experiments not only document the behavioural changes of a patient with simultanagnosia while engaging in a complex behaviour, but also link those behavioural changes to an underlying mechanism, namely a change in the size of the attentional window that is characteristically restricted in simultanagnosia. The notion of simultanagnosia being related to a restricted window of visual attention has been evident in the literature since the early 1950s (Bay, 1953). Some referred to it as "shaft vision" (Bay, 1953; Tyler, 1968), while others (e.g., Thaiss and de Bleser, 1992) described a rigid

reduction of the spatial extent of the visual "spotlight", or "searchlight vision" (Trobe, 2001). More recently, several investigations have been aimed at understanding the nature of the restricted window of attention in simultanagnosia. For example, using a gaze-contingent display, we found that participants viewing hierarchical letters through a narrowed window of vision showed similar global processing deficits with hierarchical letter stimuli to what is typically seen with patients with simultanagnosia (Dalrymple et al., 2010). Participants viewing these letters through a gaze-contingent window showed similar accuracy patterns for identifying the global level of the letters compared to patient SL, specifically showing poor performance for large letters made up of widely spaced local elements and improving as letters became smaller and more densely packed. This was a first insight into the close relationship between a restriction of visual attention in simultanagnosia and a literal restriction of vision in healthy subjects.

We recently extended this link to more complex stimuli by investigating how patients with simultanagnosia scan social scenes, and how that relates to a literal window of vision (Dalrymple et al., submitted for publication). Again we found a close relationship between patient behaviour and the behaviour of healthy participants viewing the scenes through a restricted viewing window: the patients and the restricted window groups showed reduced fixations on the eyes in social scenes compared to healthy control participants scanning the same scenes under natural viewing conditions. While the reason for the reduced fixations on the eyes remains unclear (though we offer a possible explanation below), the behavioural link between those with a restricted window of attention and those with an artificially imposed restricted window of vision is remarkable. We have reinforced this link in the present study by showing that the increase in fixations on the eyes in social scenes that occurs with recovery from simultanagnosia can be mimicked by increasing the size of a restricted window of vision with healthy participants.

The present experiments add substantially to the findings reported in Dalrymple et al. (submitted for publication) by documenting simultanagnosic behaviour over the course of recovery, and by relating changes in behaviour to the mechanisms hypothesized to underlie the disorder. To our knowledge, only one other longitudinal study of simultanagnosia has been reported in the literature. Nyffeler et al. (2005) documented the scanning behaviour of a patient at 8, 14, and 37 weeks after injury, while she explored simple line drawing (e.g., objects, schematic clock). Consistent with the current findings, this patient showed improved performance over time (e.g., better object naming, increased exploration of the stimuli). Based on a qualitative assessment of the scan patterns executed by this patient, Nyffeler et al. concluded that the recovery reflected an enlargement of a restricted attentional field. This conclusion was primarily based on the fact that the patient's scan patterns became more exploratory over the course of recovery (i.e., covered more area). The current data agrees with these conclusions, and they also speak to the idea of an expanding attentional field by simulating it with an expanding window of vision in healthy subjects. While increased scanning of simple stimuli in Nyffeler et al.'s study could be explained by other mechanisms (e.g., an improved ability to disengage attention from previously attended stimuli), Experiment 2 of the current study establishes a direct link between an expansion of the useful area of processing and a recovery of normal behaviours in simultanagnosia.

Simultanagnosia and other disorders of visual attention, such as visual neglect and extinction, have been linked to lesions to parietal areas (Posner and Peterson, 1990; Riddoch et al., 2010), but little work has been done to relate changes in patient behaviour to possible anatomical changes that may underlie recovery from these disorders. Our findings with simultanagnosia point to an anatomical change that results in an increase in the size of a restricted window of attention. It is possible that the initial restriction of attention in simultanagnosia is related to decreased cortical excitation in functional areas due to loss of input from damage to neighboring areas. Rizzo and Hurtig (1987) speculated that the spontaneous disappearance of objects despite steady fixation in simultanagnosia might reflect cortical fatigue, and Pavlov suggested that the visual deficits in simultanagnosia might be related to a "low tonus of excitation" in the visual cortex (Pavlov, 1955, p. 609). If the initial restriction of visual attention is indeed related to reduced excitation of preserved parietal areas, it is possible that, with time, regions neighboring the damaged areas may regain cortical excitation through alternate cortical pathways. Recovery of excitation in the preserved regions may in turn lead to a corresponding expansion of the window of attention. Support for this hypothesis comes from evidence that the administration of stimulants (i.e., caffeine) to patients with simultanagnosia temporarily improved their ability to see more than one object at a time (Luria, 1959). Patients also claimed to see things "in a brighter light" (Luria, 1959, p. 447). Perhaps these stimulants provided the extra excitation to preserved brain areas that otherwise returns slowly over time.

Our data provides insight into why a reduced window of attention results in reduced fixations on the eyes in social scenes, with resulting implications for social attention in general. Previous research has suggested that people look at the eyes of people in social scenes because the eyes are informative to the viewer (Birmingham et al., 2007, 2008b). Specifically, eyes and eye gaze provide information about the attentional state of the people in the scenes, e.g., to whom, or to what, people in the picture are directing their attention. This is supported by the finding that when asked to describe where people in the scene are directing their attention, subjects make significantly more fixations on the eyes than they do when asked to simply describe the scenes (Birmingham et al., 2008a; Smilek et al., 2006). In the present study, the reduced fixations on the eyes from patients and healthy subjects viewing scenes through a restricted window suggest that the eyes have lost some of their informative value when they are viewed outside the context of the whole scene. This suggests that without context to help infer attentional states, the viewer can no longer gather this important information from the eyes and must look elsewhere. The fact that fixations on the eyes increase with recovery and with a larger window of viewing suggests that with increased context, the informative value of the eyes increases. This is not an all or nothing change, but rather a graded increase in fixations to the eyes that occurs with a graded increase in context.

A restricted window of attention may not be the only explanation for the simultanagnosic deficits. Throughout this century of research on simultanagnosia, several suggestions have been made about the mechanisms underlying this complex disorder. Some have suggested decreased cortical excitation (Luria, 1959; Rizzo and Hurtig, 1987), explaining perceptual events such as the spontaneous disappearance of objects despite steady fixation (Rizzo and Hurtig, 1987). Similarly, simultanagnosia has been placed in the context of the Integrated Competition Hypothesis (Duncan et al., 1997), with the suggestion that processing resources are depleted in simultanagnosia, resulting in all or nothing competition between objects (Jackson et al., 2009). Others have suggested that an inability to disengage from attended stimuli prevents the perception of new stimuli (Farah, 1990), though recent tests of this idea have failed to support it (Clavagnier et al., 2006; Dalrymple et al., 2009). Finally, some have suggested that impaired object perception in simultanagnosia results from an inability to combine preserved space and object information (Coslett and Lie, 2008). Although all interesting and valid, it is important to note that these different theories are not necessarily mutually exclusive with each other, or with the concept of a restricted window of attention. For example, it is possible that patients can experience the disappearance of objects from awareness (e.g., Rizzo and Hurtig, 1987) *within* a restricted window of attention. Other simultanagnosic behaviours, like the inability to see more than one of two overlapping figures (i.e., objects that take up the same spatial location) (Rafal, 2001), also point to additional perceptual limitation that could occur within a limited window itself. Investigating these possibilities is an important avenue for future research.

Our findings have broad implications for theories of simultanagnosia. While it is generally agreed that simultanagnosia is characterized by a deficit of visual attention (Holmes and Horrax, 1919), it is sometimes unclear what is meant by "attention" in this context. For example, some authors suggest that patients have a disorder of object-based attention, as evidenced by impaired processing of objects (e.g., Rafal, 2001), while others suggest that patients suffer from a disorder of space-based attention (e.g., Coslett et al., 1995; Robertson et al., 1997) which is evidenced by narrowed spatial extent of the useful field of processing with otherwise fully functioning retinas (Holmes and Horrax, 1919; Thaiss and de Bleser, 1992; Tyler, 1968). Our findings support a spatial attentional account of this disorder. Furthermore, our findings provide evidence of unique properties of the disordered spatial attention that is seen in Bálint syndrome: spatial attention is restricted, but the degree of this restriction can change over time. This change in turn brings with it important consequences for the resulting perceptual experience of the patient.

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