Poor hand-pointing to sounds in right brain-damaged patients: Not just a problem of spatial-hearing

Francesco Pavani a,*, Alessandro Farné b,d, Elisabetta Làdavas c,d

Abstract

We asked 22 right brain-damaged (RBD) patients and 11 elderly healthy controls to perform hand-pointing movements to free-field unseen sounds, while modulating two non-auditory variables: the initial position of the responding hand (left, centre or right) and the presence or absence of task-irrelevant ambient vision. RBD patients suffering from visual neglect, unlike RBD patients without neglect and healthy controls, showed a systematic rightward error in sound localisation, which was modulated by the non-auditory variables. Localisation errors were exacerbated by initial hand-position to the right of the body-midline, and reduced by the leftwards initial hand-position. Moreover, for the visual neglect patients, mere presence of ambient vision worsened localisation errors. These results demonstrate that although hand-pointing to sounds has often been considered a straightforward approach to investigate sound-localisation abilities in brain-damaged patients, in some patients it may actually reveal localisation deficits that reflect a combination of impaired spatial-hearing and spatial biases from other sensory modalities (i.e., vision and proprioception).

Keywords: Spatial-hearing; Stroke; Right-hemisphere lesion; Visual neglect; Sound localisation; Multisensory integration; Hand-pointing; Proprioception

1. Introduction

Hand-pointing to sounds is one of the most commonly used tasks when investigating sound-localisation abilities in patients who suffered brain lesions (e.g., Bisiach, Cornacchia, Sterzi, & Vallar, 1984; Cornelisse & Kelly, 1987; Clarke, Bellman, Meuli, Assal, & Steck, 2000; Pavani, Farnè, & Làdavas, 2003; Pinek & Brouchon, 1992; Pinek, Duhamel, Cavé, & Brouchon, 1989; Ruff, Hersch, & Pribram, 1981; Sanchez-Longo & Forster, 1958). In the typical setting, the patient sits in the centre of a semicircle of speakers and is required to indicate the origin of a delivered sound with a pointing movement of the dominant hand. Performance of brain-damaged patients in this type of task is usually less accurate compared to healthy controls, with the largest localisation errors often being reported for brain-damaged patients with lesions in the right hemisphere (e.g., Bisiach et al., 1984; Ruff et al., 1981).

Contrary to its apparent ease, however, hand-pointing to sounds is a computationally complex task for the brain. Spatial information about the target sound and the responding-hand have to be combined across different senses and reference frames (Cohen & Andersen, 2002). The spatial position of the sound (specified through hearing and initially coded with respect to the head; e.g., see Blauert, 1983) must be reconciled with the spatial coordinates of the starting position of the responding hand.
(usually specified through proprioception, and initially coded with respect to the body and the arm; e.g., see Soechting & Flanders, 1992). In addition, converging evidence from neurophysiological studies in animals (e.g., Cohen & Andersen, 2000, 2002) and behavioural studies in humans (e.g., Pouget, Ducom, Torri, & Bavelier, 2002) have suggested that this complex multisensory coordinate-transformation may in fact occur via an oculo-centric spatial coding of sound position, implying that further spatial inputs from the visual modality can contribute to performance during hand-pointing to sounds (on this point see also Lewald & Ehrenstein, 1996, 1998, 2000; Zambarbieri, Schmid, Versino, & Beltrami, 1997).

In light of this computational complexity of hand-pointing to sounds, it can be hypothesised that poor performance of brain-damaged patients in such localisation task could reflect more than just impaired spatial-hearing. This should particularly apply for patients in which the brain lesion causes severe disturbances of visual and egocentric space, or affects key structures for the maintenance of a stable representation of space across sensory modalities.

Severe disturbances of visual and egocentric space are indeed common in brain-damaged patients with a lesion in the right hemisphere. Damage to the right perisylvian cortex and underlying white matter often results in the neuropsychological syndrome of visual neglect (Farné et al., 2004; Karnath, Ferber, & Himmelbach, 2001; Mort et al., 2003). This syndrome is characterised by patients’ failure to orient and respond to stimuli in their contralateral (left) space (see Karnath, Milner, & Valler, 2003 for recent reviews), non-spatially lateralised deficits (Husain & Rorden, 2003), distortions of visuo-spatial perception (e.g., Doricchi & Angelelli, 1999; Milner & Harvey, 1995), and uncertainties in the estimation of the egocentric reference frame (e.g., Chokron & Bartolomeo, 1997; Farné, Ponti, & Lâdavas, 1998; Ferber & Karnath, 1999). A number of studies have also demonstrated that patients with visual neglect can show auditory spatial deficit in a variety of auditory tasks (e.g., Kerkhoff, Artinger, & Ziegler, 1999; Pavani, Lâdavas, & Driver, 2002; Pavani, Meneghello, & Lâdavas, 2001; Tanaka, Hachisuka, & Ogata, 1999; Vallar, Guariglia, Nico, & Bisiach, 1995; Zimmer, Lewald, & Karnath, 2003; Bisiach et al., 1984; for recent reviews, see Pavani, Lâdavas, & Driver, 2003). However, it remains possible that part of their sound-localisation deficit reflects intervening non-auditory variables, particularly when the auditory task requires planning a hand-pointing response (see Pavani, Husain, Lâdavas, & Driver, 2004 for a detailed discussion of this point).

As to the possibility that erroneous hand-pointing to sounds in brain-damaged patients may result from the impaired integration of multisensory spatial inputs (auditory, proprioceptive, and visual) across different reference frames, a large body of evidence now indicates the parietal lobe as a crucial brain area for such multisensory convergence (e.g., for recent reviews see Calvert, Spence, & Stein, 2004). In this respect, it is interesting to note that pointing to free-field sound stimuli can become less accurate following 15 min of 1 Hz repetitive focal transcranial magnetic stimulation (rTMS) of the right posterior parietal cortex, as compared with sham rTMS (Lewald, Wiemann, & Borojerdi, 2004). While this finding supports a view of the posterior parietal cortex as a neural substrate for perceptual stability in spatial-hearing (Lewald et al., 2004), it may also reveal systematic failure to integrate multisensory spatial inputs across different reference frames for accurate pointing to sounds.

The aim of the present study was to examine the contribution of non-auditory (proprioceptive and visual) spatial variables in hand-pointing to sounds of right brain-damaged patients, in relation to the presence or absence of visual neglect and parietal lobe involvement. We asked 22 patients who suffered a stroke in the right hemisphere to perform hand-pointing movements to free-field unseen sounds, while we modulated two non-auditory spatial variables: (1) the initial position of the responding hand, and (2) presence or absence of task-irrelevant ambient vision.

The first manipulation (change of initial hand-position) wanted to examine to what extent this fundamental variable of the hand-pointing movement (e.g., Desmurget, Pelisson, Rossetti, & Prablanc, 1998; Desmurget, Rossetti, Prablanc, Stelmach, & Jeannerod, 1995) could influence sound-localisation performance in the patients. Across blocks, each patient’s hand was either positioned centrally (along the body midline), or lateralised in left or right space. Since the responding hand and arm were hidden from view throughout the experiment, this manipulation only changed the proprioceptive spatial input about initial hand-position. In neurologically healthy participants, changes of initial hand-position during hand-pointing to remembered visual targets typically induce small but consistent directional shifts depending on hand-starting location (e.g., Ghiardi, Gordon, & Ghez, 1995; Vindras, Desmurget, Prablanc, & Viviani, 1998; Vindras & Viviani, 1998). However, to our knowledge, the effects of such manipulation have not been previously investigated in hand-pointing to sounds, and for the case of brain-damaged patients.

The second manipulation (presence or absence of task-irrelevant ambient vision) was devised to assess to what extent the presence of vision could favour (or hinder) sound-localisation abilities of right brain-damaged patients. Across blocks, hand-pointing to sounds was either performed with eyes-open or blindfolded, with eyes and head always free to move after stimulus presentation. In healthy participants, under these circumstances, the mere presence of ambient vision can produce more accurate hand-pointing to sounds,
presumably as a consequence of better orienting of the eyes and the head towards the auditory target (Platt & Warren, 1972; Warren, 1970). We speculated that such facilitation should only be evident when visuospatial perception is intact. In fact, in those patients showing disturbances of visuospatial perception like visual neglect, we hypothesised that any visual guidance of hand-pointing to sounds may even further deteriorate localisation performance.

2. Methods

2.1. Participants

Twenty-two patients with unilateral ischemic lesions in the right hemisphere gave their informed consent to participate in the study. Age, sex, length of illness, and clinical details for each patient are reported in Table 1. Side and site of the lesion were documented by the neuroradiologist’s lesion description, based on CT or MRI scanning. All patients were oriented in time and space, and their Mini-Mental State Examination score (Folstein, Folstein, & McHugh, 1975) was within normal limits. They presented left hemiplegia and were right-handed by self report. Patients were screened for visuospatial neglect using two standard cancellation tests (bell-cancellation test (Gauthier, Dehaut, & Joannette, 1989) and letter-cancellation test (Diller & Weinberg, 1977)). Percentages of correctly cancelled items on left and right sides in each test are also reported in Table 1, together with a lateralisation bias index calculated as the difference between percent of correctly cancelled items on the right minus percent of correctly cancelled items on the left divided by the sum of the two (index range 0 to 1). In addition to the RBD patients, a group of 11 elderly neurologically healthy participants (mean age = 62 years, schooling = 6 years, 9 females, all right-handed) was also tested in the study. All patients and healthy participants were selected for showing normal hearing or only mild hearing loss on clinical examination.

2.2. Apparatus

Participants sat in the centre of a silent room, approximately 70 cm in front of the apparatus. This comprised three loudspeakers (0.3 W, 8 Ω) mounted horizontally on a plastic net (30 cm in height, 150 cm in length) and supported vertically, at ear level, by four metal stands fixed to the table surface. This apparatus was arranged in a semicircle so that all loudspeakers were at the same distance from the participant’s head. A strip of black fabric, attached to the plastic grid, covered the loudspeakers preventing any visual cues about their exact number and position.

Table 1
Clinical details for all patients, including performance in two standard clinical tests of visuospatial neglect (bell-cancellation test and letter-cancellation test)

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Sex/age</th>
<th>Years of schooling</th>
<th>Lesion site</th>
<th>Onset (months)</th>
<th>Bell-cancellation test</th>
<th>Letter-cancellation test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F/76</td>
<td>8</td>
<td>F T P wm</td>
<td>4</td>
<td>0 47 1.00 1.00</td>
<td>0 58 1.00</td>
</tr>
<tr>
<td>2</td>
<td>F/73</td>
<td>5</td>
<td>F T</td>
<td>2</td>
<td>0 47 1.00 1.00</td>
<td>0 24 1.00</td>
</tr>
<tr>
<td>3</td>
<td>M/69</td>
<td>5</td>
<td>F T wm</td>
<td>2</td>
<td>0 59 1.00 1.00</td>
<td>6 47 0.77</td>
</tr>
<tr>
<td>4</td>
<td>F/64</td>
<td>4</td>
<td>F Tc</td>
<td>1</td>
<td>0 18 1.00 1.00</td>
<td>0 16 1.00</td>
</tr>
<tr>
<td>5</td>
<td>M/76</td>
<td>3</td>
<td>T P</td>
<td>11</td>
<td>0 59 1.00 1.00</td>
<td>19 51 0.46</td>
</tr>
<tr>
<td>6</td>
<td>M/71</td>
<td>5</td>
<td>F P</td>
<td>2</td>
<td>18 65 0.57 0.89</td>
<td>8 75 0.81</td>
</tr>
<tr>
<td>7</td>
<td>F/68</td>
<td>18</td>
<td>F T P</td>
<td>12</td>
<td>5 82 0.89 0.46</td>
<td>9 29 0.53</td>
</tr>
<tr>
<td>8</td>
<td>M/75</td>
<td>5</td>
<td>T O</td>
<td>1</td>
<td>0 17 1.00 1.00</td>
<td>0 7 1.00</td>
</tr>
<tr>
<td>9</td>
<td>M/77</td>
<td>5</td>
<td>F T P</td>
<td>2</td>
<td>0 35 1.00 1.00</td>
<td>19 64 0.54</td>
</tr>
<tr>
<td>10</td>
<td>M/81</td>
<td>5</td>
<td>Th Tc</td>
<td>1</td>
<td>12 100 0.79 0.55</td>
<td>70 98 0.17</td>
</tr>
<tr>
<td>11</td>
<td>M/55</td>
<td>5</td>
<td>P</td>
<td>4</td>
<td>29 100 0.55 0.55</td>
<td>14 76 0.69</td>
</tr>
<tr>
<td>12</td>
<td>M/57</td>
<td>5</td>
<td>T P</td>
<td>1</td>
<td>88 94 0.03 0.01</td>
<td>71 82 0.07</td>
</tr>
<tr>
<td>13</td>
<td>M/58</td>
<td>5</td>
<td>F T P</td>
<td>&gt;24</td>
<td>100 100 0.00 0.00</td>
<td>100 100 0.00</td>
</tr>
<tr>
<td>14</td>
<td>F/51</td>
<td>12</td>
<td>F T P</td>
<td>12</td>
<td>100 100 0.00 0.00</td>
<td>69 86 0.11</td>
</tr>
<tr>
<td>15</td>
<td>F/77</td>
<td>5</td>
<td>wm</td>
<td>7</td>
<td>84 94 0.06 0.01</td>
<td>82 89 0.04</td>
</tr>
<tr>
<td>16</td>
<td>M/64</td>
<td>5</td>
<td>wm</td>
<td>2</td>
<td>73 89 0.10 0.10</td>
<td>88 79 –0.05</td>
</tr>
<tr>
<td>17</td>
<td>F/67</td>
<td>6</td>
<td>T P</td>
<td>6</td>
<td>100 100 0.00 0.00</td>
<td>98 98 0.00</td>
</tr>
<tr>
<td>18</td>
<td>F/76</td>
<td>5</td>
<td>Tc Th</td>
<td>&gt;24</td>
<td>71 82 0.07 0.07</td>
<td>82 98 0.09</td>
</tr>
<tr>
<td>19</td>
<td>M/71</td>
<td>5</td>
<td>F T wm</td>
<td>1</td>
<td>59 88 0.20 0.20</td>
<td>96 96 0.00</td>
</tr>
<tr>
<td>20</td>
<td>F/64</td>
<td>10</td>
<td>F wm</td>
<td>2</td>
<td>88 94 0.03 0.03</td>
<td>94 96 0.01</td>
</tr>
<tr>
<td>21</td>
<td>M/77</td>
<td>11</td>
<td>Bg</td>
<td>3</td>
<td>100 100 0.00 0.00</td>
<td>100 100 0.00</td>
</tr>
<tr>
<td>22</td>
<td>M/68</td>
<td>5</td>
<td>Bg</td>
<td>6</td>
<td>88 94 0.03 0.03</td>
<td>100 100 0.00</td>
</tr>
</tbody>
</table>

F, frontal; T, temporal; P, parietal; O, occipital lobe; Ic, internal capsule; Th, thalamus; Bg, basal ganglia. wm indicates brain lesions that extend to the subcortical white matter. Patients 1–11 were included in the visual neglect group. Asterisk indicates patients included in the group with parietal lesion.
A graduated scale was attached at the bottom of the plastic net. This scale was used to measure hand-pointing responses (see Section 2.3) and was visible only to the experimenter, who sat in front of the participant on the other side of the apparatus. The scale ranged between −50° and +50° (with 1° steps), 0° corresponding to the centre of the apparatus, negative values indicated positions on the left side, positive values indicated positions on the right side. With respect to the scale, loudspeakers were located at −20° (left), 0° (centre), and +20° (right). Acoustic stimuli were sine-wave tones (1.2 kHz), lasting 250 ms and presented from one loudspeaker at a time, at approximately 65 dB (SPL) as measured from the participant’s head.

2.3. Procedure

Prior to the experiment, participants were informed that their task was to indicate the azimuth of single sounds originating in front of them, by pointing with the index finger of the right hand immediately after stimulus presentation. During this instruction phase, participants were shown the graduated scale used by the experimenter to record pointing responses, and were asked to aim all subsequent pointing movements towards that scale. Participants were also instructed to keep their eyes, head, and body straight at the beginning of each trial. The experimenter checked their body and head posture as well as their eye-position before starting each trial.

Each trial began with participants resting their hand on a soft ball attached on table surface, approximately 10 cm from their body. According to the experimental condition, the hand starting-position was either central (along the midsagittal plane), 20 cm to the right or 20 cm to the left. In each trial, a single acoustic stimulus was presented. Head and eye movements after sound onset were not constrained. All visual feedback related to hand starting-position or the kinematics of pointing response was prevented throughout the experiment by means of a black cloth, suspended between the participant’s shoulders and the apparatus. The experimenter controlled sound emission through the loudspeakers by means of three remote switches, and manually recorded participants’ response at the end of each trial as the intersection between the index finger and the graduated scale. Only two of the four experimenters involved in data collection were aware of the purpose of the study.

Before starting the experiment there were 10 practice trials, which were not analysed. Practice was followed by six experimental blocks, one for each combination of hand starting-position (left, centre or right) and visual condition (eyes-open or blindfold). Blocks comprised 21 trials each (seven trials for each of the three sound positions). The order of blocks was pseudo-randomised between patients. Loudspeakers swapped positions between blocks to minimise any non-spatial acoustic cues related to individual loudspeaker’s characteristics. Sound position was randomised within each block and completely unpredictable in every trial. All blocks were run in a single session, lasting approximately 1 h.

3. Results

All patients and healthy participants responded to each presented sound. Mean localisation errors for each participant were calculated as the mean signed difference in degrees between correct and indicated sound position. Negative values indicate a leftward deviation, positive values indicate a rightward deviation. Mean errors were entered into separate mixed analysis of variance (ANOVA) with three within-subject factors (stimulus position: −20°, 0° or +20°; initial hand-position: left, centre or right; and visual condition: eyes-open or blindfolded) and one between-subject factor (group). In the first ANOVA, patients were grouped as a function of presence or absence of visual neglect. In the second ANOVA, patients were grouped as a function of whether the lesion involved the parietal lobe or not. Each analysis also included a control group of 11 elderly neurologically healthy participants. Greenhouse–Geisser correction for sphericity violation was applied when necessary. p values of all post hoc comparisons were adjusted for multiple comparisons using the Benjamini and Yekutieli method (2001).

3.1. Patients grouping as a function of presence or absence of visual neglect

Patients with lateralisation index score above 0.20 in at least one of the cancellation test were assigned to the visual neglect group (N = 11, cases 1–11), while the remaining patients constituted the non-neglect group (N = 11, cases 12–22). Mean localisation errors for each experimental group are reported in Table 2.

The ANOVA revealed a significant main effect of group (F(2, 30) = 13.38, p < .0001) caused by overall larger localisation errors for RBD patients with neglect (mean = 10°, SD = 6), than RBD patients without neglect (mean = −2, SD = 4; t(20) = 3.93, adjusted- p = .003) and healthy participants (mean = −2, SD = 7; t(20) = 4.66, adjusted- p = .001). The group factor also led to significant interactions with stimulus position.

The Benjamini and Yekutieli (2001) method for adjusting p values in case of multiple testing is a modification of the original False Discovery Rate (FDR) method proposed by Benjamini and Hochberg (1995). Unlike the classic Bonferroni correction, the statistical power of FDR methods increases with the number of contrasts (Benjamini & Hochberg, 1995). In addition, it is distribution-free (Genovese & Wasserman, 2002) and applies for the case of correlated as well as uncorrelated data sets (as here).
(Fig. 1A), initial hand-position (Fig. 1B), and visual condition (Fig. 1C), as described in detail below.

The interaction between group and stimulus position \((F(4,60) = 11.64, p < .0001; \text{Fig. 1A})\) was caused by RBD patients with neglect making significantly larger localisation errors than the other two groups for sound stimuli located at \(-20^\circ\) (RBD neglect: mean = 23, \(SD = 7\); RBD without-neglect: mean = 5, \(SD = 8\), \(t(20) = 5.90\), adjusted-\(p = .001\); healthy participants: mean = -6, \(SD = 13\), \(t(20) = 6.35\), adjusted-\(p = .001\)) or \(0^\circ\) (RBD neglect: mean = 1, \(SD = 4\), \(t(20) = 4.22\), adjusted-\(p = .001\); healthy participants: mean = -3, \(SD = 6\), \(t(20) = 5.73\), adjusted-\(p = .001\)). By contrast, no significant difference between the three groups emerged for sound stimuli located at \(+20^\circ\) (RBD neglect: mean = -2, \(SD = 9\); RBD without-neglect: mean = 0, \(SD = 6\), \(t(20) = .60\), adjusted-\(p = 1\); healthy participants: mean = 3, \(SD = 15\), \(t(20) = 1.06\), adjusted-\(p = 1\)), indicating that sound-localisation deficits of neglect patients did not emerge for sound stimuli originating from the right (ipsilesional) side of auditory space. Finally, it should also be noted that localisation errors of RBD patients without neglect were never statistically different from localisation errors of healthy participants (adjusted-\(p = 1\) for all stimulus positions).

The interaction between group and initial hand position \((F(4,60) = 3.29, p < .03; \text{Fig. 1B})\) was caused by RBD patients with neglect making significantly larger localisation errors than the other two experimental groups when initial hand-position was to the right of body-midline (RBD

<table>
<thead>
<tr>
<th>Group</th>
<th>Initial hand-position</th>
<th>Eyes open</th>
<th>Blindfolded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(-20)</td>
<td>0</td>
</tr>
<tr>
<td>RBD patients with neglect ((N = 11))</td>
<td>Left hand-position</td>
<td>23 (8)</td>
<td>9 (8)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>24 (8)</td>
<td>12 (5)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>27 (9)</td>
<td>15 (5)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>25 (8)</td>
<td>12 (6)</td>
</tr>
<tr>
<td>RBD patients without neglect ((N = 11))</td>
<td>Left hand-position</td>
<td>0 (7)</td>
<td>0 (6)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>4 (7)</td>
<td>-1 (4)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>1 (9)</td>
<td>-1 (5)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>2 (7)</td>
<td>-1 (4)</td>
</tr>
<tr>
<td>Elderly healthy controls ((N = 11))</td>
<td>Left hand-position</td>
<td>-8 (16)</td>
<td>-3 (9)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>-5 (17)</td>
<td>-4 (7)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>-6 (12)</td>
<td>-5 (9)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>-6 (14)</td>
<td>-4 (8)</td>
</tr>
</tbody>
</table>

Negative values indicate a leftward deviation, positive values indicate a rightward deviation. Standard deviations are indicated in parentheses.

**Table 2**

Mean localisation error in RBD patients with visual neglect, RBD patients without neglect and elderly healthy controls, as a function of stimulus position (\(-20^\circ\), \(0^\circ\), and \(+20^\circ\)), initial hand-position (left, centre or right) and presence or absence of ambient vision ('eyes open' or 'blindfolded' condition).
Table 3
Mean localisation error in right brain-damaged patients with and without parietal lesion, as a function of stimulus position (−20°, 0°, and +20°), initial hand-position (left, centre or right) and presence or absence of ambient vision (‘eyes open’ or ‘blindfolded’ condition)

<table>
<thead>
<tr>
<th>Group</th>
<th>Initial hand-position</th>
<th>Eyes open</th>
<th>Blindfolded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial hand-position</td>
<td>−20°, 0°, +20°</td>
<td>Mean</td>
</tr>
<tr>
<td>RBD patients with parietal lesion (N = 9)</td>
<td>Left hand-position</td>
<td>13 (14) 5 (8) 3 (12) 7 (7)</td>
<td>11 (12) 2 (7) −2 (12) 3 (6)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>14 (14) 6 (8) 2 (10) 7 (7)</td>
<td>16 (13) 6 (4) −2 (7) 7 (5)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>17 (18) 7 (10) 5 (8) 10 (9)</td>
<td>22 (12) 10 (5) 1 (5) 11 (5)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>15 (15) 6 (8) 3 (9) 8 (7)</td>
<td>17 (11) 6 (4) −1 (7) 7 (4)</td>
</tr>
<tr>
<td>RBD patients without parietal lesion (N = 13)</td>
<td>Left hand-position</td>
<td>11 (14) 4 (9) −2 (12) 4 (10)</td>
<td>10 (10) 4 (9) −3 (13) 4 (9)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>14 (12) 5 (8) −4 (8) 5 (8)</td>
<td>13 (11) 6 (7) −4 (8) 5 (7)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>12 (15) 7 (9) 0 (6) 7 (8)</td>
<td>15 (11) 7 (7) −3 (5) 6 (7)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>13 (13) 5 (8) −2 (8) 5 (8)</td>
<td>13 (10) 6 (7) −3 (8) 5 (7)</td>
</tr>
<tr>
<td>Elderly healthy controls (N = 11)</td>
<td>Left hand-position</td>
<td>−8 (16) −3 (9) 6 (16) −2 (6)</td>
<td>−7 (15) 1 (6) 3 (12) −1 (6)</td>
</tr>
<tr>
<td></td>
<td>Central hand-position</td>
<td>−5 (17) −4 (7) 4 (13) −2 (6)</td>
<td>−5 (12) −5 (8) 2 (19) −2 (9)</td>
</tr>
<tr>
<td></td>
<td>Right hand-position</td>
<td>−6 (12) −5 (9) 2 (17) −3 (9)</td>
<td>−5 (14) −2 (7) 4 (23) −1 (11)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>−6 (14) −4 (8) 4 (14) −2 (6)</td>
<td>−5 (14) −2 (7) 3 (17) −2 (8)</td>
</tr>
</tbody>
</table>

Negative values indicate a leftward deviation, positive values indicate a rightward deviation. Standard deviations are indicated in parentheses.
RBD without parietal lesion: mean = 6, SD = 7, t(22) = 3.30, adjusted-p = .02). By contrast, no statistical difference between patients and healthy controls emerged for sound stimuli at +20° (healthy participants: mean = 3, SD = 15; RBD with parietal lesion: mean = 1, SD = 8, t(18) = 0.45, adjusted-p = 1; RBD without parietal lesion: mean = −3, SD = 8, t(22) = 1.29, adjusted-p = 1).

The ANOVA also revealed a main effect of stimulus position (F(2, 60) = 4.34, p < .04), subsidiary to the two-way interaction described above, and a main effect of initial hand-position (F(2, 60) = 4.52, p < .03) caused by larger sound-localisation errors when the hand was located to the right of body-midline (mean = 5, SD = 9), than central (mean = 3, SD = 8, t(32) = 2.14, p < .040) or to the left (mean = 3, SD = 8, t(32) = 2.07, p < .05). However, note that no other interaction involving the group factor emerged (all Fs < 1.6).

4. Discussion

Recent years have witnessed a renewed interest for the study of auditory spatial abilities in brain-damaged patients, particularly in RBD patients suffering from visual neglect (e.g., Kerkhoff et al., 1999; Pavani et al., 2001; Pavani, Ladavas, et al., 2002; Tanaka et al., 1999; Vallar et al., 1995; Zimmer et al., 2003). There is now consensus that visual neglect associates with severe general disturbances in auditory space perception (for reviews, see Pavani, Ladavas, et al., 2003; Pavani et al., 2004), both in the acute (Zimmer et al., 2003) and chronic phase (e.g., Pavani et al., 2001; Pavani, Ladavas, et al., 2002). Auditory deficits in visual neglect patients emerge as increased uncertainty about sound location rather than a systematic shift in the internal representation of acoustic space (Pavani, Ladavas, et al., 2002; Zimmer et al., 2003), and correlate with the severity of the visual symptoms, possibly as a consequence of damage to common circuits for processing visual and auditory space in the superior temporal cortex and inferior parietal lobe (Pavani, Macaluso, Warren, Driver, & Griffiths, 2002; Pavani et al., 2004; Zimmer et al., 2003).

The results of the present study extend these previous findings by showing that poor sound-localisation performance of RBD patients with neglect can also reflect a combination of impaired spatial-hearing and spatial biases from other sensory modalities when the task involves a hand-pointing motor response. Proprioceptive spatial inputs related to initial hand-position, as well as the presence or absence of task-irrelevant ambient vision clearly modulate neglect patients’ performance, exacerbating or reducing their hand-pointing errors.

4.1. Effects of initial-hand position

In RBD patients with visual neglect, hand-pointing to sounds was biased by the spatial information about initial hand-position (conveyed here only through proprioception, as vision of the hand and the arm was prevented throughout the experiment). Sound-localisation errors were exacerbated when initial hand-position was to the right of body-midline, and reduced with leftwards initial hand-position (see also Ladavas & Pavani, 1998 for similar evidence in a single case report).

Previous neuropsychological work that examined the effects of initial hand-position in right brain-damaged patients has mainly focused on detection/identification performance for contralesional visual targets in patients with visual neglect (e.g., Halligan, Manning, & Marshall, 1991; Ladavas, Berti, Ruozzi, & Barboni, 1997; Mattingley, Robertson, & Driver, 1998; Robertson & North, 1992, 1993; see Robertson & Hawkins, 1999 for reviews). These studies demonstrate that visual neglect symptoms of right brain-damaged patients can be ameliorated by active (Halligan et al., 1991; Ladavas et al., 1997; Mattingley et al., 1998; Robertson & North, 1992, 1993) or passive (Frassinetti, Rossi, & Ladavas, 2001) movements of the contralesional (left) limb in left space. By contrast, no modulation of left visual neglect has typically been found with lateralised movements of the ipsilesional (right) limb.

The influence of initial hand-position on sound localisation observed in the present study may thus relate to modulation of neglect symptoms as a function of initial hand-position, observed here for the novel case of auditory than visual stimuli, and in the context of stimulus localisation instead of detection or identification. However, it should be noted that all modulations of sound-localisation performance as a function of initial hand-position were observed here for movements of the ipsilesional (right) limb, instead of movements of the contralesional limb as typically reported in the literature mentioned above (e.g., Halligan et al., 1991; Ladavas et al., 1997; Mattingley et al., 1998; Robertson & North, 1992, 1993).

An alternative explanation of the observed initial hand-position effect is that lateralised hand-positions induced spatial biases in motor planning that influenced pointing responses to sounds. Psychophysical experiments that examined hand-pointing to remembered visual targets in neurologically healthy participants have revealed that initial position of the responding hand plays a fundamental role in planning hand movements (e.g., Ghilardi et al., 1995; Vindras et al., 1998; Vindras & Viviani, 1998; though see Bizzi, Hogan, Mussa-Ivaldi, & Giszter, 1992; for a critical review see Desmurget et al., 1998). In these studies, changes of initial hand-position resulted in end-point errors that were systematically biased towards the lateralised initial position of the
responding hand (Ghilardi et al., 1995; Vindras et al., 1998; Vindras & Viviani, 1998). The effect of initial hand-position observed in the present study may thus represent the pathological exacerbation of these spatial bias in motor planning, described here for the first time for the case of hand-pointing to sounds.

Although the present study does not allow a definite conclusion as to why such pathological exacerbation should have emerged, two possibilities can be envisaged. First, the modulation of neglect patients’ performance as a function of initial hand-position could have reflected the undue prominence of spatial proprioceptive inputs, in the context of pathological uncertainty about sound location. This hypothesis predicts a correlation between initial hand-position effects and the severity of auditory spatial deficit of neglect patients, as measured in purely auditory tasks (i.e., tasks involving neither motor response or comparisons with the subjective straight ahead reference; see Pavani et al., 2001; Zimmer et al., 2003). Second, as anticipated in Section 1, initial hand-position effects could have resulted from a failure to integrate multisensory spatial inputs across the different reference frames. While our findings do not suggest a specific role of the parietal lobe in modulating sound-localisation errors in our hand-pointing task, more detailed anatomical investigations in brain-damaged patients or experimental protocols taking advantage of rTMS induced dysfunctions (e.g., Lewald et al., 2004) may contribute to clarify this issue.

### 4.2. Effect of presence or absence of task-irrelevant ambient vision

In addition to the bias related to initial hand-position, hand-pointing to sounds in RBD patients with neglect was influenced by the presence or absence of ambient vision. Despite the fact that vision was always irrelevant for the auditory task (the loudspeakers were occluded throughout, as was the responding hand), visual neglect patients’ made larger sound-localisation errors with eyes open than blindfolded.

As anticipated in Section 1, the presence or absence of ambient vision is known to affect hand-pointing to sounds in normal subjects, even in the absence of any task-relevant visual information. More accurate localisation responses are typically observed with eyes open than with a blindfold or in total darkness (Platt & Warren, 1972; Warren, 1970), even when the sound-sources themselves cannot be seen. This phenomenon (termed ‘visual facilitation’) has been attributed to better eye-hand coordination in presence of vision (Platt & Warren, 1972; see also Cohen & Andersen, 2002 for a possible neural explanation of this phenomenon). In the present study, a trend similar to normal ‘visual facilitation’ (i.e., more accurate pointing with eyes open, even though neither the sound-sources nor the responding hand were visible) was observed for RBD patients without neglect (note that this contrast yielded a significant $p$ value of .03 uncorrected for multiple comparisons). By contrast, patients with visual neglect were clearly more impaired (i.e., showed a greater tendency to point erroneously in a direction that was ipsilesional to the actual sound-source) when pointing to sounds with eyes open, versus when blindfolded.

This suggests that whilst RBD patients showing no signs of visual neglect may benefit from the presence of ambient vision in auditory pointing tasks, patients with marked visual neglect show an opposite pattern, such that they are particularly hindered by the presence of vision. One explanation of this is that, due to visual coding of sound position, any ipsilesional visual bias may extend to sound localisation, producing rightward shifts of sound-localisation responses (see also Pavani, Ládavas, et al., 2003). In visual neglect patients the mere presence of environmental visual information has indeed been shown to increase the exploration bias toward the ipsilesional side when performing tactile exploration tasks (e.g., Chedru, 1976; Gentilini, Barbieri, De Renzi, & Faglioni, 1989; Hjaltason, Caneman, & Tegner, 1993; Hjaltason & Tegner, 1992) or when localising spoken syllables (Soroker, Calamaro, Glicksohn, & Myslobodsky, 1997).

Our findings could also contribute to explain a controversial aspect in the literature about sounds localisation in right brain-damaged patients, namely the existence of rightward directional errors. Directional errors during sound localisation have been occasionally documented (e.g., Altman, Balonov, & Deglin, 1979; Bisiach et al., 1981). Although the results of the present study clearly show rightward systematic errors in neglect patients, such directional errors during hand-pointing to sounds may actually reflect non-auditory biases, rather than any directional misperception of sound positions (see also Pavani, Ládavas, et al., 2002). Specifically, we suggest that directional errors in hand-pointing to sounds in the present (and possibly in other studies of hand-pointing to sounds in right brain-damaged patients) may be at least partly attributed to visual biases resulting from visuo-spatial neglect, as well as the repeated use of the dominant (right) hand.

### 5. Conclusions

Taken together, the results of the present study indicate a role for proprioceptive and visual spatial inputs during hand-pointing to sounds, particularly in RBD patients with visual neglect. Although hand-pointing to sounds has often been considered a straightforward
approach to investigate sound-localisation abilities in brain-damaged patients, our findings suggest that any observed localisation deficit in this task may actually reflect a combination of impaired spatial-hearing and spatial biases from other sensory modalities (i.e., proprioception and vision), at least for patients suffering from visual neglect.

Acknowledgments

We are grateful to all the patients that participated in the study. This work is dedicated to the memory of Mr. Daniele Maurizzi, who provided the technical help for this study. We also thank Ms. Ivana Policardi and Ms. Anna di Santantonio for help in collecting the data. We are grateful to three anonymous reviewers for their helpful comments on a previous version of the manuscript. F.P. was supported by a Marie-Curie Fellowship of the European Community programme (HPMF-CT-2000-00586). E.L. and A.F. are supported by a MIUR (Italy) grant.

References


Pinek, B., & Brouchon, M. (1992). Head turning versus manual point-


