Perception, 2012, volume 41, pages 175 – 192

doi:10.1068/p7153

The role of vision in auditory distance perception

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Received 18 October 2011, in revised form 28 January 2012; published online 27 March 2012

Abstract. In humans, multisensory interaction is an important strategy for improving the detection of stimuli of different nature and reducing the variability of response. It is known that the presence of visual information affects the auditory perception in the horizontal plane (azimuth), but there are few researches that study the influence of vision in the auditory distance perception. In general, the data obtained from these studies are contradictory and do not completely define the way in which visual cues affect the apparent distance of a sound source. Here psychophysical experiments on auditory distance perception in humans are performed, including and excluding visual cues. The results show that the apparent distance from the source is affected by the presence of visual information and that subjects can store in their memory a representation of the environment that later improves the perception of distance.

Keywords: auditory distance perception, visual distance perception, cross-modal interactions, room size perception

1 Introduction

In order to achieve a coherent picture of the external world, our nervous system must process information coming from its different sensory modalities. The brain combines this multimodal information in order to enhance the detection, localisation and discrimination of objects and speed up reactions to them. To navigate through the environment, humans mainly use the information from visual and auditory modalities. In general, the visual and auditory systems work together to facilitate the identification and localisation of objects and events in the external world.

Previous research points to the influence of vision on the accuracy of auditory localisation judgments (see King 2009, for review). For example, although the angle of incidence from a sound source can be determined from auditory cues alone, performance is more accurate in the presence of vision (Jackson 1953; Shelton and Searle 1980; Stein et al 1989). A minor number of works have been devoted to the opposite effect (Simon and Craft 1970; Perrott et al 1990; Vroomen and de Gelder 2000). These authors showed that auditory spatial information could also improve the response to a visual target, including angular discrimination, decreased reaction times, and localisation improvement.

Very often, auditory and visual modalities convey conflicting information, and the study of how this discrepancy is resolved has attracted much attention during the last years (Kubovy and Van Valkenburg 2001; Alais and Burr 2004; King 2009; Evans and Treisman 2010). A renowned example is the 'ventriloquist effect', where the presence of a localised visual stimulus strongly biases the localisation in angle of a sound source (Radeau and Bertelson 1974; Recanzone 1998; Lewald 2002). While some have theorised that this bias comes from a complete capture of the weaker auditory signal by the stronger visual signal (Pick et al 1969; Bertelson and Radeau 1981; Warren et al 1981), Alais and Burr (2004) have shown that this effect can be explained by a simple model of optimal combination of visual and auditory spatial cues, where each modality is weighted by an inverse estimate of its variability. As our ability to make use of visual cues to localise stimuli typically leads to less variability than stems from our ability

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of using auditory cues only, when a conflict arises between these modalities, visual information tends to bias responses to auditory stimuli. However, if visual stimuli are blurred so that they become harder to localise, vision can become worse than audition, and the illusion works in reverse, with sound capturing vision (Alais and Burr 2004).

While there are many studies on multisensory localisation, most of them are devoted to localisation in azimuth and very few on the effect of joint auditory and visual information on auditory distance perception (ADP). Here we study whether the accuracy of ADP could be improved by the presence of visual information.

1.1 *Auditory and visual distance perception*

In humans, both visual and auditory modalities rely on a large number of cues for estimating the distance of an object. Visual scenes potentially contain many different sources of information (both binocular and monocular) of depth. Monocular depth cues are classified as pictorial static cues and motion cues. Even a two-dimensional image can provide static depth cues such as relative size, interposition, angular declination, heights in picture plane, light and shadow distribution, and perspective, among others (Bülthoff et al 1998; Loomis 2001). Motion-based cues are induced by relative movements between observer and objects (Ono et al 1988) and include motion parallax, kinetic depth effect, and dynamic occlusion. Stereo vision enables individuals to see objects in depth in near space (Foley 1980). The foremost binocular cue is binocular disparity, which is produced by a slight discrepancy between the left and right eye images when viewing an object (Qian 1997; Blake and Sekuler 2006; Sousa et al 2010). This disparity allows the brain to estimate the relative depths of objects in the world with respect to the fixation point, a process known as stereopsis. Convergence is another binocular cue that comes from an inward turn of the eyes required to maintain stereoscopic vision, and becomes useful as the target is positioned progressively closer to the subject (Semmlow and Heerema 1979).

For ADP of sound sources, a number of cues are thought to be important. Intensity is a primary cue for ADP (Coleman 1962), due to the fact that it decreases as the distance to the source is increased (6 dB for each doubling of distance in free field). Another important cue to perceive the distance to a sound source is the direct-to-reverberant (D/R) energy ratio (Békésy 1938; Mershon and King 1975; Mershon and Bowers 1979; Butler et al 1980; Nielsen 1993; Bronkhorst and Houtgast 1999; Zahorik 2002). In reverberant environments the intensity of the direct sound of the source decreases 6 dB for each doubling of distance, whereas the energy in the later arriving reflected portion remains relatively constant. The D/R energy ratio is an interesting cue because it does not depend on the intensity of the signal and can be effective in any environment where reflections occur (even in open fields where there is at least one reflection from the ground). Other cues involved in auditory perception of distance are: spectral content, familiarity of the source, binaural and dynamical cues (see Zahorik et al 2005 for a recent review of the literature on ADP).

It is generally agreed that the distance to an object is perceived more accurately and with less variability in the visual than in the auditory modality (Loomis et al 1998). In fact, several studies reported that, even in the presence of multiple auditory cues, ADP is often poor (Coleman 1962; Middlebrooks and Green 1991; Wenzel et al 1993; Zahorik 2002).

Previous research indicates that, for the auditory modality, the distance to a sound source is overestimated when the source is located closer than 2 m, while it is substantial and progressively underestimated for greater distances (Zahorik et al 2005). In most cases, the function relating perceived to physical distance was well fitted by a power function with an exponent considerably less than one, corresponding to a compressive nonlinearity mediating between physical and perceived distance.

Another common feature in the measurement of ADP is the high variability of the response, both within and between subjects (Loomis et al 1998; Zahorik 2002; Zahorik et al 2005).

In contrast, it has been reported that visual distance perception (VDP) is quite accurate for targets up to 20 m away if full visual cue conditions are available to the observer (Thomson 1983; Elliott 1986; Loomis et al 1992; Fukusima et al 1997). It is worth mentioning that, when the distant visual cues are restricted, visual perception of distance becomes less accurate (Gogel 1961; Philbeck and Loomis 1997). Surprisingly, when the target was presented in the dark, assessments of VDP are very similar to the ones of ADP: distance is overestimated when the target is closer than 2 m and underestimated when it is farther than 3 m. Furthermore, under these conditions the variability of the response increases significantly (Loomis et al 1998). One important issue that we want to address here is to what extent the auditory distance accuracy could be improved by the presence of additional visual cues, as happens with VDP tasks (Philbeck and Loomis 1997).

1.2 *Effect of visual information on ADP*

Most multisensory studies integrating visual and auditory modalities are focused on localisation along the horizontal axis. Even when localisation in azimuth and in depth relies on different auditory and visual cues (with different kinds of variability), similar biases to the more accurate and less variable modality (visual) have been reported in depth.

A pioneering work on the study of the role of vision in ADP was published by Gardner (1968). Its experimental setup consisted of five speakers placed at different distances in a row pointing to the participant in an anechoic chamber. The speakers were placed at eye level and the participant could only see the nearest speaker during the experiment. The results showed that, although the stimulus was reproduced only from the more distant speaker, almost without exception the participant reported that the sound came from the nearest speaker (the only one that could be seen). This effect was named by Gardner the 'proximity image' effect, and was shown to operate over a variety of source intensities, being relatively insensitive to the distance of the closest loudspeaker (Gardner 1968).

In 1980 Mershon and colleagues studied the same phenomenon but under semi-reverberant conditions. They concluded that the proximity image effect operates similarly in both reverberant and anechoic environments. They further concluded that the distance from the sound source can be overestimated or underestimated depending on the position of the visual target (in this case a dummy speaker—Mershon et al 1980).

To reexamine this effect, Zahorik (2001) performed experiments using a similar setup to that of Gardner, but in a semi-reverberant room. Under these conditions listeners possess additional auditory cues for the localisation of sound sources based on the reflections. For this experiment, half of the listeners were blindfolded before entering the test room (which was unknown to them) and remained so during the experiment. The other half of the listeners stayed with their eyes uncovered throughout the experiment. Thus, the second group of listeners could see both the test room and the five speakers. Yet, during the task they were seated in front of the row of speakers, in such a way that they could only see the closest speaker, as in Gardner (1968). His results showed that the presence of multiple visual cues (vision condition) increased ADP accuracy and lowered the variability of the judgments, compared with the results obtained under the same conditions but without visual cues (blindfolded condition). Zahorik concluded that "this experiment provides evidence to suggest that visual capture effects in distance are not as general as supposed by past studies. Under the stimulus conditions of the present experiment, which were rich in auditory cues to source distance, the effect was not observed". He further concluded that the presence of multiple visual cues during the experiment increased the accuracy of the listeners to perceive the distance of a sound source (Zahorik 2001). However, as in the original experiment performed by Gardner, the participants could only see the first test speaker during the perceptual task. Thus, it cannot be excluded that the proximity image effect could have influenced the response of listeners. In fact, although the response obtained by Zahorik in the vision condition is more accurate than in the dark, for distances greater than 2 m listeners still significantly underestimate the distance of the sound source (for distances of 4 and 5 m from the source they never exceeded 3 m). In ADP, both the biases and response variability increases with increasing source distance (Zahorik et al 2005). Therefore it is expected that the image of the first speaker may have influenced the response more when it was located at larger distances. We believe that experimental conditions, attempting to prevent potential perceptual artifacts produced by the proximity image effect, may significantly avoid underestimation of the listeners response when the source is located at distances greater than 2 m.

It is also worth noting that Zahorik used five speakers lined up, an arrangement that could provide extra auditory cues from the filtering due to the acoustic shadow that casts the first speaker (ie attenuation of high frequencies for the loudspeakers that are hidden behind the first speaker).

Our aim here is to study if ADP would be improved by the presence of visual distance information. For this purpose, we performed experiments in a semi-reverberant room in the dark (in the presence and absence of minimal visual cues), using a mobile loudspeaker that allows us to deliver sound stimuli at various distances. Thus, potential acoustic cues produced by filtering of the signal, in an arrangement similar to that used by Gardner and Zahorik, are avoided.

2 General methods

The goal of this work is to study whether the accuracy of ADP could be improved by the presence of visual information. To this end, we performed three different experiments (see table 1). First, we conducted a VDP experiment that acts as a control, and that can be treated as a baseline for the visual reference cues used in the subsequent experiments. Second, we conducted ADP experiments with two groups in the dark both in the presence and absence of minimal visual cues. In the third and last experiment, we studied how prior knowledge of a specific environment affects the ADP.

Table 1. A summary of all experiments and conditions, listed in the order they were performed.

Experiment	Condition
1: Visual distance perception No prior knowledge of the test room	i (without visual cues) ii (two visual cues) iii (four visual cues)
2: Group A. Auditory distance perception No prior knowledge of the test room	i (without visual cues) ii (two visual cues) iii (four visual cues)
2: Group B. Auditory distance perception No prior knowledge of the test room	iii (four visual cues) i (without visual cues)
3: Auditory distance perception Prior knowledge of the test room	i (without visual cues)

2.1 *Testing environment*

All experiments were performed in a semi-reverberant room $12 \times 7 \times 3$ m (length $\times$ width $\times$ height) with walls covered by sound-absorbing panels (pyramid polyurethane acoustical foam, 50 mm), the floor by a carpet, and the ceiling by fibreglass acoustic panels. The average reverberation time of the room (T30 at 1 kHz measured by the MLS method) is 0.49 s at the point of the participant. The background noise of the room at the point of the participant without stimulus is 19 dBA (RION NL-32).

2.2 *Participants*

A total of thirty-two volunteers (twenty-four male and eight female) participated in the experiments. The volunteers were undergraduate and graduate students of the Licenciatura en Composición con Medios Electroacústicos of Universidad Nacional de Quilmes. Their ages ranged from 21 to 42 years (mean = 27.68 years). Although explicit measurements of visual acuity and auditory sensitivity were not performed, all participants reported normal (or corrected) vision and normal hearing. Four of the participants wore corrective lenses. None had prior knowledge of test room dimensions (except for experiment 3). All participants were aware of the experiment and signed a written consent form.

Before entering the test room, each participant was instructed on the task to be performed during the experiment. The instructions emphasised that reports should be based on the apparent source distance, as opposed to trying to objectively estimate the accurate distance (see Carlson 1977). Once instructed, the participant was blindfolded and led into the test room, where he/she was seated in a chair positioned at the zero point. During the experiment the room was dark and participants kept their eyes uncovered.

2.3 *Visual cues*

Visual reference cues were mounted on metal posts 1.2 m high and located at 2, 4, 6, and 8 m from the participant in a straight line parallel to the rail (20 cm to the right, see figure 1c). These visual cues consisted of a pair of red LEDs (standard 3 mm, 18 mca) oriented vertically 4 cm apart (figure 1d). Before entering in the test room, all participants were informed about the physical distance to the visual references.

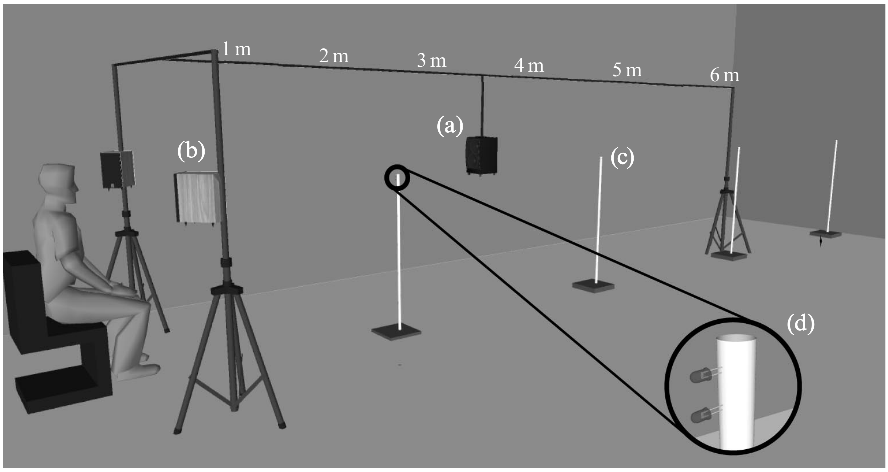


Figure 1. 3-D model of the experimental setup. (a) Mobile speaker, (b) masking system; (c) visual cues used in the experiments, (d) visual cues, formed by pairs of red LEDs (standard, 3 mm) located vertically 4 cm apart.

We used three different conditions of visual reference cues:
condition i: without visual cues;
condition ii: two reference visual cues located at 4 and 8 m;
condition iii: four visual reference cues located at 2, 4, 6, and 8 m.

For conditions ii and iii, LEDs remained lit throughout the experiment. Under all conditions participants kept their eyes open and the position of their heads were not fixed. By using experimental design we intended to provide a variety of monocular (motion parallax and accommodation) and binocular (binocular disparity and convergence) visual distance cues.

2.4 *Visual stimulus*
The visual stimulus employed in experiment 1 consisted of a pair of green LEDs (3 mm, 18 mca) located vertically, with a separation of 4 cm between them and presented at eye height in the frontoparallel plane. Thereby, angular (retinal) size information was present during the experiment. Six equally spaced eye-to-target distances (D) were used in these experiments: $D = 1$, 2, 3, 4, 5, and 6 m.

2.5 *Auditory stimulus*
The auditory stimulus employed in experiments 2 and 3 consisted of white noise bursts of 500 ms duration (measured bandwidth 50 Hz – 20 kHz $\pm$ 2 dB) with onset and offset rounded by a raised cosine of 50 ms. The signals were generated in Matlab and reproduced through the sound card at a sampling frequency of 44.1 kHz with a 24 bit resolution. The sound level of the stimulus was 70 dBA, measured at the participant's position with the source located at 1 m (RION NL-32). Thus, intensity was an important cue during the experiments. Between trials, a masking sound was presented through the loudspeakers on both sides of the head of the participant (figure 1b). Spectral content, duration, and intensity of these signals (12 s, 70 dBA measured at the participant's position) have been adjusted in order to completely mask the sound produced by the displacement of the speaker through the rail. 2 s after the end of the masking sound, the auditory stimulus was presented through the test speaker.

The experimental setup was designed and constructed in our lab and consists of a loudspeaker (figure 1a) (Genelec 8020B bi-amplified 50 W) located in front of the participant, 1.2 m above the floor (which was approximately equal to the height of the seated-participant's ears) and free to move suspended along a metal rail (6 m long). This system allows us to play auditory stimuli at different distances from the participant. The setup is completed by a masking system, consisting of two fixed speakers (Edifier R1000TCN 25 W) located at both sides of the participant and pointing to his/her ears (figure 1b). Both the speaker and the masking system were controlled by a stereo sound card (Presonus AUDIOBOX-2 out 2 in). The straight line between the participant and test loudspeaker was parallel to two walls, but slightly offset from centre line of the room.

Under these conditions two important acoustic ADP cues were present during the experiment: intensity and direct-to-reverberant energy ratio. Given the distances used here (from 1 to 6 m), binaural and spectrum cues were not expected to contribute significantly to the response (see Zahorik et al 2005).

2.6 *General procedure*
Distances to the stimuli were $D = 1$, 2, 3, 4, 5, and 6 m from the participant. For all experiments the procedure consisted of presenting the stimulus at one of the six distances and then asking participants to judge the apparent egocentric distance to the visual (LEDs) or auditory target (loudspeaker). Distance judgments were made verbally, using a scale of metres with a precision of one decimal place.

Stimuli were presented three times for each of the six test distances, forming a total of 18 trials per block. Presentation order of the trials was randomised. Only one verbal response was made per trial, and the participant did not receive explicit feedback about the correctness of his/her responses.

3 Experiment 1

The purpose of this experiment was to test the suitability of the system of visual cues. In order to do this we performed an experiment of VDP in the presence and absence of visual cues. The visual-cues conditions were used in the following order and with a 10 min break between them: condition i, condition ii, and condition iii (see table 1). None of the participants (five men and three women) wore corrective lenses.

3.1 *Results and discussion*

In figure 2a we display the median distance judgment as a function of the target distance without visual cues (condition i). The error bars represent 1 SEM ($n = 8$). Power functions of the form $Y = aX^b$ were fit to the data ($R^2 = 0.92$), using a method of least squares ($a = 0.81 \pm 0.12$ and $b = 0.87 \pm 0.1$). As can be clearly seen in the figure, in the absence of visual cues, distance to the target was underestimated for $D > 1$ m. This result agrees well with those reported in previous studies, where the restriction of distance cues created by presenting the target in the dark typically produced perceptual errors.

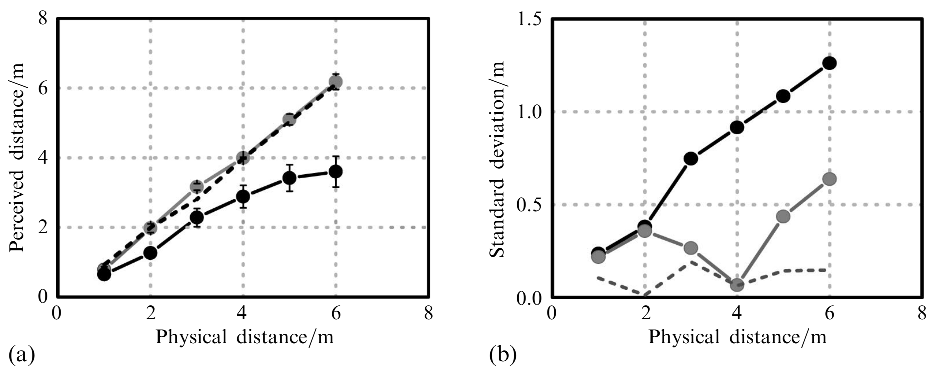


Figure 2. Experiment 1. Visual distance perception (no prior knowledge of test room). (a) Mean distance judgments as a function of physical distance obtained without visual cues (condition i, $n = 8$, black circles), with two visual cues located at 4 and 8 m from the participant (condition ii, $n = 8$, gray circles), and four visual cues located at 2, 4, 6, and 8 m from the participant (condition iii, $n = 8$, black short dashed line). (b) Distance judgment standard deviation as a function of source distance for: condition i (black circles), condition ii (gray circles), and condition iii (gray short dashed line).

However, it does not agree with previous studies that report an overestimation of the response to the target for distances smaller than 3 m (Gogel 1961; Philbeck and Loomis 1997).

By contrast, when the experiment was performed in the presence of two visual cues located at 2 and 4 m from the participant (condition ii, figure 2a) the average distance responses were highly accurate ($r = 0.98$; $a = 0.95 \pm 0.06$; exponent $b = 1.04 \pm 0.03$). This is reflected as a significant increase in the value of the b exponent compared with that obtained under condition i (2-sample t-tests; $t = 2.37$; $p = 0.032$). The response obtained in presence of four visual cues (figure 2a) located at $D = 2$, 4, 6, and 8 m from the participant (condition iii) was quite similar to that obtained under condition ii ($r = 0.99$; $a = 0.91 \pm 0.24$ and exponent $b = 1.06 \pm 0.08$).

The response in condition iii was significantly more spread than that obtained without visual cues (condition i). This is reflected as a significant increase in the value of the b exponent ($t = 3.22$; $p = 0.01$). Separate one-way ANOVAs for each distance (D) with condition as the factor were calculated. The average apparent distance was significantly different across conditions for all distances ($F_{3,21} > 4$, $p < 0.03$). A-posteriori analysis (Tukey – Kramer test) showed that estimated distances under conditions ii and iii were significantly greater than estimates under condition i for all distances tested, with the exception of $D = 1$ m where only estimates for condition iii were significantly higher than under the condition i.

Figure 2b shows the judgment variability of the data (pooled across participants and replications) for conditions i, ii, and iii. Greater judgment variability occurred when the experiment was performed without visual cues (except when compared with condition ii, where this occurs only for target distances greater than 2 m).

This last result is consistent with past research (Philbeck and Loomis 1997), where a lower variability in visual distance judgments under full-cue conditions was reported. Furthermore, under condition i (without visual cues) the variability of the response increased as the distance to the target increased, while in the presence of visual cues the variability of the response remained relatively constant at all distances tested. Also, in agreement with previous research, the restriction of distance cues caused perceptual errors, while the response was very accurate when visual distance cues were added. However, it is important to mention that in our experiment the visual cues were only effective when we provided the participant with the information of the real distance to the LED pairs. When the same cues were used without providing this information, the response observed was very similar to that obtained without visual cues (data not shown). As mentioned above, previous studies have found that visual perception of distance to an object is more accurate when added a complex visual surrounding. This happens even when a single visual reference is added, mainly if the second object is further away (Gogel 1961; Foley 1980; Sousa et al 2010). It has been suggested that this effect is related to the relative disparity between the two objects (Sousa et al 2010). We found little effect of relative disparity when listeners did not know the actual distance of the visual references. We believe that this result could be explained because the visual references used here are almost identical to the visual target and therefore their estimated distances were perceived with a similar degree of variability. However, when the participants were informed about the actual distance to the visual cues, they were able to make accurate judgments of the distance to the target relative to the references. This is consistent with the hypothesis that, if a distance to an object (reference) is known, all other distances could be derived from the relative disparities with respect to this reference (Brenner and Van Damme 1999; Sousa et al 2010).

The results obtained in the presence of visual cues (conditions ii and iii) were similar to those reported in previous studies under full-cue conditions, suggesting that the system of visual cues used in this experiment could be used as an effective visual reference for the following experiments of ADP.

4 Experiment 2

This experiment was conducted in order to examine whether the presence of visual cues could enhance the ADP. A total of sixteen volunteers (thirteen male and three female) participated in this experiment. Two of the participants wore corrective lenses. Participants were divided into two equal groups. For the first half of the participants (group A, $n = 8$) the visual cues were used in the same sequence as in experiment 1: condition i (without visual cues), condition ii (two visual cues located at 4 and 8 m), and condition iii (four visual cues located at 2, 4, 6, and 8 m). For the second half of the participants (group B, $n = 8$), condition iii was tested first and then condition i was used (see table 1). In the same way as in experiment 1, all participants were informed about the physical distance to the visual references before entering the test room.

4.1 *Results*

In figure 3a the mean subjective distance judgments obtained without visual cues are displayed as a function of the physical distance (group A, $n = 8$, condition i; see section 2). Each data point corresponds to a geometric mean across the three presentations and all the individual participants. Power functions of the form $Y = aX^b$ were fit to the data using a method of least squares ($r = 0.78$; $a = 1.33 \pm 0.2$ and exponent $b = 0.55 \pm 0.1$). These values are very similar to those obtained in a meta-analysis of the results of 21 previous auditory-distance-perception studies ($a = 1.32$ and exponent $b = 0.54$; Zahorik et al 2005).

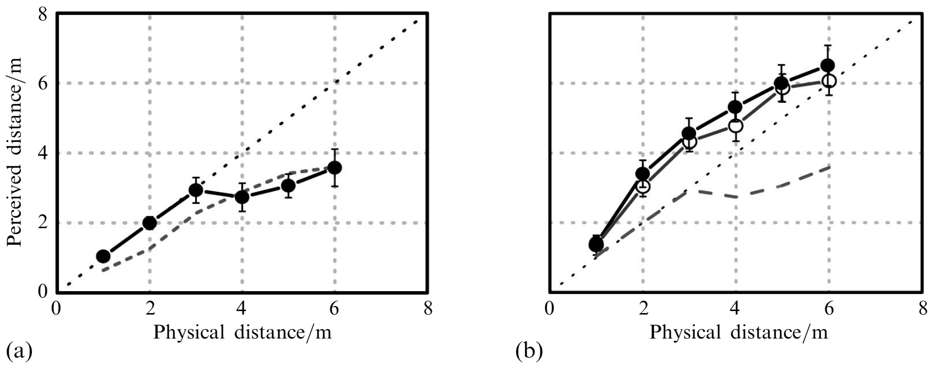


Figure 3. Experiment 2: group A—Auditory distance perception (no prior knowledge of test room). (a) Mean distance judgments as a function of physical distance obtained without visual cues (condition i, $n = 8$, black circles). As a comparison, the gray short dashed line corresponds to the results obtained in experiment 1 (condition i for vision). (b) Mean subjective distance judgments as a function of physical distance obtained with two (condition ii, $n = 8$, open circles) and four visual cues (condition iii, $n = 8$, black circles). Gray dashed lines show the results obtained without visual cues (condition i for ADP).

It is worth noting that in our experiment, for sound sources greater than roughly 3 m, perceived distance was substantially and progressively underestimated. However, the response was very accurate for the three nearest distances tested. In order to compare the response between the visual and auditory modalities under similar conditions, we also display in figure 3a the results obtained in experiment 1 without visual cues (gray short dashed line, condition i for vision). There was no significant difference among these two groups (condition i for experiments 1 and 2) for all distances (one-way ANOVA $F_{1,114} < 4$, $p > 0.05$), with the exception of $D = 2$ m ($F_{1,14} = 10$, $p = 0.007$).

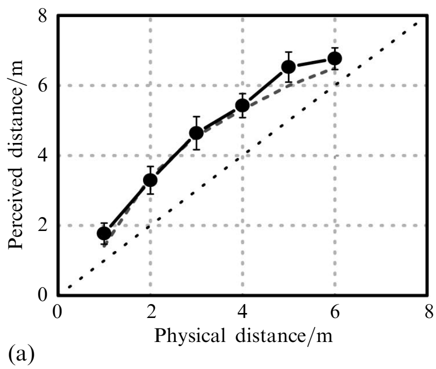
In figure 3b we display the mean subjective distance judgments as a function of physical distance obtained under condition ii (two visual cues located at 4 and 8 m) for the same group of participants ($n = 8$, group A, see table 1). Power functions of the form $Y = aX^b$ were fit to the data using the method of least squares ($r = 0.91$; $a = 1.84 \pm 0.22$ and exponent $b = 0.71 \pm 0.08$). The response was significantly more widespread than the response without visual cues. This is reflected as a significant increase in the value of the b exponent compared with that obtained under condition i (2-sample t-tests; $t = 2.61$; $p = 0.02$).

In the same figure, black circles correspond to the mean subjective distance judgments as a function of physical distance obtained under condition iii (four visual cues located at 2, 4, 6, and 8 m) and for the same group of participants ($r = 0.91$;

$a = 2.01 \pm 0.24$ and exponent $b = 0.68 \pm 0.08$). The response was very similar to that obtained under condition ii. Fitting values for the power function for the two conditions were not significantly different ($t = 0.48$; $p = 0.63$ for a, and $t = 0.43$; $p = 0.66$ for the exponent b). As in the previous case, the response was significantly more widespread than that obtained without visual cues and a significant increase in the value of exponent b, compared with that obtained under condition i was observed ($t = 2.45$; $p = 0.028$).

These last results show that in the presence of visual cues, the distance to the sound source was overestimated. Analysis of variance was conducted for each distance (D) with condition as the factor. The average apparent distance was significantly different across conditions for all distances ($F_{2,21} > 6$, $p < 0.008$), with the exception of $D = 1$ m. A-posteriori analysis (for $D > 1$ m) showed that estimated distances under conditions ii and iii were significantly greater than estimates under condition i in all cases.

In figure 4 we display the results for group B. Figure 4a illustrates the mean subjective distance judgments as a function of physical distance obtained with four visual cues (condition iii) for eight participants who had not previously participated in ADP experiments (group B) ($r = 0.98$, $a = 2.01 \pm 0.16$ and exponent $b = 0.68 \pm 0.05$). As a reference, in the same figure we display in gray short dashed line the mean subjective distance judgments under condition iii for group A. This experiment was performed in order to exclude the possibility that the results obtained in the presence of visual cues for group A could have been caused by a learning effect (due to the fact that the task was performed sequentially). Under these conditions the response from participants was not significantly different from that obtained for group A under the same conditions ($t = 0.48$; $p = 0.63$ for a, and $t = 0.43$; $p = 0.66$ for exponent b). Also, the analysis of variance for each separate condition showed no significant difference across groups ($F_{1,14} < 1$, $p > 0.3$). It is worth noting that the response was significantly more widespread than the response without visual cues (group A under condition i; $t = 2.41$, $p = 0.031$).



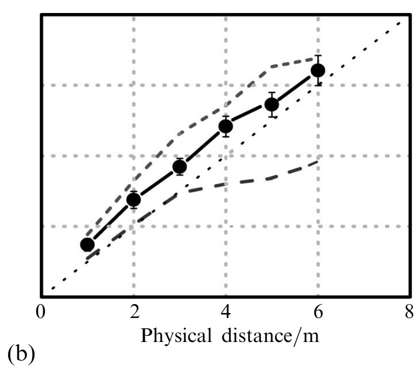


Figure 4. Experiment 2: group B—Auditory distance perception (no prior knowledge of test room). (a) Mean distance judgments as a function of physical distance obtained with four visual cues (condition iii, $n = 8$, black circles). As a reference, gray short dashed line corresponds to the results obtained in group A under the same condition. (b) Black circle corresponds to the mean distance judgments as a function of physical distance obtained without visual cue (condition i, $n = 8$). Gray short dashed line corresponds to the response obtained with four visual cues (condition iii) by participants of group B. As a reference, gray dashed line shows the response obtained without visual cues (condition i) by participants of group A.

In figure 4b (black circles) we display the results obtained without visual cues (condition i) for participants who had previously participated in the experiment with four visual cues (group B). Surprisingly, the response was more accurate than that obtained for group A under the same condition ($r = 0.95$; $a = 1.57 \pm 0.16$ and exponent $b = 0.79 \pm 0.05$). This is reflected as a significant increase in the value of the b exponent ($t = 1.93$; $p = 0.0005$). As a reference, in figure 4b we also display in gray dashed line the mean subjective distance judgments under condition i for group A.

In fact, the responses in the absence of visual cues for group B do not differ significantly from the results obtained previously in the presence of visual cues (condition iii) for any of the distances tested (ANOVA $F_{1,14} < 4$, $p > 0.06$). Furthermore, the response under this condition was slightly more widespread than that obtained in the presence of four visual cues (condition iii) for the same group of participants (group B), although this difference was not statistically significant ($t = 1.07$; $p = 0.3$).

5 Experiment 3

The purpose of this experiment was to evaluate how prior knowledge of a specific environment affects the ADP. The participants (seven male and one female) were allowed to know the test room, with the lights on, for about 5 min before performing the task. However, they were not informed about the room dimensions. After this visual inspection the participants were led to an adjacent room where they were instructed on the task at hand to be performed during the experiment. Two of the participants wore corrective lenses.

Once in the test room this experiment was done following the same procedure as in the previous one, but using condition i (no visual cues) only.

5.1 *Results*

In figure 5 the mean subjective distance judgments obtained through verbal reports without visual cues (condition i) are displayed as a function of physical distance. Surprisingly, the response obtained under these conditions was very accurate for all distances tested.

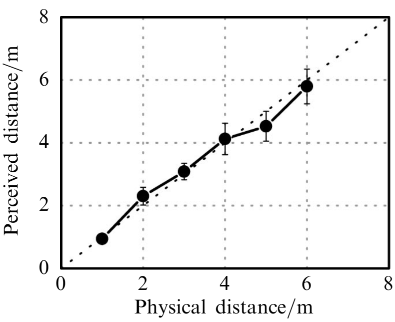


Figure 5. Experiment 3: auditory distance perception (prior knowledge of test room). Mean distance judgments as a function of physical distance obtained without visual cues for participants who were able to see the test room before the experiment (condition i, $n = 8$).

The greater accuracy observed for this condition is reflected in the values of the parameters (close to 1) of the fitting power function ($r = 0.98$; $a = 1.14 \pm 0.12$ and exponent $b = 0.89 \pm 0.06$). As a comparison, substantially lower accuracy was observed for participants of group A in experiment 2 for the same condition (experiment 2, figure 3a, exponent $b = 0.55 \pm 0.1$) ($t = 4.14$; $p = 0.0015$). Indeed, the responses obtained in figure 3 were more accurate than those from experiment 2, for all tested conditions (group A, conditions ii and iii, exponent $b = 0.71 \pm 0.08$ and exponent $b = 0.68 \pm 0.08$, respectively; and group B, conditions iii and i, exponent $b = 0.71 \pm 0.05$ and exponent $b = 0.79 \pm 0.02$, respectively), even though, with the exception of group A, condition iii ($t = 2.4$; $p = 0.034$), the increase in the value of the exponent was not statistically significant.

Finally, in figure 6 we display the variability of the judgments of distance for the following data: (a) experiment 2, group A, condition i ($n = 8$); (b) experiment 2, group B, condition iii ($n = 8$); and experiment 3, condition i ($n = 8$) (see table 1). Similar to that reported in experiment 1, the variability of the response in the absence of visual cues

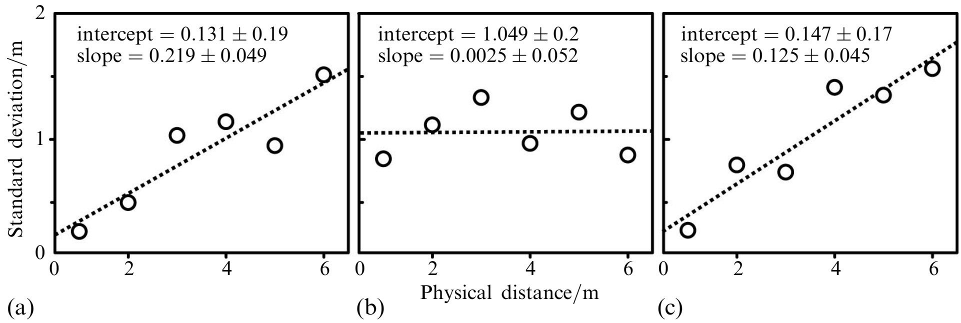


Figure 6. Distance judgment: standard deviations as a function of source distance. (a) Without visual cues (experiment 2, condition i, group A, $n = 8$). (b) Four visual cues located at 2, 4, 6, and 8 m (experiment 2, condition iii, group B, $n = 8$). (c) Without visual cues, for participants who were able to see the test room before the experiment (experiment 3, condition i, $n = 8$). Dotted lines in (a), (b), and (c) correspond to linear fittings to the data. Linear function fitted parameters are shown in the upper left for each condition.

(figures 6a and 6c) increases when the distance from the source increases while, in the presence of visual cues, variability remains relatively constant at all distances tested (figure 6b).

6 Discussion

The results obtained strongly support the original hypothesis that the presence of visual information affects the auditory perception of sound source distance. For the case of no-visual-cues condition we observed a similar behaviour to that reported in many previous studies (see Békésy 1949; Cochran et al 1968; Simpson and Stanton 1973; Bronkhorst and Houtgast 1999; Zahorik 2001, 2002; and Zahorik et al 2005, for review): the response increases linearly with source distance at short ranges, but converges to a certain limit when the source distance is increased beyond 3 m. When the experiment was conducted in the presence of visual cues (pairs of LEDs), at least three effects have been observed: (1) the distance to the sound source was overestimated at five of the six distances tested ($D = 2$, 3, 4, 5, and 6 m), (2) the responses of the participants were more spread than those obtained without visual cues, and (3) the variability of response was relatively constant at all distances tested while, in the dark, increased linearly with increasing distance from the sound source. In addition, our results show that the visual information obtained by participants during the experiment can be stored in memory to be used, minutes later, as a spatial reference in experiments that were carried without visual cues. Furthermore, a very accurate response can be obtained in the dark when the participants are allowed to inspect visually the test room (full visual cue condition) before performing the experiment.

6.1 *Relation to past results*

In experiment 2 we studied how the ADP is affected by the presence of visual cues. Considering the scarcity of studies of this issue, the comparison between last experiment and that performed by Zahorik (2001) is compelling. The methodology used in this work resembles that followed by Zahorik: (a) experiments were performed in a semi-reverberant environment; (b) stimuli were presented from a range of six different distances within a block of trials, a procedure that is known to facilitate auditory judgments of distance (Mershon and Bowers 1979); and (c) the experiment was performed in the presence and absence of visual cues.

In agreement with previously reported results, the data obtained under condition i (experiment 2, group A) were well fitted by a power function of the form $Y = aX^b$ with an exponent significantly less than one ($b = 0.55$). The fitting parameters for the case of no visual cues are very similar to those reported in a meta-analysis of 21 previous ADP studies (Zahorik et al 2005). Thus, these results give a reliable baseline accuracy of auditory distance judgments to assess the contributions of additional visual cues to the accuracy of distance perception (see Zahorik 2001). Under these conditions, participants underestimated the distance to the sound source when placed at distances greater than 3 m (figure 3a). This result is also consistent with findings from previous works (see Zahorik et al 2005, for a review). Surprisingly, when the experiment was performed without visual cues, the auditory and visual stimuli were localised at exactly the same distance from the participant (figure 3a, gray dashed line for comparison). Congruent results were reported (Philbeck and Loomis 1997; Loomis et al 1998), where similar responses were obtained for these two modalities when conducting experiments in the dark.

When visual cues were used during the experiment, the underestimation observed for condition i was significantly reversed (compare figures 3b and 4a). In fact, the distance to the sound source was overestimated for $D > 1$ m (figures 3b and 3c). In addition, the response from participants was significantly more spread, which is reflected in a significant increase of the exponent b. These results are consistent with those reported by Zahorik (2001), where the presence of visual information caused a significant increase in the exponent of the power function compared to the value obtained with no visual cues. Much of this difference was caused by differences in distance estimates for the sources located at $D = 4$, 5, and 6 m. For example, for condition i, when the sound source was placed at distances ranging from 3 to 6 m, the response tends to cluster in an 85 cm range between 2.90 and 3.75 m, whereas in the presence of visual cues (condition ii) the data tend to cluster around in a much wider range of 220 cm between 4.81 and 7.01 m.

A major difference between our results and those reported by Zahorik using visual cues is that for experiment 2 (conditions ii and iii) the participants overestimated the distance to the speaker for all distances tested, while in the experiment carried out by Zahorik (2001) all distances were underestimated. This discrepancy could have been caused by important methodological differences between the two experiments. In our experimental setup the participants could not see the loudspeaker for any of the conditions, whereas in the experiment conducted by Zahorik (under visual condition) the participants were able to see both the nearest speaker (located at 1 m) and the test room during the task. The underestimation reported by Zahorik may be due to an attraction effect on the response produced by the image of the nearest speaker. Although in the study of Zahorik (2001) the visual capture effect in distance was not as evident as in the works of Gardner (1968) and Mershon et al (1980), it cannot be completely excluded and the possibility remains that the image of the nearest speaker (that participants could see all the time) may have caused an attraction on the response.

In our experimental design we have additional precautions in order to minimise possible attraction effects. The visual cues were small, they were located outside the rail line, and remained lit throughout the experiment. This last condition avoids possible temporal effects, such as synchronisation with the auditory stimuli, which could provide additional biases in the direction of the visual cues. The fact that for group B the responses were not significantly different between the two conditions (no visual cues and four visual cues) could indicate that if there is an attraction on the perceived location of the sound source in the direction of the visual cues, this is minimal.

Another difference with previous research was observed in the behaviour of the variability of the responses. Previous works in VDP (Philbeck and Loomis 1997) and ADP (Zahorik 2001) support the idea that the presence of visual information leads to a decrease in the variability of the responses, compared with the condition of no visual cues. However, in contrast to data reported by Zahorik (2001), we did not observe a reduction of the response variability in the presence of visual cues (see figure 6). This difference may be due to methodological differences between the two experiments. In the experiment conducted by Zahorik (under visual conditions) the participants were able to see both the loudspeaker array (and therefore the distance between them) and the test room during the task, while in the experiments performed here (under conditions ii and iii) the number and complexity of visual cues was lower.

Surprisingly, when we tested condition i (without visual cues) minutes after the experiment with visual cues (group B, condition iii) the response was significantly more accurate than that for group A under the same condition. This result suggests that the information generated by visual cues during the first part of the experiment may be used, minutes later, as a spatial reference for the experiment without visual cues. In agreement with this, Loomis and colleagues (1992) reported that when visual feedback is removed after an initial exposure to a visual target, a spatial image of the perceived target location is maintained. As further reference, the experiments on visual distance perception that use direct action walking as a method of response indicate that a participant can use visual information as a guide for a subsequent task in the dark. These experiments have shown that subjects can walk blindly to targets with quite high accuracy following a period of preview with binocular vision from a fixed origin (Thomson 1983; Laurent and Cavallo 1985; Elliott 1986; Loomis et al 1992, 1998; Fukusima et al 1997).

Similar to what happened in the second part of experiment 2, the data obtained by the subjects in prior recognition of the test room served as a spatial reference to perform, minutes later, the task in the dark. Surprisingly, under these conditions the response was even more accurate than that obtained by group B, experiment 2, under condition i. Maybe the difference between the two responses is due to the number and complexity of visual cues available for each condition. While in experiment 2, participants for group B only had a maximum of 4 LED pairs as visual cues, subjects from experiment 3 were able to observe the test room well lit. The results obtained here show that the ADP of a sound source in the dark is more accurate when participants have a prior knowledge of the environment. This suggests that some kind of spatial representation of the test room can be recalled during the experiment in order to increase the accuracy of the sound source localisation in depth.

7 General discussion

The influence of vision on auditory localisation (both in angle and distance) during the perceptual analysis of a multimodal scene has been reported in many previous studies (see Jackson 1953; Gardner 1968; Thurlow and Jack 1973; Jones 1975; Mershon et al 1980; Shelton and Searle 1980; King 2009; and Zahorik 2001). Warren (1973) argues that vision provided a context in which auditory localisation judgments were made (vision serves to organise auditory space). As mentioned, our ability to use visual cues to localise stimuli is typically more accurate than our ability to use auditory cues to localise sounds sources (Bertelson and Radeau 1981; Loomis et al 1998; Battaglia et al 2003; Alais and Burr 2004; Wallace et al 2004). Thus, the spatial characteristics of the environment are perceived more accurately by the visual than the auditory modality. We suggest here a possible role of vision in ADP: to obtain reliable information about the spatial characteristics (dimensions) of the place where auditory events occur (in this case changes in the distance from the source), in order to calibrate the information coming from ADP-related auditory cues (mostly relative) and assign a distance value to the perceived sound source within this space.

Previously, Cabrera et al (2005, 2006) have suggested that auditory distance perception and auditory room-size perception could be related. This hypothesis parts from a simple but powerful idea: if the sound source and the participant are in the same room, large source – receiver distances are only possible within large rooms. Although there is no direct evidence in the literature to prove this hypothesis, there is abundant indirect evidence that indicates that the acoustical characteristics related to the size of a room affect both the apparent distance of the sound source and the reliability of distance judgments.

In addition, auditory room-size perception and ADP share an important auditory cue: reverberation. Reverberation has a large impact on the perceived characteristics of a listening environment. For example, blindfolded subjects can distinguish the size of a room by using speech and other reflected sounds (McGrath et al 1996). Furthermore, experiments by Sandvad (1999) show that subjects could usually correctly match photographs of rooms with the corresponding binaural recordings made in that environment. Many previous studies have shown that reverberation times have a strong effect on perceived room-size judgments (Mershon et al 1989; Sandvad 1999; Hameed et al 2004; Cabrera et al 2005). Although many factors contribute significantly to the exact value of the reverberation time (eg size of the room, wall materials, furniture, etc), in the absence of further information the brain interprets the acoustics cues given by the sound decay in direct relation to the room size: greater reverberation time is consistently associated with larger rooms (Cabrera et al 2006).

Besides providing information about the perceived characteristics of a listening environment, reverberation is an important cue for ADP. Previous works showed that judgments of apparent source distance made by participants are more accurate in a reverberant than in an anechoic environment (Mershon and King 1975; Nielsen 1993; Shinn-Cunningham 2000). Several authors have suggested that this effect is caused by an absolute auditory cue of distance: the direct-to-reverberant (D/R) energy ratio (Békésy 1938; Mershon and King 1975; Mershon and Bowers 1979; Butler et al 1980; Nielsen 1993; Bronkhorst and Houtgast 1999; Zahorik 2001, 2002; Zahorik et al 2005 for review).

One important issue that we want to address here is the possibility that the improvement in judgments of ADP observed in reverberant environments could be explained, besides the direct-to-reverberant (D/R) energy ratio, by the association between reverberation time and room volume. There is abundant evidence to support this hypothesis. While the presentation of a sound with no reverberation produces the impression of a very close source (Mershon and King 1975) the addition of reflected or reverberant sound leads to the perception of a more distant source (Mershon et al 1989). Bronkhorst and Houtgast (1999) demonstrate that increases in the number of simulated reflections in a virtual auditory display result in increases in the apparent distance. Nielsen (1993), in turn, reported increases for the apparent distance judgments in reverberant and semi-reverberant environments when compared to an anechoic environment. Similar results were obtained in many previous studies (Békésy 1938; Butler et al 1980; Wagenaars 1990; Begault 1992; Bronkhorst and Houtgast 1999).

Many experiments on auditory distance perception yield a compressive function for the perceived versus actual distance (Zahorik et al 2005). The upper part of the restricted range of perceived distances is commonly known as the 'auditory horizon' (Bronkhorst and Houtgast 1999; Zahorik 2002). This limit has been associated with the breakdown of the D/R cue at distances where the reverberant acoustic field entirely dominates the sound (Sheeline 1984). Thus, it has been suggested that the distance to the 'auditory horizon' depends on the acoustical characteristics of the environment. However, the results obtained here (experiments 2 and 3) strongly suggest that the 'auditory horizon' also depends on non-acoustic factors, such as the presence of multiple visual cues during and before the experiment. This is quantitatively reflected as a significant increase of the value of the power exponent compared to that obtained without visual cues. These changes of the spread of the response occurred in the same test room with constant acoustical properties.

If the hypothesis that ADP and room-size perception are related is true, the visual system would have an obvious advantage over the auditory system to provide this information because auditory room-size perception depends on the acoustic characteristics of a room, while vision is more effective in getting information on size, shape, materials, etc. This is a foremost important issue, because most of the ADP experiments were performed in the dark in unknown environments (in many cases, acoustically treated rooms). Perhaps this fact can explain the underestimation of the response reported in previous studies. However, clearly, additional work is needed to prove this hypothesis.

Acknowledgments. This work was partially funded by ANPCYT (Agencia Nacional de Promoción Cientifica y Tecnológica), CONICET (Consejo Nacional de Investigaciones Cientificas y Tecnológicas), and Universidad Nacional de Quilmes. We are grateful for the comments on the manuscript by Diego Alberto Guzman, Ramiro Aguilar, and Oscar Edelstein.

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ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

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VOLUME 41 2012

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