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Auditory localization and precedence effect: An exploratory study in infants and toddlers with visual impairment and normal vision

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ABSTRACT

The precedence effect is a spatial hearing phenomenon implicated in sound localization on reverberant environments. It occurs when a pair of sounds, with a brief delay between them, is presented from different directions; listeners give greater perceptual weight to localization cues coming from the first-arriving sound, called lead, and suppress localization cues from the later-arriving reflection, called lag. Developmental studies with sighted infants show that the first responses to precedence effect stimuli are observed at 4–5 months of life. In this exploratory study, we use the minimum audible angle (MAA) paradigm in conjunction with the observer-based psychophysical procedure to test the ability of infants and toddlers, with visual impairment and normal vision, to discriminate changes in the azimuthal position of sounds configured under precedence effect conditions. The results indicated that similar and, in some conditions, higher performances were obtained by blind toddlers when compared to sighted children of similar age, and revealed that the observer-based psychophysical procedure is a valuable method to measure auditory localization acuity in infants and toddlers with visual impairment. The video records showed auditory orienting behaviors specific of the blind children group.

1. Introduction

Children spend most of their time in reverberant environments in which sound propagates in multiple directions and reflects in surfaces such as objects, walls, ceilings, and floors. When a child localizes a sound, their auditory system must be able to resolve the perceptual competence which is produced between the direct sound and its multiple reflections. If there are no obstacles between the listener and the sound source, direct sound will arrive first and its reflections will do so later and from multiple directions. Under certain circumstances, it has been noted that a single auditory event is heard, which the

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listener locates in the direction where the sound came first, called lead. This spatial auditory phenomenon is called precedence effect and occurs when sounds are presented from different locations with a brief delay between them (Blauert, 1997; Litovsky, Colburn, Yost, & Guzman, 1999; Wallach, Newman, & Rosenzweig, 1949; Yost & Soderquist, 1984).

The precedence effect is an unconscious mechanism which allows the individual to accurately localize primary sound sources (of greater ecological relevance than secondary sources). The first publications about precedence effect described it as an *echo suppressing* mechanism. However, later research has shown that the information included in the later-arriving reflection, called lag, is not suppressed but preserved (Clifton, Freyman, Litovsky, & McCall, 1994; Yost & Soderquist, 1984). Reflected sounds contain relevant information about the presence and position of secondary sources (Clifton, Freyman, & Meo, 2002).

In most precedence effect related studies, a lead–lag click pair configuration is used, which simulates the original sound and its reflection. Although this two-source paradigm deviates from reality in many ways, it provides the basis to understand how the auditory system processes reflections in spatial auditory tasks (Goupell, Yu, & Litovsky, 2012). Generally, the reflection is a consistent, lagging, and attenuated copy of the direct sound, which is not perceived as an independent sound event. Nevertheless, an individual may easily discriminate between direct sound trials and the ones that include a direct sound and its reflection (Blauert, 1997). This occurs because the reflections modify non-spatial parameters such as loudness and pitch of the original sound (Clifton et al., 1994; Freyman, Clifton, & Litovsky, 1991).

Three percepts are involved in the precedence effect, namely fusion, localization dominance, and lag discrimination suppression (Litovsky et al., 1999). The fusion percept refers to the fusion of lead and lag into a single auditory image, which is useful to avoid multiple sound images. In fusion studies, the experimenter asks the subjects to indicate whether they heard one or two sounds. This procedure is repeated several times presenting various lead–lag delays. This effect is stronger for short delays (1–8 ms). This implies that as the reflecting surface is farther from the primary sound source, fusion becomes weaker. Echo threshold is often referred to as the value in milliseconds from which lead and lag sounds are perceived as two separate events. Echo threshold depends on the stimuli used, for adults it reaches 35 ms in the case of speech, and around 5–9 ms for click stimuli (Freyman et al., 1991; Haas, 1951).

Localization dominance percept refers to the greater perceptual weight given by the listener to the directional cues coming from the lead. Although the directional information contained in the lag sound is not completely ignored, it is the lead which contributes mostly to determine the perceived position of the auditory image. In many of the experiments measuring dominance, the participant has to decide which of the loudspeakers is closest to the location of the sound image. This percept has been the subject of most of the classic precedence effect related studies (Litovsky et al., 1999).

Lag discrimination suppression percept refers to the listener's ability to process directional information contained in the lagging sound, even when it is not heard as an auditory event separate from the lead. In these studies, one of the experimental paradigms applied involves the measurement of the participant's ability to discriminate positional changes of the lag sound. Developmental literature about this percept is sparse. This latter aspect of the precedence effect is analyzed in this research.

1.1. Developmental studies about precedence effect

What is mostly known about this phenomenon derives from research conducted on sighted adult participants. The first studies on the development of the ability to perceive sounds under precedence effect conditions were performed with newborns. These researches used two speakers positioned at 90° to the left and right of the child. Head turn responses in control (single source) and precedence effect (lead–lag pair) conditions were compared. The results were negative: the newborns did not turn their head in the precedence condition, but they did so in the control condition (Clifton, Morrongiello, Kulig, & Dowd, 1981; Morrongiello, Clifton, & Kulig, 1982). By means of a similar procedure, Clifton, Morrongiello, and Dowd (1984) concluded that there is a transition period between 2 and 6 months, in which the precedence effect begins to operate. In a later study, Muir, Clifton, and Clarkson (1989) determined that the first reliable responses to precedence effect stimuli appear from 4 months old onwards.

Research conducted with older children focused on developmental aspects of precedence effect percepts. Morrongiello, Kulig, and Clifton (1984) assessed the performance of 6 month old infants, 5 year old children, and adults in a fusion task. Results showed that, for click stimuli, 6 month old infants obtained a mean echo threshold of 25 ms, value which doubled that obtained by 5 year old children and adults. Litovsky and Godar (2010) studied the link between localization dominance and fusion percepts in a study conducted with 4–5 year old children and adults. They implemented two experiments, a localization task and a fusion task. Results indicated that, below echo threshold, participants localized the lead-lag pair in the lead's position. Above the echo threshold, the performance of children on the localization task was poor. The authors concluded that, even when the lead and lag sounds are perceived as separate events, the lag position is not easily perceived by children.

Regarding to the lag discrimination percept, as far as we know, the only study conducted on children was the one published by Litovsky (1997). The author applied the minimum audible angle (MAA) procedure, which allows to estimate the smallest difference in the lateral position of a sound source that can be reliably detected (Mills, 1958). The experiment was conducted with the participation of 18 month old children, 5 year olds and adults. Results showed that, in all groups, a better performance was observed in the single control condition. In precedence conditions, the changes of the lag sound position were harder to detect than the changes in the lead sound position. Furthermore, it was observed that the MAA mean thresholds for 18 month old children, in the three experimental conditions, were greater (a poorer performance) than the MAA obtained by 5 year olds and adults.

Scientific research on the development of spatial hearing in visually impaired children is very scarce (Humphrey, Dodwell, Muir, & Humphrey, 1988; Warren, 1984). In general, the auditory localization behavior is studied within the framework of broader research on the cognitive and motor skills development of blind children. Studies performed on visually impaired children under 3 years old do not employ psychophysical procedures to estimate, for instance, auditory localization thresholds. In addition, these studies do not supply information regarding the acoustic parameters of the auditory stimuli used, which consist mainly of the sound of toys and the voice of the mother or experimenter. To our knowledge, there have been no previous studies on auditory localization under precedence effect condition in children with visual impairment.

1.2. Purpose

The purpose of this exploratory study was to test the ability of infants and toddlers, with and without visual impairment, to discriminate changes in the right/left position of sounds configured under precedence effect conditions. Auditory spatial acuity was measured with a single interval 2-alternative-forced choice right/left discrimination task, and the MAA estimates procedure was applied. The design was based on Litovsky' study (1997). In contrast with the reference study, the behavioral responses of the participants were assessed by means of the observer-based psychophysical procedure (Olsho, Koch, Halpin, & Carter, 1987). Instead of considering a target response, a trained observer judged the occurrence of a change in the stimulus position based on any kind of behavioral response from the children. This method has been implemented in previous studies with sighted infants and toddlers in order to measure auditory sensitivity and localization acuity with the MAA procedure, among other phenomena (Grieco-Calub, Litovsky, & Werner, 2008; Morrongiello, Fenwick, & Chance, 1990; Trehub, Schneider, Thorpe, & Judge, 1991).

From the findings of previous research in children with normal vision, it was assumed that participants would have a poorer performance in precedence conditions with respect to the single control condition. Performances of sighted and visually impaired children about the same age are compared.

2. Method

2.1. Participants

A total of 6 visually impaired infants and toddlers (3 females and 3 males), but with no other disability, aged 9–37 months of chronological age (mean chronological age = 103 weeks; SD = 48 weeks) were included in this study. For three preterm infants of less than 24 months, corrected age was calculated. The blind group included five children blind from birth, with reduced light perception, and one child with severe visual impairment. Causes of the visual impairment were retinopathy of prematurity and bilateral congenital cataract (see Table 1). Participants were recruited from educational and early intervention institutions for visually impaired children of Córdoba, Argentina.

In addition, 45 full-term young children with normal vision were evaluated: fifteen 6 month old infants (6 females and 9 males; mean age = 27.8 weeks; SD = 1.2 weeks), fifteen 12 month old infants (8 females and 7 males; mean age = 53.3 weeks; SD = 1.6 weeks), and fifteen 18 month old toddlers (8 females and 7 males; mean age = 78.9 weeks; SD = 1.7 weeks).

Criteria for participation included surpassing a hearing screening for early detection of hearing loss and that the participants were free from colds and ear infections at least seven days prior to testing. The study received institutional approval. Prior to the participation of a child on the test, parents were asked to sign a consent form.

2.2. Stimuli

Stimuli were 25 ms wideband (500–8500 Hz) noise with 2 ms rise–fall times, presented with an signal-to-noise ratio greater than 20 dB, as measured at the approximate position of the child's head. Stimuli were generated using MATLAB (Mathworks Inc.) software. For each trial, the computer program generated a random noise from which an aleatory segment that formed the burst was extracted (in lead and lag discrimination trials the two bursts consisted of the same token of noise). During testing, stimuli were amplified and played back over loudspeakers.

Table 1
Blind participant by age, severity of impairment and cause of blindness.

Chronological age	Corrected age	Severity of impairment	Cause of blindness
9 months 3 weeks	7 months 1 week	Blindness (light perception)	Retinopathy of prematurity
17 months 3 weeks	16 months 2 weeks	Severe visual impairment	Retinopathy of prematurity
20 months 2 weeks	18 months 2 weeks	Blindness (light perception)	Retinopathy of prematurity
21 months 1 week		Blindness (light perception)	Bilateral congenital cataract
36 months 2 weeks		Blindness (light perception)	Retinopathy of prematurity
37 months 3 weeks		Blindness (light perception)	Retinopathy of prematurity

Each trial consisted of 15 noise bursts, presented at a rate of 2/s, according to three stimulus conditions: Single (control condition), Lead and Lag discrimination (precedence effect conditions). In the Single condition, the first 4 noise bursts were presented from midline, followed by 11 noise bursts presented randomly from either the left or right loudspeaker. In precedence effect conditions, trials also began with 4 single source noise bursts from midline. In the 11 bursts that followed, there were 2 noise samples per burst, with the onset of one delayed relative to the onset of the other by 5 ms. In Lead discrimination condition, the leading source came from the right or left (containing directional information) and the lagging source, from the middle (not containing directional information). In Lag discrimination condition, the leading source came from the middle and the lagging source from the right or left.

2.3. Apparatus

Testing was conducted in a sound-attenuated room (3.80 m long, 4.24 m wide, 2.54 m high, volume 41 m^3) with a reverberation time (RT60) of 540 ms. In the room, there was a conveniently located acoustically transparent dark curtain that hid the experimental setup. Listeners were seated facing an arc-shaped apparatus spanning 150° of an imaginary circumference in the horizontal plane with the infant situated at the center of a 165 cm radius. The apparatus has a graduated rule, three loudspeakers (Pioneer model TS-G1040), and a pulley system that allows moving the left and right mobile loudspeakers on the arc. Throughout testing, the center loudspeaker was fixed at 0°, whereas the other two were positioned at identical angles to the left and right of midline. All speakers had matching frequency responses within ±2 dB for all frequencies between 100 and 15,000 Hz. A MATLAB (Mathworks Inc.) program was developed for stimuli presentation, which was accomplished via a sound card (SoundBlaster PCI512) with a power amplifier (BOSS Rev-650). A video camera (Sony DCR-SR40) was positioned at 0° to get a front view of head, eye and torso movements of participants. Behind the curtain, there was a monitor that received input from the video camera and allowed to view the child's behavior and monitored the session.

Two equal reinforcers were located at 60° to the left and right from the infant. The reinforcer consisted of a mechanical toy situated in a smoked acrylic box. The toy remained silent and unseen until the reinforcer was activated, then the box was illuminated and, simultaneously, the toy moved rhythmically back and forth while playing children's music, providing a display interesting to both sighted and blind children (Fig. 1).

2.4. Procedure

Testing consisted of a single-interval 2-alternative-forced choice right/left discrimination task in the azimuthal plane. The participants were seated on their parent's lap facing the experimental setup. When an infant was quiet and facing directly ahead, a trial initiated. Two trained observers watched the participant through a video monitor and evaluated their behavioral responses according to the observer-based psychophysical procedure (Olsho et al., 1987). The observers had to press a button during the trial period to indicate a judgment that a change in the position of the source occurred (from the center to left/right). To estimate the MAA threshold, any child behavior was considered as a response, e.g. head turn, directional eye movement with head still or others. A correct judgment from the two observers resulted in the activation of a reinforcer on the correct side for 5 s. If both or one observer made an incorrect decision, no reinforcement was delivered and a time out period of 5 s ensued. If no directional motor response was made 5 s after the stimulus shifted from midline, the trial was considered a nonresponse trial and the procedure was the same as with incorrect trials. The infant received first two familiarization trials with the loudspeaker positioned on the maximum angular position.

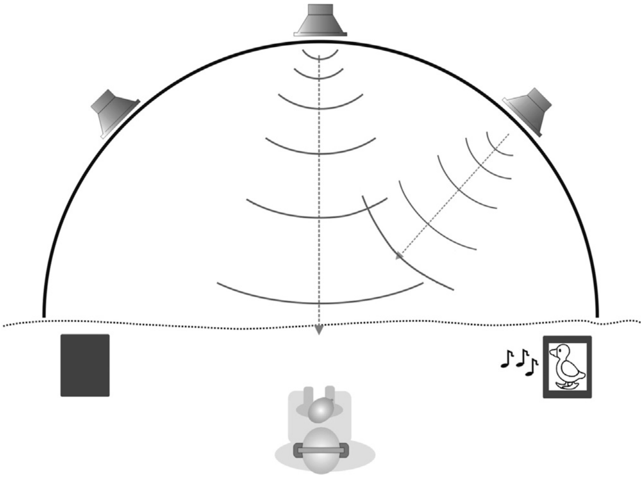

Fig. 1. Schema of the experimental setup. It illustrates a trial assessed as correct in a precedence condition.

Percent agreement and inter-rater agreement (kappa) for the two experimenters for all judgments in this study were 95% and .92 ($p = .000$) in single-source and lag condition, 94% and .90 ($p = .000$) in lead condition, respectively. Additionally, agreement was calculated by a pediatric audiologist, who evaluated a randomly selected sample of videotaped sessions. In this case, percent agreement and inter-rater agreement (kappa) were 91% and .87 ($p = .000$) in single-source, 89% and .84 ($p = .000$) in lead condition and 88% and .82 ($p = .000$) in lag condition, respectively.

Both observers and parents wore earplugs and ear muffs to avoid the possibility of them recovering information about directional auditory cues (Simpson, Bolia, McKinley, & Brungart, 2005) and in the case of the parents, this also prevented systematically cueing the child regarding stimulus location.

Each blind child resolved, on different days, the three experimental conditions, in a randomized order. In the normal vision group, within each age range, participants were randomly selected and assigned to one of three precedence conditions according to stimulus type (single source, lead or lag discrimination).

2.5. Data analysis

MAA values were estimated with the adaptive method applied in children by Litovsky (1997). Changes in the angular position of the loudspeakers were established using the two-down/one-up Levitt method (Levitt, 1971). For each adaptive track, MAA was calculated at the 71% correct point on a psychometric function. This method indicates that with two correct answers the loudspeakers' angular position has to decrease, while a single incorrect response implies it has to be increased. The initial angle was 55° for single source and lead condition; as for lag condition, it was 75°.

The test concluded once seven reversals were reached (which occurs when the angle is increased after a decrease or vice versa) or, earlier, if the child was fussy or lost interest, requiring at least four reversals to complete the test. The mean number of trials required to estimate MAA thresholds was 27.1 (range 16–40 trials). The MAA threshold was the angular value that would have corresponded in the next step after the last reversal.

In the case of the visually impaired group, differences in MAA thresholds among precedence effect condition (Single, Lead, and Lag) were analyzed using a Friedman Test and the p-values were determined on the exact distribution of the test statistic for small size samples. Significant differences ($p \leq .05$) were analyzed using the post hoc Nemenyi test (Demšar, 2006).

In regards to the sighted group, the influence of Age (6, 12, and 18 months) and Precedence Effect condition (Single, Lead, and Lag) on the MAA thresholds obtained by the participants was analyzed with a two-way ANOVA. Moreover, a separate analysis of the simple effects for each factor was performed. Significant F values ($p \leq .05$) were analyzed using post hoc Tukey's HSD test. When possible, a comparison was examined between the performance of visually impaired and sighted children grouped according to similar age. Differences between groups were analyzed using a Mann–Whitney U test and the p-values were determined on the exact distribution of the test statistic for small size samples.

Additionally, the video record of each child was scored independently by a naive experimenter to identify the type of behavioral response made on correct trials by blind and sighted children. The following types of auditory orienting behaviors were identified: (a) a single head turn (a head turn toward the right or left hemifield containing the sound source, so as to face the sound source with the face or ear), (b) several head turns (head turn to one side then to the other, once or more times, toward the right or left hemifield containing the sound source before facing the sound source with the face or ear), (c) eye movements with still head (eye movements toward the right or left hemifield containing the sound source while the head remains motionless), and (d) lateral inclination (leaning the head and body laterally toward one of the two hemifields).

3. Results

3.1. MAA thresholds obtained by blind and sighted children

Fig. 2 shows the estimated MAA for each visually impaired child and the mean MAA for sighted children of 6, 12, and 18 month old, for each precedence effect condition. As shown, all children had much higher MAA thresholds (a poorer performance) in the Lag condition (Fig. 2c) and, in general, they obtained similar thresholds in the Single and Lead conditions (Fig. 2a and b, respectively).

MAA values for each visually impaired child for Single, Lead, and Lag conditions can be found in Table 2. The youngest visually impaired infant (7 months corrected age and 9 months of chronological age) had the highest thresholds in the Single and Lag conditions. In the Lead condition, the younger and older visually impaired children showed the higher thresholds of the group.

The analysis of the Friedman Test performed showed significant differences between the MAA thresholds obtained by visually impaired children in each of the precedence effect conditions (Single, Lead, and Lag), $\chi_r^2 = 12$, $p = .000$. A Nemenyi post hoc procedure, for which the critical difference for $\alpha = .05$ was 1.353, shows that the mean MAA in Lag condition was significantly higher than those in Single and Lead conditions, and that the mean MAA in Single condition was significantly lower than that in Lead condition. Regarding to sighted children, mean MAA values (and standard deviations) obtained for the group of 6, 12, and 18 month old children, respectively, were 20.1° (3.2), 13.5° (3.8) and 8.4° (1.9) for single source; 20.7° (2.6), 16.1° (2.7) and 10.5° (3.8) for lead discrimination; and 69.4° (1.9), 68.5° (4.3) and 58.4° (4.2) for lag discrimination. The influence of the Precedence Effect condition and Age (6, 12 and 18 months) on MAA thresholds was analyzed. The analysis revealed main effects of Precedence, $F(2, 36) = 1136.24$, $p = .000$, $\eta^2 = .98$; and Age, $F(2, 36) = 39.54$, $p = .000$, $\eta^2 = .69$. Post hoc

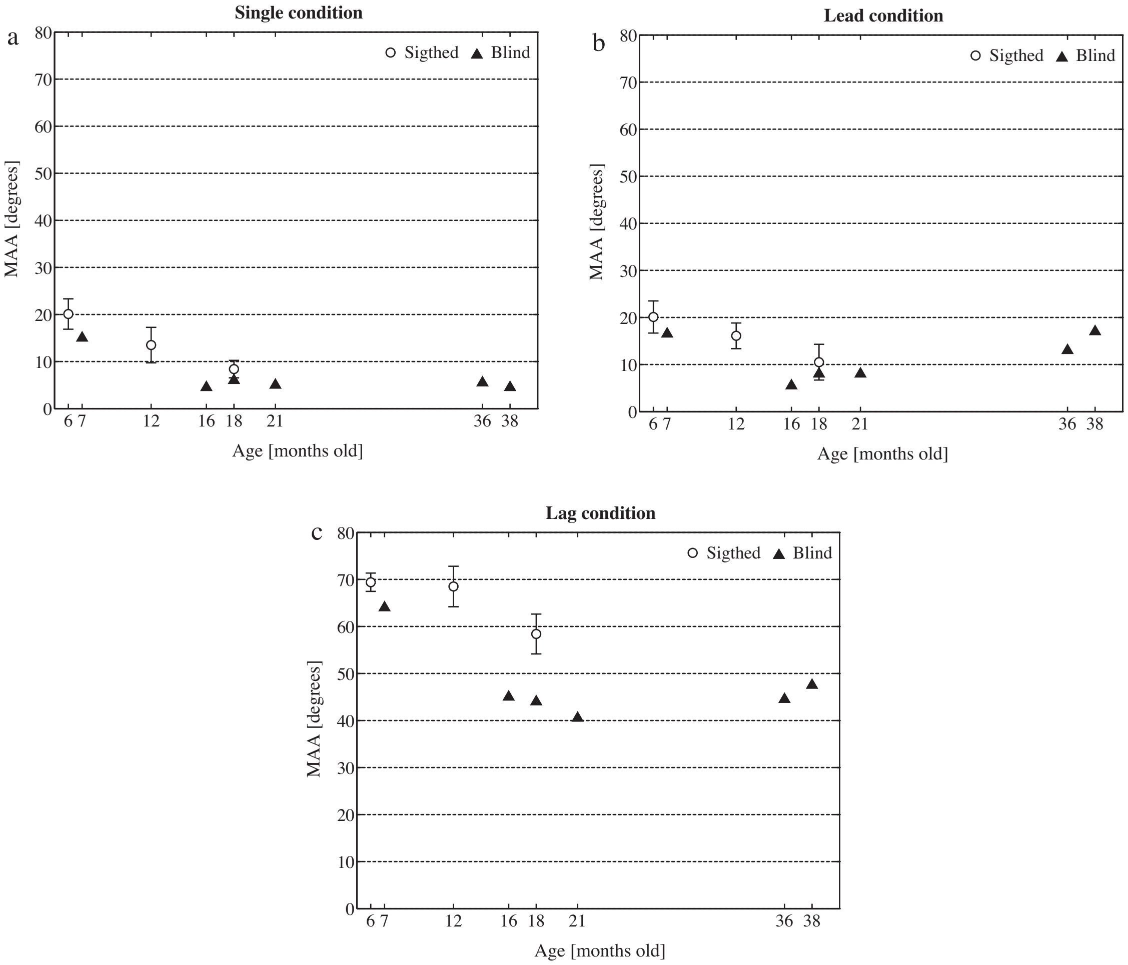

Fig. 2. MAA estimates for each age in the sighted and blind group in Single (a), Lead (b), and Lag conditions (c). For preterm blind children of less than 24 months corrected age is shown. Error bars represent ±1 standard deviation.

Tukey HSD test analysis shows for the first main effect that the Lag condition was significantly harder ($p = .000$) than the other two precedence conditions (Single and Lead), between which no major differences were found. The second main effect evidenced that (a) 6 month old infants had significantly higher MAA thresholds than 12 month olds ($p = .01$) and 18 month old children ($p = .000$), (b) 12 month olds had significantly higher thresholds than 18 month old children ($p = .000$). When analyzing the effect of Age (6, 12, and 18 months) on the MAA thresholds for each separate precedence condition (Single, Lead and Lag), it has been observed a significant main effect of Age in the Single, $F(2, 12) = 18.45$, $p = .000$, $\eta^2 = .75$; Lead, $F(2, 12) = 10.42$, $p = .000$, $\eta^2 = .63$; and Lag condition, $F(2, 12) = 13.91$, $p = .000$, $\eta^2 = .70$. Post hoc Tukey HSD test analysis revealed that (a) for the Single condition, 12 and 18 month old children, among which there were no statistically significant differences, performed on average significantly better than 6 month old infants ($p = .013$ and $p = .000$, respectively); (b) for

Table 2
MAA thresholds (in degrees) for each visually impaired child according to their age and precedence condition.

Age (months)[a]	Precedence condition		
	Single	Lead	Lag
7	15.0	16.5	64.0
16	4.5	5.5	45.0
18	6.0	8.0	44.0
21	5.0	8.0	40.5
36	5.5	13.0	44.5
38	4.5	17.0	47.5

[a] For preterm blind children of less than 24 months corrected age is shown.

Table 3
Percentage of correct trials by type of orienting behavioral response of blind and sighted children in each precedence condition.

	Blind group				Sighted group			
	Single	Lead	Lag	Total	Single	Lead	Lag	Total
Single head turn, face to sound source	72	44	51	56	94	94	95	94
Several heads turns, face to sound source	12	15	10	13	6	6	5	6
Eye movement with still head	5	31	26	20				
Several heads turns, ear to sound source	4	5	9	6				
Single head turn, ear to sound source	4	1		2				
Lateral inclination	3	4	4	3				

the Lead condition, average performance of 18 month old children was significantly better than 6 month olds ($p = .002$) but not better than 12 month olds. Furthermore, there were no significant differences on the average performance of this last group and that of the 6 month olds; (c) for the Lag condition, 18 month children performed on average significantly better than 6 and 12 month old infants ($p = .001$ and $p = .002$, respectively), among which there were no significant differences.

3.2. Comparison of MAA thresholds obtained by toddlers of about 18 months old

The comparison between MAA thresholds for each precedence condition of the 18 month old sighted group ($N = 5$ in each precedence effect condition) and the group of visually impaired children of similar age ($N = 3$ in each precedence effect condition; 16, 18, and 21 months; mean age = 18.3 months) revealed significant differences in favor of visually impaired participants for the Lag condition ($U = 0$; $p = .036$). Regarding the Single and Lead condition, mean MAA values for blind toddlers, 5.2° (0.8) and 7.2° (1.4) respectively, were lower than that of sighted children, 8.4° (1.9) and 10.5° (3.8) respectively, but the differences did not reach levels of statistical significance.

3.3. Auditory orienting behaviors

The video record of the session of each participant was analyzed in order to determine what type of auditory orienting behaviors could be noticed when there was a change to either right or left in the position of the sound, particularly, in the trials which were evaluated as correct. Table 3 shows the percentage of correct trials according to the type of behavior made by visually impaired and sighted children for each precedence condition.

First of all, it has been noted that the most frequent orienting behavior response for all experimental conditions was the single head turn so as to face the sound source. In the case of sighted children, this behavior occurred in 94–95% of the correct trials, whereas several head turns so as to face the sound source were made only in 5–6% of the cases. Visually impaired children, on the other hand, performed directional eye movements with still head (5–31% of the trials), single or several head turns so as to face the sound source with the ear (1–9% of trials), or leaned their head and body toward the correct hemifield (3–4% of the trials). These particular responses of the group of visually impaired children, and which were not present on sighted children, were generally more frequent in the Lead and Lag precedence conditions.

4. Discussion

The precedence effect is a spatial hearing phenomenon that has been studied mainly with adult participants. This ability is not present in newborns (Clifton et al., 1981; Morrongiello et al., 1982) and the first responses under precedence effect stimuli can be observed from 4 months old onwards (Muir et al., 1989). The purpose of the present study was to test the ability of infants and toddlers, with and without visual impairment, to discriminate changes in the right/left position of sounds configured under precedence effect conditions.

4.1. Performance on single condition

In the group of visually impaired children, it was noted that the highest MAA threshold for the Single condition (direct sounds) was reached by the youngest infant (15°, 7 month old of corrected age and 9 months of chronological age). For this condition, it was evidenced that there was a tendency to a better performance as the age of the visually impaired children increased. This result coincides with the obtained by sighted children for this condition: the mean MAA thresholds of the 12 and 18 month old children were significantly lower than the ones of the 6 month olds. These results concur with those reported by developmental research on localization thresholds of direct sounds in the horizontal plane, in which the MAA estimates procedure were applied (Ashmead, Clifton, & Perris, 1987; Litovsky, 1997; Morrongiello, 1988).

The performance of visually impaired children between 16 and 38 months of chronological age for the Single condition was homogeneous; MAA values were between 4.5° and 6°. These values are similar to the ones obtained by Litovsky (1997) for the Single condition in the 18 month group (5.65°) and are well below the ones reported by Grieco-Calub et al. (2008) for a group of sighted children of ages between 26 and 36 month old, who had an MAA threshold closer to 14°. In the latter case, the better performance of visually impaired children could be due to aspects related to the presentation of sound stimuli. While in the study of Grieco-Calub et al. the stimulus level was randomly varied, in the present research the level remained constant. Grieco-Calub et al. point out that the localization task could be more difficult for children when the intensity is roved.

Blind and sighted toddlers of similar age have similar performances for the Single condition. Although the mean threshold of blind children was slightly lower, differences did not reach statistical significance. The only study, to our knowledge, which estimates MAA in blind children tested participants with congenital or acquired blindness between 6 and 20 years old (14 years old as mean) and a sighted group with ages ranging between 12 and 15 years old. Results revealed that the mean threshold of visually impaired children (1.75°) was significantly lower than that of the sighted group (over 3°) (Ashmead et al., 1998).

4.2. *Performance on precedence conditions*

The results obtained showed that precedence condition had a significant effect on the MAA thresholds of visually impaired and sighted children, the Lag was more difficult than the Single and Lead conditions. These are expected results since it is easier to localize direct sounds, and, of the two precedence conditions, it is more difficult to discriminate changes in the position of the lag sound than changes in the lead sound (Arias, 2009; Litovsky & Macmillan, 1994; Litovsky, 1997; Perrott, Marlborough, Merrill, & Strybel, 1989). For the Lag condition, visually impaired and sighted children thresholds were still quite high in comparison with the ones reported by blind and sighted adults, which vary between 2° and 4° (Arias, 2009; Litovsky, 1997).

The mean thresholds of visually impaired and sighted children for the Lead condition were slightly higher than the MAAs for Single condition. The poorer performances on Lead condition suggest that the presence of the lagging source at midline could influence the children's ability to extract directional information from the lead. Nevertheless, these differences were not significant for the sighted group. Although Litovsky (1997) obtained significant differences between single and lead conditions, in another study, Litovsky and Godar (2010) found that, for echo thresholds lower than 10 ms, 4 and 5 year old children had a similar performance for lead and control condition in a dominance localization task. A similar performance for the Single and Lead conditions indicates that children are as good at discriminating changes in the position of the direct sounds as well as changes in the position of sources under precedence condition when the directional information comes from the leading source.

Regarding the performance of visually impaired children, the highest MAA thresholds (poorer performance) for the Lead condition, were those of the younger and older children (16.5° and 17°, respectively). Also, in the Lag condition it was noted that the lower performances were those of these two particular participants (64° and 47.5°, respectively). In reference to the Single control condition, for Lead-Lag precedence conditions there was a greater variability of the performance of visually impaired children, which possibly stems from the greater difficulty of the task and the individual differences in performance. It is worth mentioning that a recent study reported a high intra-group variability in the performance of 6 and 18 year old sighted children who were evaluated with the MAA estimates procedure, which diminished significantly as the age of the participants raised (Kühnle et al., 2013).

In regard to the group of sighted children, the performance on precedence conditions improved as the age increased. For the Lead condition, 6 month old infants had significantly higher mean thresholds than 18 month olds. In the case of 12 month old infants, they had better mean MAA thresholds than the 6 month olds, and poorer performances than 18 month old participants, even though such differences did not reach levels of statistical significance. In the most difficult Lag condition, only 18 month old children had significantly lower MAA thresholds (58.4°), while 6 and 12 month old infants had very high thresholds (approximately 70°), close to the upper limit resolution of the arc-shaped apparatus. It is worth pointing out that the mean thresholds obtained for the group of sighted 18 month old children for lead and lag precedence conditions (Lead: 10.5°; SD: 3.8°; Lag: 58.4°; SD: 4.2°) were lower and had less variability than the ones reported by Litovsky (1997) for a group of same age (Lead: 23.1°; SD: 11.1°; Lag: 64.6°; SD: 21.6°). These differences may be attributed to the implementation of the observer-based psychoacoustic procedure on this study, which could have favored the achievement of lower thresholds for the more difficult conditions as it considers any orienting behavior of the child for response evaluation.

As mean MAA values of visually impaired and sighted participants (averaging 18 months of age) were compared, it has been observed that, in both Lead and Lag conditions, visually impaired children averaged lower thresholds (a better performance) than sighted children, being the differences statistically significant for the most difficult Lag condition. These results are consistent with others that showed a better performance of blind adult participants in reflected sound localization tasks. A study with visually impaired and sighted adults, which analyzed the percept of discrimination suppression with the MAA procedure, exhibited a higher performance of visually impaired participants which was evidenced particularly in the most difficult Lag condition (Arias, 2009). Dufour, Després, and Candas (2005) analyzed the influence of irrelevant reflections in a sound localization task in sighted adults and adults with either congenital or acquired blindness. Participants were presented with a primary source localization task, which could be placed near a reflecting wall or not, without providing any information regarding the acoustic characteristics of the room or their own location within the environment. The results revealed that when near-the-wall sources had to be localized, the visually impaired participants of both groups had more errors than sighted individuals. The authors concluded that visually impaired individuals had a greater auditory sensitivity to the presence of reflections.

The neuropsychological mechanisms involved in the precedence effect and how they are modified by development remain little known. Studies performed on cats indicate that the ablation of the auditory cortex affects significantly its capacity to localize sounds under precedence effect conditions (Cranford, Ravizza, Diamond, & Whitfield, 1971; Whitfield, Cranford, Ravizza, & Diamond, 1972). It has been proposed that the initial stages of the fusion percept and localization dominance occur in the brain stem, at the level of the inferior colliculus (Litovsky & Delgutte, 2002; Litovsky & Yin, 1998a, 1998b; Tollin, Populin, & Yin, 2004) and electrophysiological evidence collected in adults shows the involvement of the auditory cortex in the suppression of the directional information contained in the lag sound (Liebenthal & Pratt, 1999). These last results coincide with the ones reported by subjective studies which state the importance of cortical level processing on this perceptual phenomenon. Premature infants of 10 months old of chronological age and 7 months of corrected age evidence an echo threshold similar to one of full-term infants at 7 months, that is to say, their performance corresponds with that of full term children who have a similar auditory system maturity level (Burnham, Taplin, Henderson-Smarta, Earnshaw-Brown, & O'Grady, 1993); children and adolescents between 6 and 16 years old with temporal lobe epilepsy with no associated pathologies, localize direct sounds but not sounds under precedence effect conditions (Hochster & Kelly, 1981).

4.3. *Auditory orienting behaviors*

The analysis of the types of auditory orienting behaviors performed by children when they answered correctly revealed qualitative differences between the performance of visually impaired and sighted children. While sighted children executed, in almost the entirety of correct trials (94–95%), a single head turn in order to face the sound source, visually impaired children presented this type of response in a lower proportion (44–72% of trials) and evidenced a wider variety of auditory orienting behaviors.

The head turn and the eye movements are fundamental components of the overall orientation response (Sokolov, 1963), which encompasses a series of physiological and behavioral changes that appear when confronted with a new and significant stimulus. Orientation is part of the process which makes it possible to focus on potentially relevant environmental situations for subsequent exploration (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000). The head turn allows the location of the sound source in the zone of maximum efficiency of the auditory system, which is $\pm 30^{\circ}$ from midline (Blauert, 1997). The head turns from one side to the other, in direction of the sound source, provide dynamic cues to resolve the ambiguities of the perceived source position and help to maximize the information provided by the binaural and monaural localization cues; i.e. interaural time difference (ITD), interaural level difference (ILD), and monaural filtering caused by interaction of the sound wave with the head, torso, and pinna (Perrott, Ambarsoom, & Tucker, 1987; Thurlow, Mangels, & Runge, 1967).

Frequently, some visually impaired children exhibited eye movements while their head remained still during stimuli presentation. Eye movements have been considered an early directional auditory response in sighted newborns (Butterworth & Castillo, 1976; Mendelson, Haith, & Gibson, 1976; Wertheimer, 1961) and in visually impaired infants (Prechtl, Cioni, Einspieler, Bos, & Ferrari, 2001). It has also been observed in adults with congenital blindness (Després, Candas, & Dufour, 2005), although the mechanisms involved in its preservation in the absence of visual stimuli remain unknown. In comparison with the head turn, it is less effective because it does not provide dynamic localization cues. This response was more frequent under Lead-Lag conditions (31% and 26% of trials, respectively) when compared to Single condition (5%), possibly due to the greater difficulty of the task.

It is worth pointing out that, in some trials, some visually impaired children faced the sound source with the ear, as if they "looked" with it. Very little is known about this behavior. Morrongiello et al. (1990) observed, in a localization task with sighted infants of 8–24 weeks old, the presence of head turns in the opposite direction of the sound source. Even though the incidence of this behavior was low (1–18% of correct trials), it was found that in older infants this response was significantly less frequent than in younger infants. While the head turn in order to face the source leads the binaural cues (ITD and ILD) to values close or equal to 0, the behavior of facing the source with the ear maximizes these differences. Leonhardt (2001) reported this behavior to be frequent in some visually impaired children and argued that it shows a preference to collect auditory information with one or another ear.

4.4. *Conclusions and recommendations*

This exploratory study measured the auditory localization ability under precedence effect condition in sighted and visually impaired children. The results suggested that developmental aspects of the precedence effect is not determined by early visual-spatial experiences: under some conditions, it could be demonstrated that blind toddlers better processed spatial information contained in reflected sounds when compared to sighted children of similar age. The observer-based psychophysical procedure proved to be a valuable technique to measure auditory localization acuity in infants and toddlers with visual impairment. Moreover, the evaluation of the videotaped session of each participant showed a specific auditory orienting behavior in the blind children group: the head turning behavior so as to face the sound source with the ear. This response (e.g., to a person who talks to him/her) is frequently misinterpreted in clinical settings as an indicator of refusal or lack of interest of the blind child.

It should be noted, however, that the small sample of blind infants and toddlers with normal audition and no other additional disability, which was possible to recruit for the study, limited the scope of the statistical analysis and it is not representative of the entire population of children who are blind. Future research with a larger sample of blind children should examine the effects of age and level of visual impairments on performance.

The pedagogical and clinical implications of these results, in early intervention, can be synthetized as follows: (1) the efficient processing of echoic information has relevance for navigation and echolocation in later stages of development (Wallmeier, Geßele, & Wiegrebe, 2013), therefore, it is important to elicit the interest of blind toddlers for the auditory and multimodal properties of reflective objects and surfaces; (2) the auditory cortex of an infant is modulated by the acoustic exposure through the adaptation to specific soundscapes provided by the culture (Blesser & Salter, 2006), consequently, everyday environments must provide blind children with a variety of opportunities so as to help them to get meaningful auditory information and motivation to perceive space by means of the sense of hearing.

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