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Spatial gradient for unique-feature detection in patients with unilateral neglect: Evidence from auditory and visual search

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Patients with unilateral spatial neglect following right hemisphere damage are impaired in detecting contralesional targets in both visual and haptic search tasks, and often show a graded improvement in detection performance for more ipsilesional spatial locations. In audition, multiple simultaneous sounds are most effectively perceived if they are distributed along the frequency dimension. Thus, attention to spectro-temporal features alone can allow detection of a target sound amongst multiple simultaneous distracter sounds, regardless of whether these sounds are spatially separated. Spatial bias in attention associated with neglect should not affect auditory search based on spectro-temporal features of a sound target. We report that a right brain damaged patient with neglect demonstrated a significant gradient favouring the ipsilesional side on a visual search task as well as an auditory search task in which the target was a frequency modulated tone amongst steady distractor tones. No such asymmetry was apparent in the auditory search performance of a control patient with a right hemisphere lesion but no neglect. The results suggest that the spatial bias in attention exhibited by neglect patients affects stimulus processing even when spatial information is irrelevant to the task.

Keywords: Spatial neglect; Auditory perception; Search; Head-related transfer function.

INTRODUCTION

Spatial neglect is a common outcome of unilateral focal lesions, particularly following damage to the right cerebral hemisphere (Heilman & Valenstein, 1993; Hier, Mondlock, & Caplan, 1983). The syndrome produces a pathological inability to direct attention to sensory stimuli located within the contralesional hemispace despite intact sensory functioning (Driver & Mattingley, 1998). A frequently used task to assess spatial neglect is visual search, in the form of a cancellation task (Albert, 1973; Edgeworth, Robertson, & McMillan, 1998; Weintraub & Mesulam, 1985). Neglect patients will typically initiate a search for target items from the ipsilesional side of the display, often failing to search or detect targets within the contralesional side of the display. This spatial asymmetry in their search performance is thought to reflect a pathological bias in attention towards the ipsilesional hemispace and a resulting neglect of the contralesional space (Kinsbourne, 1993). In the present study we examined whether such an attentional bias also affects search performance for arrays of auditory stimuli where the target is spectro-temporally salient.

Visual search paradigms traditionally used in the study of normal search behaviour (Treisman & Gelade, 1980) permit investigation of the spatial bias in neglect patients' search performance. Here, a single target item must be detected from an array of distractors, and performance accuracy and latency is examined across different arrays where the

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spatial location of the target is manipulated. Neglect patients' performance on this type of search task also implies an ipsilesionally biased asymmetry that can be attributed to impairments in spatial attention. Patients are slower and more error prone in detecting the target when it is located on the contralesional side, relative to when it is located on the ipsilesional side of space (Eglin, Robertson, & Knight, 1989; Morris et al., 2004; Pavlovskaya, Ring, Groswasser, & Hochstein, 2002; Riddoch & Humphreys, 1987). The asymmetry can be apparent even when the target item is distinguished from the distractors by a single, unique feature, such as its colour or shape (Eglin et al., 1989; Pavlovskaya et al., 2002; Riddoch & Humphreys, 1987). A useful aspect to the visual search task in neglect is the ability to examine spatial gradients in attention. Detection latency and accuracy typically get worse at more contralesional positions within the array, producing a gradient in performance as a function of spatial location (Morris et al., 2004).

Spatial neglect can affect multiple sensory modalities including audition (Pavani, Husain, Ladavas, & Driver, 2004) and touch (Vaishnavi, Calhoun, & Chatterjee, 2001). As for vision, there is evidence that neglect patients can also be biased in their haptic exploration of space. In one study, right brain damaged (RBD) patients with neglect manually explored and identified more blocks on the ipsilesional than contralesional side of an array, whilst blindfolded (Schindler, Clavagnier, Karnath, Derex, & Perenin, 2006). This asymmetry in search behaviour was not apparent for RBD patients without neglect or for healthy controls. The degree of search asymmetry shown by neglect patients was also significantly correlated between visual and haptic conditions of the task, supporting the notion that neglect reflects an attentional disturbance at a supramodal level.

It is not surprising, however, that a spatial deficit following brain injury affects both visual and haptic exploration, particularly as stimuli in both modalities are invariably distributed in the spatial dimension. In typical visual search tasks, even if a salient non-spatial feature, such as the colour of a target, captures observers' attention, they must ultimately direct their eyes or covertly direct their attention to the spatial location of the target within the array. In audition, multiple simultaneous sounds are most effectively perceived if they are distributed along the frequency dimension (i.e., if they have different fundamental frequencies) (Bregman, 1990). Thus, attention to spectro-temporal features alone can allow detection of a target sound stream presented amongst multiple simultaneous sound streams, even if these streams are spatially separated (Asemi, Sugita, & Suzuki, 2000; Darwin & Hukin, 1999; Eramudugolla, McAnally, Martin, Irvine, & Mattingley, 2008). In fact, it has been suggested that cues to spatial location may play a relatively minor role in helping a listener separate target sounds from simultaneous distractor sounds (Culling & Summerfield, 1995; Darwin, 1997). In auditory search tasks in which a set of steady tones with different frequencies are presented simultaneously, salient spectro-temporal features such as frequency-modulation (FM) can capture attention automatically (Asemi et al., 2000; Cusack & Carlyon, 2003). Presumably, attention is directed only along frequency/temporal dimensions in such tasks, and any spatial cues should be redundant. If this is the case, neglect patients should not demonstrate a spatial asymmetry when required to search spatially separated simultaneous tones, where the target is spectro-temporally distinguishable from the distractor tones - e.g., an FM tone amongst steady-tone distractors.

Tasks used to demonstrate deficits in auditory spatial attention in neglect patients typically involve an explicit spatial component, e.g., sound localization/lateralization (Pavani et al., 2004), reporting the detection of sounds in terms of their location (left/right or both – extinction) (Spierer, Meuli, & Clarke, 2007), or reporting the temporal order of sounds also in terms of their location (leftfirst/right-first - temporal order judgment) (Karnath, Zimmer, & Lewald, 2002). Thus, it is possible that spatial deficits in audition arise when patients have to attend to spatial information to register their response to the stimuli (Deouell & Soroker, 2000). There is evidence that although patients may extinguish the left stimulus during simultaneous bilateral presentation of sounds, they can report the identity of the extinguished sound (Deouell & Soroker, 2000; Soroker, Calamaro, Glicksohn, & Myslobodsky, 1997). This suggests that the processing of sound identity is largely intact in auditory neglect, but that difficulty assigning spatial information to sounds can result in a failure to consciously detect the sound, or can cause contralesional sounds to be attributed to ipsilesional locations (alloacusis). Furthermore, there is evidence that the mismatch-negativity (MMN) for orienting to auditory spatial oddballs is significantly diminished for the left relative to the right ear, whereas the amplitude of MMNs for frequency or duration

oddballs are relatively intact in neglect (Deouell, Bentin, & Soroker, 2000). Together, these findings suggest that the detection of sounds based on a spectro-temporal auditory feature, such as frequency modulation, should be relatively unaffected by neglect patients' spatial bias in attention.

Studies of neurologically normal individuals indicate, however, that spatial attention can affect auditory processing even in the absence of an explicit spatial component to the task. In a study by Mondor and Zatorre (1995), participants' ability to discriminate whether a sound was a complex or pure tone was fastest when the tone was preceded by an irrelevant spatial cue (noise burst) that was presented from a speaker close to the location of the tone. Furthermore, response latency increased monotonically with increasing distance between the tone and the spatial cue. This indicates that spatial attention can modulate auditory processing, even if the spatial dimension is irrelevant to the auditory task. By this account, if neglect patients' focus of attention is pathologically biased towards the ipsilesional side, an auditory search task where the target can be discriminated on the basis of spectro-temporal features alone will still be subject to spatially asymmetric performance. However, one might argue that in Mondor and Zatorre's study, the noise burst acted as an exogenous cue that forced attention toward the cued location automatically, thus forcing a spatial effect. In contrast, auditory search does not employ an exogenous cue and thus there is no focus on location. It is not clear whether the spatial bias in attention that affects neglect patients modulates their performance on an auditory search task in which their attention is directed to the spectro-temporal features of the sounds rather than to the spatial location of sounds. In the present study, we used an auditory search task with FM-targets amongst steady-tone distractors to compare the performance of two patients: a RBD patient with visual neglect, and a RBD patient without clinical evidence of spatial neglect.

METHOD

Participants

Approval for patient recruitment and testing was obtained from the Monash University and hospital committees for Ethical Research involving Humans.

SK was a right-handed 80-year-old man who, 5 years prior to the testing, had been diagnosed with a right hemisphere infarct within the territory of the middle cerebral artery (Figure 1A). SK's visual fields were intact on confrontation testing and pure tone audiometry in the range of 0.5–8 kHz revealed no asymmetric hearing loss (Mean thresholds: Left ear = 34.17 dB, Right ear = 43.33 dB). He demonstrated moderate neglect symptoms on a cancellation task (Star Cancellation (Wilson, Cockburn, & Halligan, 1987)), omitting 26% of targets within the contralesional side of the page and none on the ipsilesional side. On a line bisection task, the mean deviation of his responses was 17.75 mm to the right of true midline (total line length = 200 mm).



Figure 1. Axial slices of RBD patients' MRI brain scans. (A) Patient SK's scan shows necrotic regions involving anterior portions of the superior and middle temporal lobe, inferior frontal gyrus and insula, internal capsule and lentiform nucleus on the right side. (B) Patient AP's scan shows lesions within the inferior frontal gyrus, superior temporal lobe and extending into the inferior parietal lobe. (C) Overlay of both patients' lesions mapped onto the MNI template.

AP was a right-handed 60-year-old man who had a middle cerebral artery stroke 3 years prior to testing (Figure 1B). The patient had intact visual fields as tested by confrontation and his auditory thresholds for pure tones in the 0.5–8 kHz range also revealed no asymmetries in his hearing (Mean thresholds: Left ear = 43.33 dB, Right ear = 57.75 dB). He omitted 11% of targets on the left and 4% of targets on the right side of the Star Cancellation task, and he displayed no bias in his responses on the line bisection task (mean deviation from true midline = 0 mm). Patient AP's relative lack of spatial neglect when compared with SK meant that he was suitable as a RBD control.

Stimuli

Visual search arrays

The visual search array consisted of 12 randomly distributed black circles (O) presented on a white background. Each circle subtended 1.1° of visual angle in diameter. The array was organised into four vertical divisions of equal width (8.1°), and each division contained three randomly distributed circles. These divisions were not apparent to the patient and were used to manipulate the location of the search target, which was a black circle with a tail (Q) (Figure 2A). In this task, the unique feature of the target captures the observer's attention to its location (Treisman & Gormican, 1988). The spatial location of the target was varied from trial to trial and appeared with equal probability in one of the four divisions of the display.

Auditory search arrays

In order to manipulate the spatial origin of sounds without using an array of speakers, auditory stimuli were presented in virtual auditory space (VAS) over headphones. VAS was generated by measuring the direction-dependent filtering properties of the listener's outer ears, head, and torso the Head-Related Transfer Functions (HRTFs). VAS stimuli can be localised with comparable accuracy to external stimuli (Hartung, Sterbing, Keller, & Takahashi, 1999; Martin, McAnally, & Senova, 2001). The location of auditory stimuli was varied only in azimuthal space in the interaural plane, and a set of standard HRTFs from a neurologically normal participant was used for both patients. Standard HRTFs provide a high degree of fidelity for most listeners when sound

source locations are varied only in the azimuthal plane (Wenzel, Arruda, Kistler, & Wightman, 1993).

Arrays of six complex steady tones with different fundamental frequencies (range: 150-680 Hz) were presented simultaneously and from different locations in VAS. Within each array, tones were never harmonically related to each other, in order to enhance the listener's ability to perceptually segregate the tones into separate streams (Bregman, 1990). The target was an FM tone (modulation depth = 10% of F_0 ; freq = 4 Hz), presented with equal probability at one of four possible azimuthal locations in VAS (Figure 2B). All tones (steady and FM) were equalized for RMS power. The locations of all tones within a given array was balanced such that the average of the F_0 s for tones on the left side compared with those on the right side of VAS was approximately equivalent (Mean difference between left and right = -1.51Hz), and there was no correlation between the target tone F_0 and its spatial location. The search arrays were presented at 70-80 dB SPL.

Procedure

The stimuli were presented using a Dell Inspiron 8100 portable computer running DMDX software (Forster & Forster, 2003). Auditory stimuli were delivered over headphones (Sennheiser HD437). Each type of search task (auditory or visual) was administered in a separate block of trials. A trial began with a black fixation spot presented for 700 ms at the centre of the computer screen, which was replaced by the search array for 5000 ms. Targets were present on 50% of trials and patients used their ipsilesional hand to make a speeded key press (mouse button located at the patient's midline) to indicate presence or absence of a target. For the visual search task, patients made a key press as quickly as possible if a target Q was present in the display. Both patients easily discriminated between steady and FM ('warbling') tones presented in isolation. For the auditory search task, patients made a key press as quickly as possible if they detected a warbling tone amongst the array of steady tones. Patients were tested over several sessions and the order of presentation of the two search tasks was varied between sessions. Between 150 and 230 trials of each search task were administered to each patient. Patients were never informed that the tones in the auditory search task were spatialized.

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Figure 2. Stimulus display (A,B) and Patient results (C–F). (A) Visual search array with target Q among distractor Os. (B) Schematic of auditory search array in VAS with an FM target among steady tones. Shaded areas represent possible target locations. Search time as a function of target location (left extreme to right extreme) and task (visual and auditory) for RBD neglect patient SK(C) and for RBD control patient AP (E) Error bars represent ± 1 standard error of the mean. Percentage targets missed as a function of target location and task for patient SK (D) and patient AP (F).

RESULTS

Visual search task

The two patients made very few false alarms on the visual search task (Mean FA rate: SK = 0.0%, AP = 0.6%).

SK's performance on the visual search task demonstrated a lower rate of target detection when the target was presented within the left side of the display relative to the right side (Figure 2C), and this was accompanied by longer response latencies for detected targets on the left side relative to the right side of the display (Figure 2D). Statistical analysis indicated that SK's mean response time for targets presented on the left side was significantly slower than those for targets on the right (t(145) = 13.85, p < .001). A regression analysis of SK's response time data for visual search indicated a significant negative linear relationship between the spatial location of the target and SK's detection latency (R = 0.729, (F(1, 148) = 166.47, p < .001). This relationship was modelled by the following equation: $y = -0.729x - (704.61 \pm 54.61)$, where response latency decreased as the spatial location of the target became more ipsilesional.

Patient AP's pattern of performance on the visual task differed from that of SK (Figure 2E,F). AP's response times were faster for targets presented at locations near fixation relative to targets at the more eccentric locations, but there was no asymmetry in response times between the left and right hemifields (t(78) = 0.59, p > .10), and the spatial gradient was close to zero: R = 0.159 (Figure 2F). The rate of target detection for AP was also symmetrical about fixation (Figure 2E).

Auditory search task

The patients' false alarm rates on the auditory search tasks were low (Mean FA rate: SK = 0.0%, AP = 10.6%), indicating that they were generally able to discriminate between steady and FM tones within the arrays.

SK's data indicated a reduced rate of target detection (Figure 2C) and slower responses to detected targets when they were located on the left relative to the right side of VAS (Figure 2D). Responses to FM targets on the contralesional side were significantly slower than responses to ipsilesional targets (t(73) = 5.21, p < .001). There was a significant negative linear relationship between response time and target location (R = 0.619, (F(1, 74) = 45.27, p < .001)). This relationship was modelled by the following equation: $y = -0.619x - (410.90 \pm 61.07)$.

AP's detection of the FM target was better when it was located near the midline in VAS relative to more eccentric locations (Figure 2E). His responses were also faster for targets at central than eccentric locations (Figure 2F). The spatial gradient of these responses was near zero: R = 0.189, and comparison of contralesional with ipsilesional response times indicated a marginally significant difference with responses on the right being slower than those on the left (t(106) = 2.04, p = .045).

DISCUSSION

We examined whether the ipsilesionally biased performance of a neglect patient on a visual search task is also reflected in his performance on an auditory search task in which the target is not defined by its spatial location but by its spectro-temporal features. As expected, the patient was faster and more accurate at detecting a visual target amongst distractor items when the target was placed within the ipsilesional side of the display than when it was placed on the contralesional side. Critically, a similar spatial gradient was evident on an auditory search task in which the target was an FM tone amongst steady tones. SK's detection accuracy and latency was better when the tone was located in ipsilesional versus contralesional VAS. Furthermore, a control RBD patient who demonstrated no significant spatial gradient in his performance on the visual search task, also displayed symmetric detection accuracy and latency on the auditory search task. This suggests that the asymmetric performance of SK is unlikely to reflect aberrant auditory processing due to right hemisphere damage per se, and that it is associated with his attentional disturbance.

The control RBD patient's target detection was enhanced for targets located near the centre of the display compared to targets at more eccentric positions, and this was apparent for both the visual and auditory search tasks. As both patients were instructed to fixate their gaze centrally prior to each search trial, it is possible that this central focus of attention biased AP's search performance in both modalities. A similar pattern of search performance in healthy individuals has been observed previously using a version of the visual search task used here (Morris et al., 2004). It is likely that ipsilesional biases in saccade generation would have contributed to the spatial gradient observed for visual search in SK (Ptak, Schnider, Golay, & Muri, 2007), but this cannot explain his auditory search performance. The observed effect of spatial neglect on auditory search also cannot be explained by any reference to an internal visual spatial representation, as FM target location was irrelevant to the task and the patients were not informed, prior to the task, about the sounds being distributed in VAS. It is also unlikely that damage to the right temporal cortex could impair SK's ability to make FM/steady tone discriminations for stimuli in the left half of space, exclusively. This is because frequency information from both sides of space is represented to some degree in each cerebral hemisphere (Hausler & Levine, 2000), and both patients had similar degrees of damage to the superior temporal lobe (Figure 1C). Instead, we suggest that the spatial attentional bias underlying neglect differentially prioritised the processing of left- compared with right-sided auditory targets.

It has been suggested that the processing of sound identity and spectro-temporal features may be relatively spared in neglect, compared with the processing of auditory spatial information. Indeed, it is proposed that the detection of sounds is impaired in spatial neglect when they cannot be assigned a spatial location (Deouell et al., 2000): 'a necessary (if not sufficient) condition for conscious awareness of an external event is that this event will have a sort of "location tag" attached to it' (p. 362). In our auditory search task, the patient was not required to assign any location information to the targets, yet his attentional bias affected the detection of these targets. This indicates that the attentional deficit in neglect is not dependent on an explicit spatial element to the task. It is possible that distractors presented within the right hemifield in both the auditory and visual tasks could have automatically captured SK's attention towards that side of space (Bartolomeo & Chokron, 2002), contributing to the observed spatial gradient of search performance in both domains. For example, if the target location is fixed and the number of distractors on either side of the target is systematically varied, we might expect detection performance at that location to decrease with increasing distractor load. This decrement is likely to be most apparent for the detection of contralesional targets.

Our data also contrast with the accepted view in auditory scene analysis literature that spectro-temporal cues are more important than spatial cues for parsing simultaneous sound streams. The present results suggest that detection of a salient spectrotemporal feature such as frequency modulation is affected by the spatial origin of the sound and the location of the listener's current focus of attention. In a neglect patient, this focus is chronically and pathologically biased towards the contralesional side of space, resulting in faster processing of auditory frequency and temporal information from the attended direction. It is not clear from our data whether spatial attention biases auditory processing prior to or after stream segregation (Carlyon, 2004; Sussman, Ritter, & Vaughan, 1998). There is evidence, however, that the parsing of sequential sounds into separate streams, based on frequency, is disturbed in neglect patients if the sounds are presented to the left ear (Carlyon, Cusack, Robertson, & Foxton, 2001).

In summary, our results from two RBD patients show that attention to the spatial location of a sound appears to be relatively automatic in spatial neglect, and can prioritise the processing of other non-spatial features of the attended auditory input. The data also show that attentional biases can affect the detection of unique-features in audition, such as frequency-modulation, which previous work in normals suggests is automatically detected (Asemi et al., 2000; Cusack & Carlyon, 2003).

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