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Audiovisual integration in low vision individuals

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ABSTRACT

Behavioral and neurophysiological studies have shown an enhancement of visual perception in crossmodal audiovisual stimulation conditions, both for sensitivity and reaction times, when the stimulation in the two sensory modalities occurs in condition of space and time congruency. The purpose of the present work is to verify whether congruent visual and acoustic stimulations can improve the detection of visual stimuli in people affected by low vision. Participants were asked to detect the presence of a visual stimulus (yes/no task) either presented in isolation (i.e., unimodal visual stimulation) or simultaneously with auditory stimuli, which could be placed in the same spatial position (i.e., crossmodal congruent conditions) or in different spatial positions (i.e., crossmodal incongruent conditions). The results show for the first time audiovisual integration effects in low vision individuals. In particular, it has been observed a significant visual detection benefit in the crossmodal congruent as compared to the unimodal visual condition. This effect is selective for visual stimulation that occurs in the portion of visual field that is impaired, and disappears in the region of space in which vision is spared. Surprisingly, there is a marginal crossmodal benefit when the sound is presented at 16 degrees far from the visual stimulus. The observed crossmodal effect seems to be determined by the contribution of both senses to a model of optimal combination, in which the most reliable provides the highest contribution. These results, indicating a significant beneficial effect of synchronous and spatially congruent sounds in a visual detection task, seem very promising for the development of a rehabilitation approach of low vision diseases based on the principles of multisensory integration.

1. Introduction

The environment we continuously interact with provides a large amount of sensory information, which is processed by our different senses. These inputs are bound together by our brain, and used to construct a unified representation of the external world through the process commonly known as 'multisensory integration' (e.g., Alais, Newell, & Mamassian, 2010). The principles governing multisensory integration and crossmodal interactions have been investigated by a considerable body of empirical research (see Calvert, Spence, & Stein, 2004, for a review).

In animals, neural recordings at the single unit level of Superior Colliculus (SC) have highlighted several peculiarities governing the multisensory integration (see Stein & Meredith, 1993 for an extensive coverage of this topic). The so-called 'spatial rule of multisensory integration' postulates that the neural response enhancement produced by multisensory stimuli is dependent on the spatial alignment and/or overlap of the excitatory receptive fields of their individual sensory components (e.g., Stein, 1998; Stein & Meredith, 1993; Wallace, Meredith, & Stein, 1992). Studies from humans indicate that these effects occur over spatial separations of 30–40° and are not limited to stimulus presentations within the same hemispace. Integrative effects have been reported in audiovisual (Bolognini, Frassinetti, Serino, & Làdavas, 2005; Frassinetti, Bolognini, & Làdavas, 2002; Frassinetti, Pavani, & Làdavas, 2002; Frassinetti, Bolognini, Bottari, Bonora, & Làdavas, 2005; Hairston, Laurienti, Mishra, Burdette, & Wallace, 2003; Harrington and Peck, 1998; Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994; Teder-Sälejärvi, Di Russo, McDonald, & Hillyard, 2005) and visuotactile (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002) detection tasks, as well as in the case of audiotactile localization judgments (Caclin, Soto-Faraco, Kingstone, & Spence, 2002). In fact, facilitatory multisensory interactions (i.e., neuronal response enhancement) can be observed even when the stimuli are spatially misaligned in their external positions, provided that the relevant neurons contain sufficiently large receptive fields (RFs), such that each stimulated position falls within their excitatory zones (Wallace & Stein, 2007).

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A second principle driving multisensory integration concerns the relative timing of the two sensory events. For example, the multisensory enhancement typically happens when the stimuli are presented simultaneously or fall within the 'temporal window' of integration (Meredith, Nemitz, & Stein, 1987; Spence & Squire, 2003). Another feature of multisensory integration is that the percentage of gain (e.g., the enhancement in the visual stimulus detection in this study) is proportionally greater when unimodal stimuli are less effective (i.e., principle of inverse effectiveness; Rowland & Stein, 2008; Stein, London, Wilkinson, & Price, 1996; though see Holmes, 2007, 2009 for critique). Electrophysiological studies on humans (Senkowksi, Saint-Amour, Höfle, & Foxe, 2011) and non-humans primates (Cappe, Murray, Barone, & Roullier, 2010) demonstrate that the RT facilitation in the redundant target effect exceeds predictions on the basis of probability summations of unisensory stimuli (i.e., RT facilitation explained by integrative process; Miller, 1982). Similarly, Noesselt et al. (2010) have shown that the simultaneous presentation of auditory sounds enhances the behavioral visual detection for lower-intensity visual stimuli but not for higher-intensity visual stimuli. These psychophysical results provide some pieces of evidence consistent with the inverse effectiveness principles.

A number of audiovisual behavioral studies have reported crossmodal enhancement effects in relation to stimulus intensity (Andersen & Mamassian, 2008; Frassinetti et al., 2002a, 2002b, 2005; Hairston et al., 2003; Marks, Szczesiul, & Ohlott, 1986). In particular, a series of behavioral studies pointed out facilitatory effect of auditory stimuli in visual detection tasks performed by either neurologically intact people with normal vision (with masked subthreshold visual stimuli; Frassinetti et al., 2002a; with induced myopia; Hairston et al., 2003) or brain-damaged patients with visual deficit (Frassinetti et al., 2005). Frassinetti et al. (2005), for instance, showed that in patients affected by hemianopia or neglect, the audiovisual interaction could improve visual perception in the damaged/neglected visual hemifield (i.e., where visual stimuli presented in isolation were less effective), consistently with the principle of inverse effectiveness (e.g., Stein & Meredith, 1993). Moreover, the visual detection enhancement emerged only when auditory and visual stimuli originated from the same spatial position supporting the spatial rule of multisensory integration (e.g., Stein & Meredith, 1993).

In accordance with previous evidence (e.g., Andersen & Mamassian, 2008; Dufour, Després, & Pebayle, 2002; Frassinetti et al., 2002a, 2002b, 2005; Hairston et al., 2003; Marks et al., 1986), the present study aims to investigate the possibility of using auditory information to induce a visual detection improvement in patients with deteriorated visual functions not caused by brain injuries, such as patients suffering from low vision. Low vision is a condition of permanent reduction of visual field and visual acuity, not correctable by glasses, due to several eye diseases, varying in severity and nature (World Health Organization, 2009). In age-related macular degeneration (De Jong, 2006; Varma, Fraser-Bell, Tan, Klein, & Azen, 2004) there is a reduction of central visual acuity, in the diabetic retinopathy the visual field can be endanger both at the center and at the periphery due to a degeneration of retinal blood vessels (Frank, 1995). In others low vision diseases, such as glaucoma (Salmon, 1999) and retinitis pigmentosa (Bird, 1995), the alteration of the retina leads to blindness, initially reducing the visual acuity of the peripheral portion of the visual field and then affecting the central one. Previous research on low vision has focused on unisensory mechanisms of visual perception and, more precisely, on reading performance (Cheong, Legge, Lawrence, Cheung, & Ruff, 2008), fixation stability (Falkenberg, Rubin, & Bex, 2007), color (Naïli, Despretz, & Boucart, 2006), eye movements (Crossland & Rubin, 2006) and visual search (Liu, Kuyk, & Fuhr, 2007).

To the best of our knowledge, the present study is the first attempt to investigate possible multisensory interactions in low vision. It was designed to investigate whether co-occurring sounds, not carrying any information about the presence of the visual target (note that sounds could also be presented alone), could improve visual target detection in low vision individuals. In particular, the hypothesis is that the presentation of simultaneous and colocalized task irrelevant sounds should produce a benefit for detecting visual stimuli presented in those spatial positions where visual acuity is highly compromised (according to the principle of inverse effectiveness). By contrast, participants' performance should not improve for those spatial positions where visual acuity is spared.

2. Materials and methods

2.1. Participants

Thirty-one low vision participants (14 female; mean age of 55 years; range from 19 to 82 years; two left handed and two with no hand preference; see Table 1 for details) took part in the study. Participants were mostly members of the "Unione dei Ciechi e degli Ipovedenti" (Italian Association for Blindness and Low Vision) of Trento. The experiment was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki (most recently amended in 2008, Seoul), as well as the ethical guidelines laid down by the University of Trento. All participants gave their informed consent prior to their inclusion in the study and were naïve as to the purpose of the experiment.

2.2. Apparatus and stimuli

The setup was a semi-circular plastic structure (130 cm length) covering around 112 degree of visual angle and positioned at 70 cm from the participants. Eight LEDs (light emitting diodes) and eight speakers were mounted on this support, resulting in a symmetric arrays of 8 overlying acoustic and visual positions at 8, 24, 40 and 56 degrees of visual angle in either hemifields (see Fig. 1). All the semi-circular structure was covered with an acoustic permeable black curtain so that only the 8 LEDs were visible. A laptop pc (Dell Precision M6300) and a Matlab script (The MathWorks, Inc.) have been used to deliver the stimuli and collect participant's response. A keyboard was positioned in front of the participants to allow them to provide the responses.

Auditory stimuli consisted of the presentation of a 100 ms white noise burst (80 dB as measured from the participants' head position). Sounds were played using the integrated sound card of the laptop computer connected to an external loudspeaker to amplify the signal. The signal was then switched between 8 relays (N4100F-2) by using the digital outputs of an Interface Board Module (Velleman Extender USB VM140) to activate the desired speaker. Speakers were round-shaped (5 cm diameter of Mylar; Pro Signal ABS-210-RC range 350–20,000 Hz, 8 Ω, 1 W RMS Power). A between-trials balanced random amplitude modulation of the generated signal was introduced (values of 85, 90, 95 or 100% of the whole signal amplitude) to compensate for the minor speakers' difference in propagating the acoustic stimuli. Visual stimuli consisted of the presentation of a 100 ms (i.e., same duration as the auditory stimuli) green visual targets (LED, Avago Technologies model HM65-Y30DD). The luminance of each LED associated to each speaker has been calibrated to 80 cd/m^2 set in a dark environment. LEDs were oval-shaped with a diameter of 5 mm (0.4 degrees of visual angle) and a viewing angle of 100° (i.e., the angle from which the 80 cd/m^2 luminance was maintained constant), so that the visual stimulus has a constant luminance despite its position on the setup (i.e., minor difference in the direction towards the participant's position). The onset of the visual and auditory stimuli was synchronized using a digital oscilloscope (Agilent Technologies MSO 6054A).

2.3. Procedure and experimental design

Participants sat at 70 cm in front of the semi-circular structure in a dimming room (average luminance 40 cd/m^2). The chosen ratio between LED (80 cd/m^2) and room luminance calibration was thought to reduce any possible flash light reflection. Participants were asked to keep their head and their eyes as steady as possible by looking straight ahead to the central position of the apparatus. The experimenter sat in front of the participant (behind the apparatus) to check whether head and eyes were always in the requested (constant) position. Each trial started automatically after the participant response. It is worthy of note that crossmodal trials were always synchronous thus reducing the possibility that the sound acted as a cue for any possible eye movement that could affect visual detection performance.

Participants were requested to detect the presence – not the spatial position – of the visual stimuli and ignore the sound. The participants were not informed about the number and spatial locations of the speakers. For each trial, participants were presented with five different conditions: Visual stimulus alone (i.e., unimodal visual condition, UV), acoustic stimulus alone (i.e., unimodal acoustic condition, UA or catch trials), simultaneous presentation of a visual and auditory stimulus (i.e., crossmodal condition). Note that there were two different types of

Table 1
Participants' age and information about their clinical pathologies.

Patient	Age	Visus	Visual pathology	Duration (in years)
1	30	1/10	Stargardt disease	20
2	65	1/10	Macular distrophy	15
3	25	1/20	Acute maculopathy	20
4	64	1/20	Corneal opacity (Left eye OFF)	54
5	66	1/20	Maculopaty, acute glaucoma (Left eye OFF)	11
6	51	1/10	Glaucoma, keratoconus	18
7	70	1/10	Acute degenerative maculopathy	34
8	66	1/10	Maculopathy	23
9	55	1/10	Macular distrophy	25
10	56	1/10	Restricted maculopathy, optical neuritis	7
11	52	1/20	Bilateral congenital glaucoma	47
12	69	1/20	Retinal degeneration, angioid streaks	16
13	73	1/10	Exudative maculopathy	5
14	57	1/20	Stargardt disease, *inverted retinitis* pigmentosa	37
15	72	1/20	Myopic choroiditis, incipient cataract	22
16	72	1/10	Retinal scar, strabismus, cataract	64
17	73	1/10	Albinism, acute myopia	5
18	24	1/10	Nistagmus, degenerative retinopathy	24
19	72	1/20	Chorioretinopaty, angioid streaks	42
20	60	1/10	Maculopathy	33
21	68	1/20	Myophic choroiditis	24
22	68	1/10	Diabetic retinopathy	20
23	25	1/20	Optic chiasm aneurysm	3
24	59	1/10	Maculopathy	6
25	54	1/20	Corneal opacity	24
26	39	1/10	Maculopathy	29
27	61	1/10	Myophic maculopathy	19

crossmodal condition: trials in which the visual and the auditory stimuli were presented from the same spatial position (i.e., crossmodal congruent condition, CC) and trials in which the two different modalities were presented from different spatial positions (i.e., crossmodal incongruent condition, CI). Audiovisual position disparities in CI trials were either of 16 (i.e., CI16) or 32 (i.e., CI32) degrees.

The participants were instructed to use both the hands to press two buttons on a keyboard placed in front of them ('F' key for 'Yes, I saw the light' and 'J' key for 'No, I did not see the light'). 'F' and 'J' keys were pressed using, respectively, the left and the right index fingers. Response mapping was not counterbalanced between participants. The whole experimental section was divided in 8 blocks. Each block consisted of 72 trials (i.e., 8 UV trials, one for each visual position; 24 UA trials/catch trials, 3 for each of the 8 acoustic positions; and 8 CC trials, visual and acoustic stimuli presented synchronously from each of the 8 positions). Finally, there were 32 CI trials (4 for each visual position) in which acoustic stimuli were presented to the left or to the right of the visual stimulus at either 16 or 32 degrees (see also Section 2.4). The proportion of conditions in the experimental design has been chosen for different reasons: to respect the same design used by Frassinetti et al. (2005) and to shortening as much as possible the duration of the experimental section because of the very high patients' mean age. Each participant was presented with 576 trials in total. To verify that the procedure was clear, before the actual experimental section, the participants were asked to undergo a brief test with the same experimental conditions (i.e., 10–20 trials randomly chosen from the sequence of a block). The

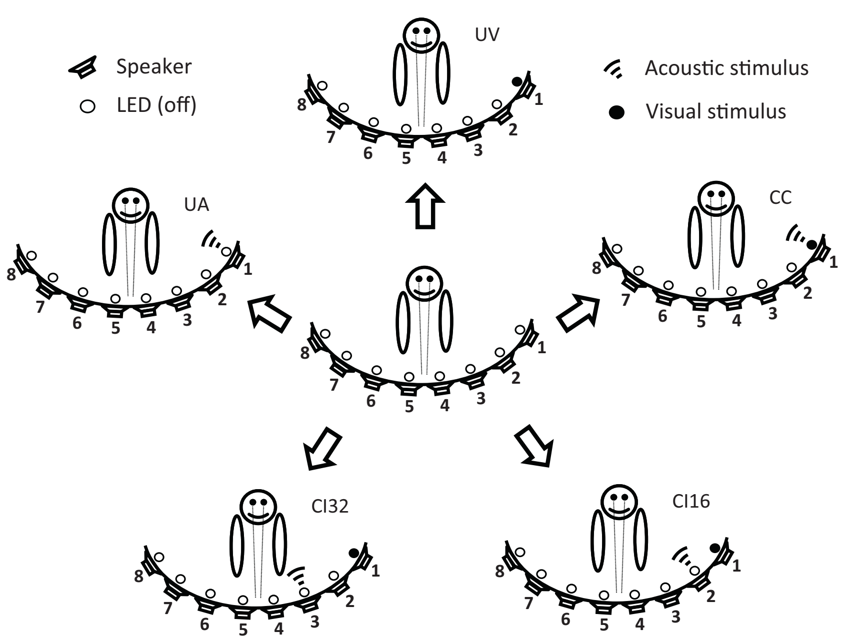

Fig. 1. Schematic representation of the experimental apparatus. The viewing distance is 70 cm. Each speaker is placed symmetrically at an eccentricity of 8, 24, 40 and 56 degrees from the center, in either hemifields. In the central panel, the initial trial is represented with LEDs and loudspeakers turned off. In the surrounding panels, the five conditions are represented in a clockwise orientation starting from the top: unimodal visual (UV), crossmodal congruent (CC), crossmodal incongruent with 16 degrees of audiovisual disparity (CI16), crossmodal incongruent with 32 degrees of audiovisual disparity (CI32), and unimodal acoustic (UA; i.e., catch trial).

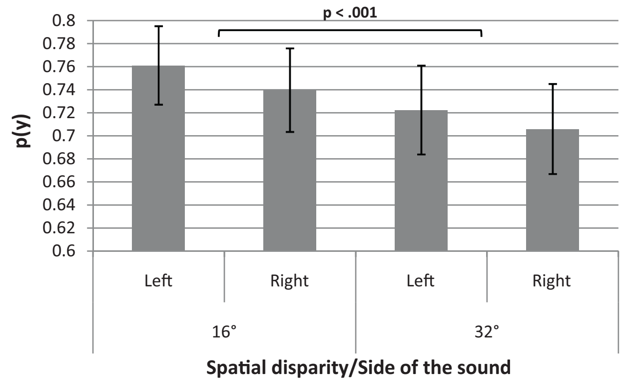

Fig. 2. Mean proportion of 'yes' responses, for each sounds-LED spatial disparity (i.e., 16 and 32 degrees) and side of presentation (i.e., sounds presented to the left or to the right of the LED). Performance for the two sound disparities (averaged for left and right side) differs significantly ($p < .001$).

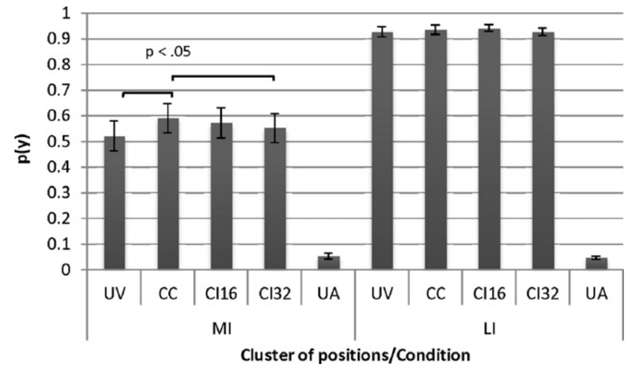

Fig. 3. Mean proportion of 'yes' responses, reported for each cluster of positions (i.e., most impaired four positions, MI; less impaired four positions, LI), and each experimental condition (i.e., unimodal visual, UV; crossmodal congruent, CC; crossmodal incongruent at 16 and 32 degrees of disparity, respectively CI16 and CI32; unimodal acoustic, UA). Performance comparisons UV vs. CC and CC vs. CI32 differ significantly ($p < .05$). Difference between UV and CI16 is marginally significant ($p = .06$). Proportions of UA (catch trials) in the two clusters of positions (i.e., MI vs. LI) did not differ significantly.

whole experimental section lasted around 90 min with a rest between each of the 8 blocks.

2.4. Data analysis

Participants' performance was analyzed by computing the proportion of 'yes' responses.

In relation to the 8 spatial positions, 50 values have been obtained namely: 8 values for the UA condition (catch trials), 8 values for the UV condition, 8 values for the CC condition, and 26 different values for each CI condition corresponding to left and right performance at 16° or 32° of disparity. Indeed, CI values were 26 instead of 32 because of the 'lack' of some positions. For example, for the visual spatial position at −56° on the left visual hemifield, there were no sounds on the left neither at 16° (i.e., at −72°) nor at 32° (i.e., at −88°). In this case, conditions on the right at 16° (i.e., at −40°) and 32° (i.e., at −24°) were presented two times. Next, CI positions were clustered and averaged according to the side (i.e., right or left) and the distance of the sound from the reference visual position (i.e., 16° and 32°), giving rise to four CI values for each participant (i.e., CI16L, CI32L, CI16R and CI32R). Finally, proportion values for UA, UV, CC, CI16 and CI32 (the last two were calculated by averaging the values for left and right sides) related to each of the eight spatial positions have been ordered starting from the lowest to the highest as measured by the performance in the UV condition (i.e., ascending order).

After ordering the data in such described way, the first position (i.e., the one in which the proportion of 'yes' responses in the UV condition was the lower, that is, the most impaired visual position) could have been either in the periphery or in the center, depending on the participant's visual deficit (see Table 2 for details). Four participants have been discarded from the subsequent analysis because they had a very high UV performance in the first spatial position (i.e., in the most impaired spatial position the UV performance was above 95% of 'yes' responses).

3. Results

A first analysis was conducted to assess whether there was a difference between side of the sound (left or right) and disparity (16° or 32°) with respect to the visual stimulus positions in the CI conditions. Greenhouse–Geisser correction was applied to the within participants analysis of variance (ANOVA) with factors disparity and side of the sound. The results show a significant difference between spatial disparity 16° (proportion of 'yes' responses, $p(y) = .75$) and 32° ($p(y) = .71$), $F(1, 26) = 28.2$, $p < .001$, indicating that the integration enhancement effect decreases as a function of the increasing distance between the sound and the visual stimuli (see Fig. 2). This result is in line with the spatial rule of multisensory integration (e.g., Stein & Meredith, 1993). Neither the effect of side of the sound (left side: $p(y) = .74$ vs. right side: $p(y) = .72$), $F(1, 26) = 1.12$, $p = .30$, nor the interaction between side of the sound and spatial disparity, $F(1, 26) = .09$, $p = .76$, were significant.

Given that there was no difference between incongruent conditions as a function of the side of the sound (i.e., on the left or on the right of the visual stimulus), mean proportion of 'yes' responses were collapsed for the left and right incongruent positions (i.e., for each spatial position, CI16L with CI16R and CI32L with CI32R were averaged) to obtain only two different CI values for each participant in relation to the spatial disparity (i.e., CI16 and CI32). Then, proportion of 'yes' responses corresponding to the four most impaired positions (i.e., MI positions, namely the first four ordered positions) and the proportion of 'yes' responses for the less impaired/spared four positions (i.e., LI positions, namely the ordered positions from the fifth to the eighth) were clustered for each participant and condition (see Table 2 for an example with the UV performance). A within participants ANOVA with the factors cluster of positions (i.e., MI vs. LI) and condition (i.e., UV, CC, CI16 and CI32) revealed a significant general effect of condition, $F(3, 78) = 4.5$, $p = .006$, a significant effect of cluster of positions $F(1, 26) = 48.6$, $p < .001$, and a significant interaction between condition and cluster of positions, $F(3, 78) = 3.2$, $p = .03$. As expected, results show a difference between the stimulation conditions, while the emerged interaction show that this differences may be present only in one of the two clusters of positions (i.e., MI vs. LI, see Fig. 3). In fact, the post hoc comparisons pointed out a significant difference in the MI cluster of positions between UV and CC ($p(y) = .52$ vs. $p(y) = .59$, $p = .03$) indicating that the CC condition provided a significant performance improvement with respect the UV condition.

As expected, a sound in the same spatial position of the visual stimulus provides a significant improvement in the visual detection task, but, this improvement is no longer present when the sound is at 32° from the visual stimulus (UV, $p(y) = .52$ vs. CI32, $p(y) = .55$, $p = .46$).

Surprisingly, a sound at 16° from the visual stimulus also provided a marginally significant enhancement in the visual detection task performance as compared to the unimodal visual condition (UV, $p(y) = .52$ vs. CI16, $p(y) = .57$, $p = .06$). Furthermore, the performance was significantly better in the congruent position than in the one with a audiovisual disparity of 32° (CC, $p(y) = .59$ vs. CI32, $p(y) = .55$, $p = .015$). Finally, performance at 16° was not different from the one observed in the congruent position (CC, $p(y) = .59$ vs. CI16, $p(y) = .57$, $p = .32$), indicating that for low vision patients there could be visual acoustic integration also with such relatively wide disparity. No difference between conditions has been found in the LI cluster of positions (for all comparisons $p = 1$; UV, $p(y) = .93$, CC, $p(y) = .93$, CI16, $p(y) = .94$ and CI32, $p(y) = .93$). Taken together, these results support the principle of inverse effectiveness, given that the multisensory enhancement has been found in the MI cluster of positions (i.e., where visual stimuli are less reliable) and not for the LI cluster of positions (i.e., where stimuli were highly effective; see,

Table 2
For each participant, the spatial positions have been ordered as a function of the performance in the unimodal visual (UV) condition. MI indicates the cluster of the most impaired four positions; LI the cluster of the less impaired four positions.

Patient	Unimodal visual performance $p(y)$ and spatial position							
	Most Impaired positions (MI)				Less Impaired positions (LI)			
1	.01 (5)	.01 (6)	.13 (7)	.38 (4)	.88 (1)	.99 (2)	.99 (3)	.99 (8)
2	.38 (5)	.63 (4)	.88 (8)	.99 (1)	.99 (2)	.99 (3)	.99 (6)	.99 (7)
3	.01 (3)	.13 (4)	.13 (5)	.25 (6)	.38 (8)	.63 (1)	.75 (2)	.99 (7)
4	.01 (1)	.25 (2)	.75 (8)	.88 (5)	.99 (3)	.99 (4)	.99 (6)	.99 (7)
5	.50 (3)	.63 (4)	.88 (1)	.88 (5)	.88 (8)	.99 (2)	.99 (6)	.99 (7)
6	.01 (1)	.01 (2)	.13 (3)	.99 (4)	.99 (5)	.99 (6)	.99 (7)	.99 (8)
7	.75 (5)	.88 (2)	.88 (3)	.99 (1)	.99 (4)	.99 (6)	.99 (7)	.99 (8)
8	.75 (5)	.99 (1)	.99 (2)	.99 (3)	.99 (4)	.99 (6)	.99 (7)	.99 (8)
9	.25 (8)	.88 (7)	.99 (1)	.99 (2)	.99 (3)	.99 (4)	.99 (5)	.99 (6)
10	.88 (1)	.88 (3)	.88 (6)	.88 (7)	.88 (8)	.99 (2)	.99 (4)	.99 (5)
11	.25 (1)	.63 (6)	.63 (7)	.75 (8)	.99 (2)	.99 (3)	.99 (4)	.99 (5)
12	.01 (5)	.13 (3)	.13 (4)	.13 (6)	.25 (7)	.88 (1)	.88 (2)	.99 (8)
13	.88 (3)	.88 (5)	.99 (1)	.99 (2)	.99 (4)	.99 (6)	.99 (7)	.99 (8)
14	.63 (4)	.63 (8)	.75 (2)	.88 (1)	.88 (5)	.99 (3)	.99 (6)	.99 (7)
15	.01 (5)	.13 (3)	.25 (4)	.38 (6)	.88 (1)	.88 (2)	.99 (7)	.99 (8)
16	.38 (1)	.38 (5)	.63 (3)	.63 (4)	.63 (8)	.75 (6)	.75 (7)	.88 (2)
17	.88 (2)	.88 (5)	.99 (1)	.99 (3)	.99 (4)	.99 (6)	.99 (7)	.99 (8)
18	.50 (4)	.99 (1)	.99 (2)	.99 (3)	.99 (5)	.99 (6)	.99 (7)	.99 (8)
19	.25 (4)	.25 (5)	.25 (6)	.50 (3)	.88 (7)	.99 (1)	.99 (2)	.99 (8)
20	.13 (4)	.99 (1)	.99 (2)	.99 (3)	.99 (5)	.99 (6)	.99 (7)	.99 (8)
21	.01 (1)	.01 (5)	.13 (4)	.13 (6)	.88 (2)	.88 (7)	.99 (3)	.99 (8)
22	.25 (1)	.25 (6)	.25 (8)	.38 (7)	.50 (5)	.63 (2)	.75 (3)	.75 (4)
23	.01 (6)	.01 (7)	.01 (8)	.50 (5)	.75 (1)	.75 (3)	.99 (2)	.99 (4)
24	.50 (5)	.75 (1)	.75 (3)	.88 (6)	.99 (2)	.99 (4)	.99 (7)	.99 (8)
25	.01 (7)	.01 (8)	.13 (6)	.50 (4)	.50 (5)	.75 (2)	.88 (3)	.99 (1)
26	.01 (5)	.25 (4)	.38 (6)	.99 (1)	.99 (2)	.99 (3)	.99 (7)	.99 (8)
27	.13 (1)	.25 (5)	.88 (6)	.88 (8)	.99 (2)	.99 (3)	.99 (4)	.99 (7)

e.g., Frassinetti et al., 2002a, 2002b, 2005; Hairston et al., 2003; Noesselt et al., 2010, for similar results).

Finally, responses to catch trials were analyzed to examine whether participants were less able to ignore the sounds presented alone in the MI than in LI cluster of positions. A pairwise comparison t-test did not reveal any significant difference (MI, $p(y) = .053$ and LI, $p(y) = .047$, $t(26) = .86$, $p = .39$).

4. Discussion

The present study represents the first attempt to investigate the mechanism of multisensory integration in low vision. In particular, it provides evidence of an audiovisual integration effects in low vision individuals. The aim of this study was twofold. On one hand, it purported to verify whether there is an enhancing effect of a spatially congruent sound in a visual detection task in people suffering from low vision diseases. On the other hand, it was aimed to test how this possible effect varies as a function of the visual impairment. In fact, according with the principle of inverse effectiveness (Stein & Meredith, 1993; Stein et al., 1996), it might be hypothesized that a beneficial effect of one modality (i.e., auditory) on another modality (i.e., visual) should be greater when the second is weakly effective to induce a behavioral response (see Bolognini et al., 2005).

Our results show that a synchronous sound presented from the same spatial position significantly enhances the performance of low vision individuals in a yes/no visual detection task as compared to the condition where the visual stimulus was presented in isolation. Moreover, a significant acoustic crossmodal effect is observed for the most impaired visual positions (i.e., MI cluster), but not for those in which the visual sensory signal is still reliable (i.e., LI cluster). That is, a significant enhancement is observed in the spatial positions in which the unimodal visual performance is mostly deteriorated. This result is in line with previous behavioral studies highlighting the role of the visual stimulus reliability in visual acoustic crossmodal tasks (Frassinetti et al., 2002a, 2002b, 2005; Hairston et al., 2003; see Noesselt et al., 2010, for both behavioral and neuroimaging evidence).

The visual detection performance in the crossmodal congruent condition and at 16 degrees of disparity does not differ significantly, while when the sound was presented at 32 degrees of disparity performance does not significantly differ from that in the unimodal visual condition. Therefore, the absence of any difference between unimodal visual condition and audiovisual pairs separated by 32 degrees of disparity shows that the enhancement effect cannot be attributed to a general unspecific alerting effect induced by the mere presence of auditory stimuli on bimodal trials (e.g., Posner, 1978). To our surprise, the results show a marginally significant performance enhancement as compared to the unimodal visual condition also in case of a sound disparity of 16 degrees, regardless of whether the visual stimulus was central or peripheral. This pattern is, however, partially consistent with the performance observed by Frassinetti et al. (2002b, 2005) in neglect patients without hemianopia, who showed an enhancement of visual detection when the sound was at 16 degrees in the peripheral visual field. The authors argued that this effect could be due to the presence of an attentional deficit that may enlarge the size of the area where the crossmodal integration occurs. However, Frassinetti et al. (2002a) found an analogous effect also in neurologically intact people with normal vision, in which attentional deficit can be likely excluded. These authors have explained this spatial disparate enhancement effect by referring to electrophysiological evidence, showing that auditory receptive fields in multimodal neurons are larger than visual receptive fields (Middlebrooks & Knudsen, 1984).

A second possible explanation for the enhancement effect of the sound at 16 degrees may refer to the inverse ventriloquism effect, in which the sound leads the fusion process by providing a most reliable spatial cue. For instance, Alais and Burr (2004) asked participants to localize the spatial position of a visual stimulus or a sound (i.e., left/right judgment) presented either in unimodal or crossmodal fashion. The authors found that when the visual stimulus is well discriminable, an acoustic stimulus has no influence on the performance. By contrast, the more the visual stimulus is blurred, the more participants' judgment is biased towards the source position of the sound. This interesting result suggests that the spatial ventriloquism effect seems to be determined by the contribution of both modalities, in a simple model of optimal combination, in which the most reliable sensory signal will provide the highest contribution (e.g., Ernst & Banks, 2002). Thus, the marginally significant effect of the sound found also at 16 degrees in the present study may be the result of a lack in the reliability of the visual information that constitute, together with the sound, an unique crossmodal event. As a consequence, multisensory enhancement may be observed not only when the low reliable visual stimulus and the sound's spatial position coincide, but also when the disparity between the two stimuli is around 16 degrees.

Wallace et al. (2004) found that the audiovisual interaction effects were modulated by the participant's perception (judgment) of the unity of the event. In that study, localization bias (i.e., sound localization towards the visual stimulus) and reports of perceptual unity occurred even with substantial spatial (i.e., 15 degrees) and temporal (i.e., 800 ms) disparities. Similarly, one could suggest that the multisensory enhancement in the CC and CI16 emerged in the present study because low vision participants perceived acoustic and visual stimuli as being originated from the same event. By contrast, the sound at 32 degrees of disparity does not provide a significant enhancement, supporting the existence of a spatial boundary in which visual acoustic fusion effect breaks off (cf. Wallace et al., 2004). Although these values seem large in comparison with some previous reports of crossmodal biases (e.g., Lewald & Guski, 2003; Lewald, Ehrenstein, & Guski, 2001), other studies have nevertheless reported substantial localization biases with similarly large disparities (e.g., Bermant & Welch, 1976; Bertelson & Radeau, 1981). Irrespectively of the causal explanation for the effect of the disparate sound on visual detection highlighted in the present study, the enhancement seems to be consistent throughout the visual field. In fact, the MI cluster of positions is constituted by positions either in the peripheral or in the central visual field in relation to the patients' pathology. Thus, it is unlikely that it has been determined just by the effect of those particular positions in the periphery (like found by Frassinetti et al., 2002a in healthy participants), where acoustic RFs have temporal borders which extend to the peripheral space more than the nasal borders (i.e., RFs are elongated towards the periphery; Middlebrooks & Knudsen, 1984; Stein, Meredith, Huneycutt, & Mc Dade, 1989).

Future research on low vision can be aimed to better define the spatial boundaries of the audiovisual enhancement effects here found. Moreover, the issue of the temporal disparity between acoustic and visual stimuli could also deserve further investigations. In the present study, audiovisual stimuli were always presented simultaneously. However, it has been demonstrated that sensory integration can take place also between stimuli that are not temporally coincident, but which fall within the 'temporal window' of integration (Meredith et al., 1987; Spence & Squire, 2003). Therefore, it might be interesting to investigate whether the behavioral enhancement effect found for spatial disparities in the present experiment might result for temporal disparities as well.

The results of the present study might provide useful insight for future audiovisual training rehabilitation programs to provide a visual amelioration also for low vision impairments. Passamonti, Bertini, & Làdavas (2009) found that an audiovisual training could produce long lasting visual improvements in hemianopic patients. By allowing eye movements, Passamonti and colleagues asked participants to gaze towards the spatial positions from which the sound was delivered and were informed that visual stimulus would be presented later in the same positions. In this way, sounds were used as cues to inform the participants to gaze in the right spatial position thus improving visual detection. The learned visual strategy was then generalized also to the unimodal visual condition providing an improvement also for visual stimuli in isolation. Furthermore, this advantage was also transferred to other visual skills such as visual search, reading, and even to daily life activities. Until now, the majority of low vision rehabilitation has focused only on the visual modality (Markowitz, 2006; Liu et al., 2007; Nilsson, Frennesson, & Nilsson, 2003). The multisensory effect emerged in this study provides new insights on multisensory integration mechanisms in patients with visual deficit and seems to have good chances to provide a further step forward for low vision rehabilitation.

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