Acoustical Vision of Neglected Stimuli: Interaction among Spatially Converging Audiovisual Inputs in Neglect Patients

Francesca Frassinetti¹,², Francesco Pavani¹,³, and Elisabetta Ladavas¹

Abstract

Cross-modal spatial integration between auditory and visual stimuli is a common phenomenon in space perception. The principles underlying such integration have been outlined by neurophysiological and behavioral studies in animals (Stein & Meredith, 1993), but little evidence exists proving that similar principles occur also in humans.

In the present study, we explored such possibility in patients with visual neglect, namely, patients with visuospatial impairment. To test this hypothesis, neglect patients were required to detect brief flash of light presented in one of six spatial positions, either in a unimodal condition (i.e., only visual stimuli were presented) or in a cross-modal condition (i.e., a sound was presented simultaneously to the visual target, either at the same spatial position or at one of the remaining five possible positions).

The results showed an improvement of visual detection when visual and auditory stimuli were originating from the same position in space or at close spatial disparity (16°). In contrast, no improvement was found when the spatial separation of visual and auditory stimuli was larger than 16°. Moreover, the improvement was larger for visual positions that were more affected by the spatial impairment, i.e., the most peripheral positions in the left visual field (LVF).

In conclusion, the results of the present study considerably extend our knowledge about the multisensory integration, by showing in humans the existence of an integrated visuo-auditory system with functional properties similar to those found in animals.

INTRODUCTION

The integration of multiple sensory inputs is present in all animals as well as in humans. Presumably, whenever different sensory information converge onto individual neurons in the central nervous system, there is the potential for cross-modal (or multisensory) integration. There are many sites in the brain where such convergence takes place. One of the densest concentrations of multisensory neurons is found in the deep layers of the superior colliculus (King & Palmer, 1985; Meredith & Stein, 1983, 1986a; Gordon, 1973; Stein & Arigbede, 1972; Stein, Magalhaes-Castro, & Kruger, 1976; Stein, 1984). The superior colliculus receives visual, auditory, and somatosensory inputs (Stein, 1984) and plays an important role in attending and orienting to these sensory stimuli (Sparks, 1990). Each sensory representation in the superior colliculus is organized in map-like fashion, with different maps overlapping and aligned with one another (receptive field alignment). Together, these aligned maps generate a comprehensive multisensory map. As a result, stimuli of any modality (i.e., visual, auditory, or somatosensory) that originate from the same event excite neurons in the same region of the superior colliculus. The principles underlying this integration have been outlined by single-unit studies in cats and guinea pigs (King & Palmer, 1985; Meredith & Stein, 1983, 1986a, 1986b; Meredith, Nemitz, & Stein, 1987; for a review, see Stein & Meredith, 1993) and have largely been investigated with regard to the interaction between visual and auditory stimuli.

A first principle related to the characteristics of this multisensory integrated system concerns the spatial proximity of multisensory stimuli (the so-called spatial rule). According to this principle, visual and auditory stimuli originating from the same position in space will fall within the excitatory receptive fields of a visual-auditory multisensory neuron. The physiological result of this pairing is an enhancement in the bimodal neuron’s response. The angular distance that can separate visual and auditory stimuli and still result in a facilitatory effect depends on the size of the visual and auditory receptive fields. Auditory receptive fields are larger than visual receptive fields (Jay & Sparks, 1987; Middlebrooks & Knudsen, 1984; King & Palmer, 1983; King & Hutchings, 1987; Knudsen, 1982) and, as a consequence, the auditory stimulus will excite neurons over a large region, including the region excited by the visual stimulus. In contrast, when a sound appears in a spatial position

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outside the excitatory receptive field of the bimodal neuron, the neural response to the visual stimulus is no longer enhanced. In addition, when the acoustic stimulus falls within an inhibitory region of the auditory receptive field, it will depress neuron’s responses to the visual stimulus.

A second crucial aspect of multisensory integration concerns the relative timing of the two sensory events (the so-called temporal rule). Maximal multisensory interactions are achieved when periods of peak activity of unimodal discharge train overlap. This situation is usually achieved when stimuli are presented simultaneously, although a temporal window for multisensory interactions might overcome small temporal discrepancies between stimuli.

A further principle of multisensory integration concerns the nature of the multimodal response. Response to stimuli combination is much more than simply the sum of the responses to the individual stimuli; instead, the response enhancement is superadditive. For example, even when visual and auditory individual stimuli evoke no response, their combination becomes effective and produces a surprisingly vigorous response (Meredith & Stein, 1986a). This third principle, known as inverse effectiveness, provides an explanation for a greater enhancement when two weak, rather than two potent, stimuli are combined.

Although multisensory integration has been extensively investigated in the colliculus, the rules that govern the integration of multisensory information in this subcortical structure apply to other brain regions as well. These areas include the superior temporal polysensory area and the hippocampus of primates, and the anterior ectosylvian sulcus, the lateral suprasylvian cortex, and the visual cortex in cats (Stein & Meredith, 1993; Stein, Meredith, & Wallace, 1993; Wallace, Meredith, & Stein, 1992; Clemo, Meredith, Wallace, & Stein, 1991).

A very close parallel between the physiology of individual neurons in the superior colliculus and attentive and orienting responses has been documented in behavioral experiments conducted with cats (Stein, Hayeucut, & Meredith, 1988; Stein, Meredith, Huneycutt, & McDade, 1989). Animals were trained to fixate a central LED and then orient toward and approach a visual stimulus (i.e., a flash of light) presented at seven different spatial positions. During testing, brief low-intensity noise bursts could accompany the visual stimulus, originating either from the same spatial position (spatial coincidence) or from a different position (spatial disparity). The ability to detect and orient to the visual stimulus was substantially improved when the auditory stimulus was presented simultaneously and in spatial coincidence with the visual stimulus, and was significantly degraded when the auditory cue was presented simultaneously but in spatial disparity with the visual stimulus.

There have been recent attempts to demonstrate that similar principles of multisensory integration can also occur in humans. Stein, London, Wilkinson, and Price (1996) tested a group of normal subjects in a visual luminance judgement task. Subjects were required to fixate directly ahead and to rate the intensity of each visual stimulus immediately after it was presented. The task was performed either in a unimodal condition (i.e., only visual stimuli were presented) or in cross-modal conditions (i.e., a sound was presented simultaneously to the visual target either at the same spatial position or at one of the remaining spatial positions). An auditory stimulus was found to significantly enhance the perceived intensity of the visual stimulus, although the effect was not spatially selective (i.e., it was evident regardless of the position of the auditory cue). Interestingly, the enhancement of perceived light intensity was mostly pronounced when visual stimuli were of low intensity, as predicted by the inverse effectiveness rule. The absence of spatial correspondence effect in Stein et al.’s study might be due to the fact that bimodal neurons are not involved in functions for which stimulus localization in space is not essential. The perceptual task of assessing stimulus intensity is likely to be one of these. Spatial visual–auditory correspondence effect has been described in human literature by Hughes, Nelson, and Aronchick (1998) in a study where stimulus location in space was the main feature of the task. When normal subjects were required to localize stimuli by directing saccades to visual targets presented in different spatial locations, saccades to bimodal (auditory and visual) targets were faster than any of the saccades to either type of unimodal targets. Moreover, there was a tendency for auditory stimuli presented in the same position or at close disparity from the visual target to produce shortest latency saccades.

In the neuropsychological domain, there is no evidence demonstrating that similar principles of multisensory visuoauditory integration occur also in humans. Such lack of studies is surprising because this integrated system can offer an unique opportunity to improve the performance of patients with visual neglect, namely, patients with spatial representational deficit. The integration of visual and auditory information can potentially enable patients to detect “bimodal” stimuli for which unimodal components are below behavioral threshold. Patients with neglect fail to report, respond, or orient to visual stimuli presented contralaterally to the lesioned hemisphere (for a review, see Robertson & Marshall, 1993). In addition to the visual spatial deficit, they show an impairment of auditory space perception (Pavani, Meneghelli, & Ladavas, in press), as revealed by their inability to discriminate the relative spatial positions of sound presented in the contralesional space. In contrast, their performance is comparable to that of normals when the acoustic stimuli are presented in the ipsilesional space. Sound localization deficit has also

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been documented by Deouell, Bentin, and Soroker (2000). They found that the typical event-related brain potentials, elicited in response to a change in sound spatial position, was reduced in neglect patients when the sound was presented in the left hemispace. This can be interpreted as the consequence of the inability of these patients to perceive in the contralesional space a change in sound position due to the auditory location deficit.

Therefore, the aim of the present study is to verify whether bimodal presentation of auditory and visual stimuli can improve visual stimulus detection in patients with visual neglect. Moreover, consistent with the expectation based on the electrophysiological studies, the magnitude of facilitation should vary with the degree of spatial correspondence between the acoustic and the visual stimulus. This aim was tested by asking patients to fixate to a central stimulus and to detect visual stimuli horizontally displayed at 8°, 24°, and 40°, in the left visual field (LVF) as well as in the right visual field (RVF). The task was performed either in a unimodal condition (i.e., only visual stimuli were presented) or in cross-modal conditions (i.e., a sound was presented simultaneous to the visual target). In the cross-modal conditions, sounds could be presented either at the same spatial position as the visual target or at one of the remaining five spatial positions (see Figure 1).

The existence of a multisensory integrated system coding both visual and auditory stimuli can be demonstrated by showing an improvement of visual stimulus detection in the cross-modal conditions as compared to the unimodal condition. Moreover, according to the characteristics of this integrated system, we should expect two different outcomes. The spatial rule, described above, predicts an improvement of visual detection when visual and auditory stimuli originate from the same position in space or at close disparity (e.g., 16°). In contrast, no improvement should be expected for larger spatial separation between the two different sensory stimuli (e.g., 30°). Moreover, according to the inverse effectiveness rule, the improvement should be bigger for the visual positions that are more affected by the spatial impairment, that is, the most peripheral positions in the LVF, because the activity of bimodal neurons is greater when two weak, rather than two potent, stimuli are combined.

RESULTS

In the present study, patients almost never produced false alarms: They did not erroneously report the presence of the acoustic stimulus when they were instructed to report only the visual stimulus, that is, catch trials. Patients who erroneously responded to acoustic stimuli for more than 20% of trials were excluded from the investigation.

To test the hypothesis that an acoustic stimulus enhances visual stimulus detection, it is necessary to compare the number of visual detections made in unimodal condition to those made in cross-modal condition. An increment of contralesional detections in cross-modal trials, compared to unimodal trials, indicates the existence of an integrated auditory–visual system. Percentages of correct detections made by patients are shown in Figures 2–4.

Percentages of visual stimulus detection were analyzed separately for each LED position (V1, V2, V3, V4, V5, and V6), using six separate one-way ANOVAs carried out on mean percentage of correct responses, converted in arcsine values. Each ANOVA was carried out with condition as main factor: One unimodal visual condition (e.g., V1) and six cross-modal conditions, in which the acoustic stimulus was presented either in the same visual position (e.g., V1–A1) or in one of other five alternative positions (e.g., V1–A2, V1–A3, V1–A4, V1–A5, V1–A6). Whenever necessary, pairwise comparisons were conducted using the Duncan test. The level of significance was always set at \( p < .05 \). The results will be separately presented for each visual stimulus position.

V1

The ANOVA revealed a significant effect of condition, \( F(6,36) = 2.5, p < .04 \). Visual detection accuracy (31%) increased by presenting an acoustic stimulus in the same spatial position (A1 = 66%, \( p < .02 \)) or in the near relative right spatial position (A2 = 62%, \( p < .03 \)). In contrast, no beneficial effect was observed when the spatial disparity of the two stimuli was larger than 16°.
The ANOVA showed a significant effect of condition, $F(6,36) = 2.3, p < .05$. Visual detection accuracy (54%) increased by presenting an acoustic stimulus in the same spatial position ($A2 = 76\%, \text{ } p < .02$) or in the near relative left ($A1 = 73\%, \text{ } p < .02$) or right ($A3 = 77\%, \text{ } p < .01$) spatial position. In contrast, no significant improvement was found when the spatial disparity of the visual and auditory stimulus was larger than $16^\circ$ ($A4 = 61\%, \text{ } A5 = 65\%, \text{ } \text{and } A6 = 62\%$) (see Figure 3).

**V3**

The ANOVA showed also for this spatial position a significant effect of sound position, $F(6,36) = 3.07, p < .02$, but, at variance with V1 and V2, the effect did not follow the spatial rule described in the Introduction. Visual detection accuracy (63%) improved by presenting the acoustic stimulus in the same spatial position ($A3 = 90\%, \text{ } p < .005$), at a spatial disparity of $16^\circ$ ($A2 = 88\%, \text{ } p < .006; \text{ } A4 = 89\%, \text{ } p < .006$) but also at a spatial disparity larger than $16^\circ$ ($A1 = 90\%, \text{ } p < .003; \text{ } A5 = 86\%, \text{ } p < .006; \text{ } A6 = 77\%, \text{ } p < .04$) (see Figure 4).

**RVF**

For visual stimuli presented in the RVF (V4, V5, and V6), the ANOVA did not show a significant difference between unimodal and cross-modal conditions. However, it should be noted that patients’ performance in responding to RVF stimulation was close to normal ($V4 = 95\%, \text{ } V5 = 91\%, \text{ } V6 = 91\%$).

**DISCUSSION**

The present study shows that a cue from one modality (audition) substantially modified stimulus detection in a
separate modality (vision). In neglect patients, a sound presented at the same position (or at close disparity) as a visual stimulus influenced detection of previously neglected visual targets.

Before going on to understand the implications of this finding in the context of a cross-modal interaction between vision and audition, we need to explore the possibility that the improvement in responses to stimuli combination might reflect a generalized arousal phenomenon. The presence of two stimuli, instead of one, might have produced greater activity throughout the brain by increasing neural sensitivity to any and all stimuli. Recently, Robertson, Mattingley, Rorden, and Driver (1998) have suggested that nonspatial phasic alerting events (e.g., warning tones) can overcome neglect patients’ spatial biases in perceptual awareness. In that study, neglect patients with right hemisphere damage were asked to judge whether a visual event on the left preceded or followed a comparable event on the right. In this task, patients were aware of left events half a second later than right events. Such spatial imbalance in the time course of visual awareness was corrected when a warning sound alerted the patients phasically. However, at variance with our results, the beneficial effect of sound on visual perception was not spatially based. The acceleration of perceptual events on the contralesional side was found both when the warning sound was presented on the left or the right side of space.

Although such a principle might have played the same role in our study, it is important to note that it cannot explain alone the pattern of results. This is because, by varying the positions of different sensory stimuli and evaluating their effects on visual detection, we found that the improvement was evident only when stimuli followed a rather clear-cut spatial rule. Indeed, acoustic stimuli produced a greater increase of visual responses when the two stimuli were spatially coincident, or when they were located near one another in space, at a distance of 16\(^\circ\). In contrast, when the spatial disparity between the two sensory stimuli was larger than 16\(^\circ\), patients’ visual performance remained unvaried.

 Crucially, this pattern of results was particularly evident for the most peripheral stimuli in the LVF (i.e., V1 and V2), where neglect was more severe. For position V1, an improvement of visual detection was found when the visual stimulus and the auditory target were spatially coincident (i.e., A1) or immediately adjacent (16\(^\circ\), i.e., A2). In contrast, at bigger distances, no improvement was found on visual detection by combining two sensory modalities. The same pattern of results emerged when the visual stimulus was presented in position V2, where neglect was still severe. Again, an improvement was found when the visual and the auditory stimuli were spatially coincident or immediately adjacent (16\(^\circ\), i.e., A1, A3). Similar to position V1, the combination between two sensory modalities for distances larger than 16\(^\circ\) did not reveal a visual detection improvement.

Therefore, we can conclude that the amelioration of visual detection observed in the present study cannot be explained as a result of a generalized arousal phenomenon. Instead, it is in keeping with the functional properties of multisensory neurons described in animals’ studies (Stein & Meredith, 1993). A first functional property of bimodal neurons is that their response is enhanced only when both auditory and visual stimuli are located within their respective excitatory receptive fields, and is reduced if either stimulus falls into an inhibitory surround or outside the receptive field. The angular distance that can separate visual and auditory stimuli and still result in a facilitatory effect depends on the size of their visual and auditory receptive fields. Auditory receptive fields are larger than visual receptive fields. In the barn owl, a nocturnal predator that relies heavily on sound localization to capture prey, auditory receptive fields average approximately 30\(^\circ\) in azimuth and 50\(^\circ\) in elevation compared with visual receptive fields, which average only about 12\(^\circ\) in diameter (Knudsen, 1982). Because the auditory receptive fields are relatively large, the auditory stimulus will excite neurons over a large region, including the region excited by the visual stimulus. This explains why, in the present study, the influence of the auditory stimulus extends itself to visual stimuli located not only in the same position but also in the near position, at a disparity of 16\(^\circ\).

A further characteristic of bimodal neurons is that auditory receptive fields are rarely symmetric, and instead their temporal borders extend to the peripheral space more than the medial borders (Stein & Meredith, 1993). As a consequence, an auditory stimulus enhances the responses to a visual stimulus more extensively when it is temporal than medial to it. Thus, a temporal auditory stimulus is likely to enhance the physiological effects on a visual stimulus at a distance of 32\(^\circ\), because it falls into the excitatory region of the auditory receptive field. In contrast, an auditory stimulus even slightly medial to 32\(^\circ\) should encroach in the inhibitory medial border and inhibit the physiological effects of a visual stimulus. Partially, this is what occurred when the visual stimulus was presented at V3. An improvement of visual detection was found when the visual stimulus was presented in combination with an auditory stimulus coincident with it or 16\(^\circ\) and 32\(^\circ\) disparate to it in the periphery (i.e., in A2 and A1, respectively). This outcome is entirely compatible with the characteristics of the bimodal neurons. In contrast, these characteristics do not predict the facilitatory effect found when the acoustic stimulus is presented at A5, namely, at 32\(^\circ\) in the medial portion of the auditory space. However, it is worth mentioning that in this position neglect was not so severe, with the exception of two patients (P.E. and E.T.) who were severely impaired.1 When a single visual stimulus was presented at V3, three out of seven patients performed nearly normal (88% of correct
responses), without a difference in accuracy between the two visual fields.

The absence of a specific spatial effect at V3 may be consistent with the inverse effectiveness rule, which predicts a greater enhancement when two weak, rather than two potent, different sensory stimuli are combined. In animal work (Meredith & Stein, 1986a), the enhancement of correct responses with combined stimuli was observed when single-modality stimuli evoked a poor performance. Visually responsive multisensory neurons show proportionately greater response enhancement with subthreshold (not reported) stimuli. As stated by Stein and Meredith (1993, p. 151), “when the visual cue was sufficiently intense to produce 70–80% correct responses alone, the addition of the auditory cue often produced no further increment, thereby giving the impression that multisensory enhancement will not be evident with cues that are already highly effective.” In contrast, the superadditive feature of this type of interaction reached its extreme when unimodal stimuli were rarely or never responded.

In the present study when visual stimuli were presented in the most peripheral positions of the LVF, where the impairment was more severe, multisensory enhancement was greater and the pattern of responses followed the characteristic spatial rule of multisensory integration. Instead, when the visual stimuli were presented in the less peripheral position, where the impairment was less severe, multisensory enhancement was reduced and the responses were not spatially specific.

In conclusion, the present results show that the spatially specific combination of auditory and visual stimuli produce an improvement in visual detection accuracy. This beneficial effect is observable only when two multisensory stimuli are presented. By contrast, the occurrence of two unimodal visual stimuli, although presented in the same spatial position, does not produce an amelioration of visual detection (Ladavas, Carletti, & Gori, 1994). In this study, where a left exogenous noninformative visual cue was presented immediately before the visual target, an amelioration of performance in LVF target detection was not found. These results document the importance of multisensory integrated systems in the construction of the spatial representation and in the recovery of related disorders, like visual neglect. Moreover, they considerably extend our knowledge about the multisensory integration, by showing the existence of an integrated visuoauditory system in humans. Although this is the first neuropsychological evidence of a specific auditory–visual system in humans, other neuropsychological findings converge in showing that human and nonhuman primate brains share similar multisensory systems devoted to the integrated coding of spatial information, e.g., a visuotactile system (Ladavas, di Pellegrino, Farnè, & Zeloni, 1998; Ladavas, Zeloni, & Farnè, 1998) and an auditory–tactile system (Ladavas, Pavan, & Farnè, 2001).

**METHODS**

**Subjects**

Seven patients with right brain damage and left visual neglect were recruited from the San Camillo Hospital in Venice (Italy) and the Fraticini Hospital in Florence (Italy) and gave their informed consent to participate in the study. All patients had unilateral lesion due to cerebrovascular accident (CVA). Lesion sites were confirmed by CT scanning and are reported in Table 1 together with details concerning sex, age, and length of illness of each patient. The presence of visual field defects was evaluated with clinical examination in all patients; only patients without visual field defects were included.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age/Sex</th>
<th>Time From CVA (Months)</th>
<th>Lesion Site</th>
<th>Line Cancellation (Omissions, %)</th>
<th>Bell’s Test (Omissions, %)</th>
<th>Line Bisection (Means Percentages Displacement, %)</th>
<th>Drawing From a Model (Presence of Neglect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.D.</td>
<td>70/male</td>
<td>10 FTP</td>
<td></td>
<td>Left 16 Right 0</td>
<td>Left 47 Right 24</td>
<td>Left 32 Right –</td>
<td>–</td>
</tr>
<tr>
<td>V.E.</td>
<td>80/male</td>
<td>1 F</td>
<td></td>
<td>Left 0 Right 0</td>
<td>Left 59 Right 7</td>
<td>Left 45 Right +</td>
<td>+</td>
</tr>
<tr>
<td>P.E.</td>
<td>71/male</td>
<td>168 FT</td>
<td></td>
<td>Left 0 Right 0</td>
<td>Left 53 Right 0</td>
<td>Left – Right +</td>
<td>+</td>
</tr>
<tr>
<td>E.T.</td>
<td>77/female</td>
<td>1 TP, BG, IC, Th</td>
<td></td>
<td>Left 40 Right 0</td>
<td>Left 100 Right 53</td>
<td>Left 39 Right +</td>
<td>+</td>
</tr>
<tr>
<td>M.S.</td>
<td>74/female</td>
<td>3 FTP</td>
<td></td>
<td>Left 0 Right 0</td>
<td>Left 47 Right 0</td>
<td>Left 11 Right +</td>
<td>+</td>
</tr>
<tr>
<td>R.E.</td>
<td>77/female</td>
<td>1 FTP</td>
<td></td>
<td>Left 5 Right 0</td>
<td>Left 100 Right 18</td>
<td>Left 32 Right +</td>
<td>+</td>
</tr>
<tr>
<td>P.C.</td>
<td>77/female</td>
<td>1 F</td>
<td></td>
<td>Left 100 Right 34</td>
<td>Left 100 Right 88</td>
<td>Left 11 Right +</td>
<td>+</td>
</tr>
</tbody>
</table>

F = frontal; T = temporal; P = parietal; BG = basal ganglia; IC = internal capsule; Th = thalamus. Percentages of errors (line cancellation and Bell’s test), percentage of rightward displacement (line bisection), and presence of neglect (drawing from a model).

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**Table 1. Summary of Clinical Data for the Patients**

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selected for the present study. Hearing was normal in all patients; moreover, patients always detected acoustic stimuli regardless of their spatial position, thus showing no clinical sign of auditory neglect. All patients were fully oriented in time and place and were right-handed.

The assessment of visuospatial neglect was based on patients’ performance in a series of clinical tests including: crossing out lines of many different orientation (Albert, 1973), crossing out bells in a display of drawings of several objects (Gauthier, Dehaut, & Joannette, 1989), bisecting three horizontal lines (40 cm length), and drawing a flower from a model. The patients’ performance in each test is presented in Table 1.

**Apparatus**

The apparatus consisted of six piezoelectric loudspeakers (0.4 W, 8 Ω), arranged horizontally at subject’s ear level. Loudspeakers were mounted on a vertical plastic net (height 30 cm, length 150 cm) supported by four wooden stands fixed to the table surface and arranged in semicircle. Each loudspeaker was located at an eccentricity of 8°, 24°, and 40° to either side of the fixation point. A strip of black fabric attached to the plastic grid covered the loudspeakers, preventing any visual cues about their position. Six LEDs were visible, poking out from the black fabric. Each LED was placed directly in front of each of the six loudspeakers. Note that we refer to the auditory positions by labels A1 to A6 when moving from left to right, and similarly we described the corresponding lateral visual target positions by labels V1 to V6 (see Figure 1).

Acoustic stimuli presented through loudspeakers were pure tones (1500 Hz, 70 dB), lasting for 150 msec. Visual stimuli presented by means of LEDs (luminance 80 Cd m⁻²) was a single flash (150 msec). Timing of stimuli and responses were controlled by an ACER 711TE laptop computer, using a custom program (XGen Experimental Software, http://www.psychology.nottingham.ac.uk/staff/cr1/) and a custom hardware interface.

**Procedure**

Patients sat in a dimly lit room, approximately 70 cm in front of the apparatus, with their body midline aligned with the center of the apparatus. They were instructed to keep their head straight and to fixate on a small yellow triangle (1°) pasted in the center of the apparatus throughout the entire experiment. Fixation was checked visually by one experimenter who stood behind the apparatus, facing the patient. The experimenter started each trial only when the correct head posture and eye position were achieved.

In each trial, three different combinations of visual and acoustic stimuli could be presented: (1) a single visual stimulus presented alone (unimodal visual condition), (2) a single auditory stimulus presented alone (unimodal auditory condition, i.e., catch trials), and (3) a visual stimulus and an auditory stimulus presented simultaneously (cross-modal condition). In cross-modal conditions, for each visual position the auditory stimulus could be presented either in the same position as the visual target or in one of the remaining five positions.

In each experimental condition, there were eight trials for each type of stimulation. Trials were given in a different pseudorandom order within each experimental condition. The total number of trials was equally distributed in four experimental blocks run in two sessions. Each session lasted approximately 1 hr and was run on consecutive days.

Patients were instructed to detect the presence of visual stimuli (light) and ignore auditory stimuli.

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**Note**

1. P.E. and E.T., who were more impaired in the contrale- sional field, showed improvement when the two stimuli were spatially coincident. This improvement, although reduced, was evidence also when the spatial disparity between visual and auditory stimuli was larger than 16°. The pattern of performance found in V5 needs to be investigated more deeply, because this position was located near the fovea. Indeed, it is possible that visual stimuli presented near the fovea are processed more accurately by unimodal visual neurons than stimuli presented in more eccentric retinal positions. If this is the case, then bimodal neurons are probably less activated by stimuli presented near the fovea and, as a consequence, their effect is less evident.

**REFERENCES**


