Effect of early versus late onset of partial visual loss on judgements of auditory distance

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Abstract

Significance It is important to know whether early- versus late- onset vision loss are associated with differences in the estimation of distances of sound sources within the environment. People with vision loss rely heavily on auditory cues for path planning, safe navigation, avoiding collisions and activities of daily living. This is the first study of its kind.

Purpose Loss of vision can lead to substantial changes in auditory abilities. However, it is unclear whether differences in sound distance estimation exist in people with early-onset compared to late-onset partial vision loss, and to normal vision. We investigated distance estimates for a range of sound sources and auditory environments in groups of participants with early- or late-onset partial visual loss, and sighted controls.

Methods Fifty -two participants heard static sounds with virtual distances ranging from 1.2m to 13.8m within a simulated room. The room simulated either anechoic (no echoes) or reverberant environments. Stimuli were speech, music, or noise. Single sounds were presented and participants reported the estimated distance of the sound source. Each participant took part in 480 trials.

Results ANOVA showed significant main effects of visual status ($P<0.05$) environment (reverberant vs anechoic, $P<0.05$) and also of the stimulus ($P<0.05$). Significant differences ($P<0.05$) were shown in the estimation of distances of sound sources between early-onset VI participants and sighted controls for closer distances for all conditions except the anechoic speech condition, and at middle distances for all conditions except the reverberant speech and music conditions. Late-onset VI participants and sighted controls showed similar performance ($P>0.05$).

Conclusions The findings suggest that early-onset partial vision loss results in significant changes in judged auditory distance in different environments, especially for close and middle distances. Late-onset partial visual loss has less of an impact on the ability to estimate the distance of sound sources.

The findings are consistent with a theoretical framework, the Perceptual Restructuring Hypothesis, that was recently proposed to account for the effects of vision loss on audition.

Keywords: spatial hearing; vision loss; auditory; distance perception; sound localization

Loss of vision (full or partial) can have a substantial effect on auditory spatial abilities [1-3]. For some tasks, these changes lead to an enhanced auditory performance, as has been observed for blind individuals performing azimuthal localization [4,5], echolocation [6-8] or distance discrimination tasks [9,10]. For other tasks, auditory performance may be significantly degraded, as has been reported for blind individuals performing bisection [11] or elevation [12,13] tasks. These findings would have important clinical implications for people with vision loss, as they rely on auditory cues for various activities including path planning, orientation and obtaining spatial information about objects in the environment. As an explanation regarding why certain auditory abilities are enhanced while others become degraded, the Perceptual Restructuring Hypothesis, has been proposed. This comprises a framework of nine principles derived from a broad range of evidence from within the literature [45]. As an example, the principle "P2. Discrimination. The ability to discriminate small changes in sounds is improved by blindness" was based on published evidence that auditory discrimination abilities improve following complete vision loss [9,14,15]. Principle P9 in the framework informed existing evidence that age of onset of vision loss was a critical factor that affected changes in sensory abilities: "P9. Age of onset. Changes in auditory ability are greater the earlier in life that vision is lost." [16-18]. However, to date the majority of the studies in the literature investigating the effects of age of onset of visual loss have focused only on fully blind individuals (for a review, see [3]). Very little evidence exists on whether the same principles apply for people with partial vision loss, and no data exists on absolute distance judgement task. The current study investigated whether early versus late onset of partial visual impairment (VI) affects performance for an absolute distance judgement task. Some studies of fully blind participants are described briefly for various tasks before studies of participants with VI are presented.

Voss, Lassonde, Gougoux, Fortin, Guillemot, Lepore [10] tested fully blind participants with either early onset visual loss (who lost their vision before 11 years of age), late onset loss (who lost vision after 16 years of age) and sighted controls for a minimum-audible-angle discrimination task. Sounds were presented either in front of the interaural plane, or behind it. The performance (percentage of correct responses) for the front of the interaural plane was significantly higher for the early-onset group than for the late-onset and sighted groups both of whom performed similarly. For sounds presented behind the interaural plane, the early- and late-onset groups performed similarly, and this was significantly better than sighted controls.

Wanet, Veraart [19] examined a spatial localization for judging the distance of tones in near space in early- and late-onset blind groups, and sighted controls. Performance was impaired for the early-blind group only. Gougoux, Lepore, Lassonde, Voss, Zatorre, Belin [20] investigated frequency-change discrimination for early-onset, late-onset, and normally sighted participants. Early-blind participants showed significantly better performance than the other two groups. Wan, Wood, Reutens, Wilson [18] also reported enhanced performance for early- compared to late-onset blind participants for frequency discrimination and pitch-timbre categorization tasks. Taken together, these studies show differences in auditory spatial abilities and in frequency discrimination between those with early- and late-onset complete visual loss. Although late-onset loss is sometimes associated with changes in auditory spatial abilities, more often similar performance is reported when late-onset blind and sighted controls are compared.

The term VI (as used in the current study, which is also sometimes referred to as low vision) encompasses a range of conditions involving partial visual loss in which some vision is preserved [21-24]. It is distinct from full visual loss, which involves full blindness or light perception only [10,25-27]. Studies that have examined people with VI have reported auditory abilities that are either significantly enhanced, degraded or show no differences when compared to sighted controls. Poorer azimuth judgements by individuals with VI was reported by Lessard, Pare, Lepore, Lassonde [4]. For spatial auditory judgements, a shift in perceived sound location towards the center of an array of loudspeakers was observed compared to sighted controls[23]. Data from our lab has shown a greater severity of VI was associated with an increase in judged sound source distances (Kolarik *et al*) [28], and also participants with VI disrupted the relationship between judged room size and sound source distance [21]. On the other hand, other studies have reported an enhancement in auditory abilities in individuals with VI including auditory azimuth judgments [24], dynamic sound localization [29], and self-reported enhanced abilities to locate the position of the speaker during a conversation and to be able to follow as it switched from person to person in a conversation.[22] Other studies have shown no difference between VI and sighted controls for auditory abilities such as distance discrimination [9] and static sound localization [29].

There are currently no studies that have examined absolute distance judgments in early- and late-onset partial vision impairment. The aim of the current study was to investigate whether age of onset (before 10 years and after) affected absolute auditory distance judgements in people with VI. As previous studies reported that fully blind individuals with late-onset visual loss made spatial judgements similar to those for sighted controls for various tasks [19,20], it was hypothesized here that performance of judged distance would be greater for early-onset VI participants when compared to late-onset VI participants.

Materials and methods

Data collection used the same methods as reported by Kolarik, Raman, Moore, Cirstea, Gopalakrishnan, Pardhan [28].

Participants

In total, 52 participants took part in the experiment. They were recruited from Sankara Nethralaya Eye Hospital in Chennai in India. To avoid confounding effects of age, they were chosen to be aged 33 years or less. Participants were categorized into three groups: normally sighted controls (18 participants, 13 female, mean age 21 yrs, range 20-25 yrs), early-onset VI (24 participants, 10 female, mean age 23 yrs, range 18-31 yrs), and late-onset VI (10 participants, 2 female, mean age 23 yrs, range 18-33 yrs). The criteria for early- and late-onset VI, respectively, were for vision loss to occur before (early) or after (late) 10 years of age, similar to criteria used in the literature for fully blind individuals; Voss, Lassonde, Gougoux, Fortin, Guillemot, Lepore [10] defined early-onset as before 11 years of age. The late-onset VI group was relatively small as generally there is a low incidence of people with late onset VI who are younger than 33 years. However, similar group sizes have been used in other studies of VI, e.g. [5,20]. Group characteristics are shown in Table 1. Analyses of age across the three groups using one-way ANOVA, and visual acuity across the VI groups using an independent samples t-test, showed no significant differences ($P > 0.05$).

All participants were screened to ensure that they had normal or near-normal hearing, using procedures described by the British Society of Audiology [30]. Pure-tone average (PTA) better-ear hearing thresholds across 0.5, 1, 2, 4, 6, and 8 kHz were less than or equal to 25 dB HL. The experimental procedure and possible consequences were described to all participants, who then provided informed consent. The tenets of the Declaration of Helsinki were followed throughout testing. Ethical approval was given by the Anglia Ruskin University Ethics Panel as well as Sankara Netharalya Ethical Board.

TABLE 1. Details of participants with VI, including cause of visual loss, age of onset of visual loss group, age at testing, age of onset of visual loss, duration of visual loss, and better-eye visual acuity. LogMAR is the Logarithm of the Minimum Angle of Resolution.

Cause of vision loss, visual loss onset group	Age (yrs)	Age of onset of visual loss (yrs)	Duration of visual loss (yrs)	Better-eye visual acuity (LogMAR)
Hypoplastic Disc, early	25	Birth	25	0.40
Neuritis, early	23	1	22	0.40
Stargardt's, early	24	6	18	0.50
Bietti's crystalline dystrophy, early	31	4 months	31	0.50
Retinitis Pigmentosa, early	21	Birth	21	0.60
Retinitis Pigmentosa, early	20	Birth	20	0.60
Cone rod dystrophy, early	18	Birth	18	0.70

Stargardt's, early	31	Birth	31	0.70
Retinitis Pigmentosa, early	26	Birth	26	0.70
Familial Exudative Vitreoretinopathy, early	22	Birth	22	0.80
Nystagmus, early	20	Birth	20	0.90
Amblyopia, early	18	Birth	18	0.90
Stargardt's, early	21	Birth	21	1.00
Stargardt's, early	23	Birth	23	1.00
Hypoplastic Disc, early	24	Birth	24	1.00
Retinitis Pigmentosa, early	18	Birth	18	1.10
Stargardt's, early	23	Birth	23	1.10
Healed retinitis, early	23	Birth	23	1.10
Myopic maculopathy, early	29	Birth	29	1.18
Retinochoroidal Coloboma, early	23	Birth	23	1.18
Retinitis Pigmentosa, early	20	4	16	1.28
Cone rod dystrophy, early	18	Birth	18	1.28
Leber congenital amaurosis, early	22	Birth	22	1.28
Retinitis Pigmentosa, early	24	Birth	24	1.28
Retinitis Pigmentosa, late	20	12	8	0.40
Retinitis Pigmentosa, late	19	17	2	0.60
Marfan Syndrome, late	20	10	10	0.70
Stargardt's, late	33	28	5	0.70
Behcets, late	26	16	10	0.78
Vogt-Koyanagi-Harada, late	27	20	7	0.78
Retinitis Pigmentosa, late	25	14	11	0.90
Cone dystrophy, late	18	10	8	1.00
Retinitis Pigmentosa, late	18	11	7	1.10
Stargardt's, late	20	17	3	1.28

Apparatus and stimuli

Participants were tested in a quiet room using Sennheiser HD219 headphones. Stimuli were produced using techniques developed in previous experiments [9,31-34] within a large simulated room 35 m (length) x 30 m (width) x 10 m (height). An image-source model [35] was used to generate a simulated room that was either anechoic [36] or reverberant [37]. The reverberation time T60 (i.e. the duration needed for the sound level to reduce by 60 dB) was 700 ms, chosen to match prior work [32,37]. The image-source model generates a room impulse response between a simulated sound source position and a receiver. By convolving the room impulse response and a sound sample, stimuli were simulated at virtual distances from the listener at 1 m height, 0° elevation and 0° azimuth. In the reverberant room, the virtual position of the participant was in the near-left corner with the head at 30° relative to the longer wall, as shown in Fig. 1 of Kolarik, Raman, Moore, Cirstea, Gopalakrishnan, Pardhan [28]. Spatial rendering of the stimuli was produced by convolution of the direct sound component with a non-individualized head-related transfer function from a publicly available database [38].

The stimuli were speech, music, and broadband noise, as used in our previous work [28,32,33]. Speech sounds were 1.5-s sentences spoken by a male in English, sampled at 22.05 kHz, taken randomly from the Bench–Kowal–Bamford corpus [39]. All our participants were English literate. The music sound was a jazz trio lasting 7.3 s, sampled at 22.05 kHz [40]. The noise was 90 ms broadband (0.6–12 kHz) white noise, with rise/fall times of 10 ms, sampled at 44.1 kHz [10]. The simulated distances tested were 1.22, 1.72, 2.44, 3.45, 4.88, 6.90, 9.75 and 13.79 m [41]. The presentation level was 65 dB SPL (unweighted) at a virtual distance of 1 m, and the level reduced as the simulated distance from the listener became larger.

Procedure

Participants were blindfolded throughout the experiment. They were told to imagine that they were seated within a room with loudspeakers positioned directly in front of them at various distances. Participants were instructed that they would hear a series of single sounds that would be played at a range of distances and they should verbally report in metres and centimeters how far away the sound was after each presented. Their responses were recorded by the experimenter. The sounds were played in a pseudo-random order, in blocks of 80 trials. Within each block the stimulus type (speech, music, or noise) and room condition (anechoic or reverberant) were held constant. Prior training and feedback was provided. The response time was not limited. There were 480 trials in total over 6 blocks (order randomized): 10 repetitions for each of the 8 simulated distances for each block and 3 stimulus types x 2 room conditions. The experiment took 1 hour and 40 minutes.

Results

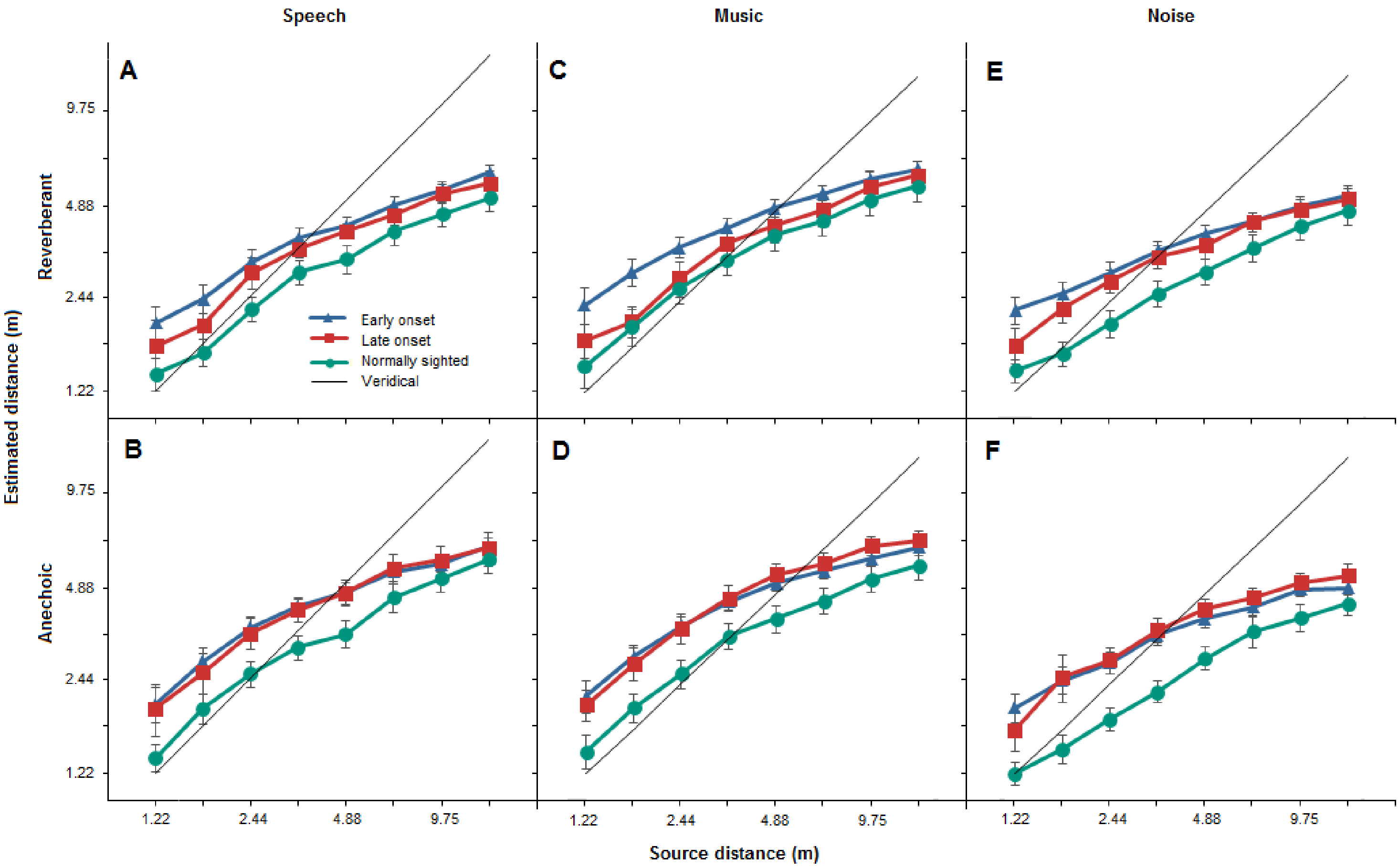

Figure 1. Estimated source distance judgements for each virtual source distance, both plotted on a logarithmic scale. Symbols show geometric mean data for normally sighted participants (green circles), early-onset VI participants (blue triangles), and late-onset VI participants (red squares). Solid line shows where the datapoints would lie if judgements were veridical. Data for speech, music, and noise are shown in the left, middle and right panels, respectively. The upper and lower panels show data for virtual reverberant and anechoic rooms, respectively. Error bars show ±1 standard error across participants.

Fig. 1 shows mean source distance judgements as a function of simulated source distance. In all conditions, normally sighted controls gave the most veridical judgements for the closest virtual sounds, and distance was systematic underestimated as the virtual distance increased. This has been reported in the literature. In all conditions, the distances estimated by the normally sighted controls were lower than for the two VI groups. Early-onset VI participants reported the furthest distance estimates. The distance estimates of the late-onset VI group appeared to lie in between those of the early-onset and normally sighted controls. Both early- and late-onset VI participants over-estimated the distances of closer sound sources, consistent with previous findings for blind individuals [31].

To assess the significance of the effects described above, data were first averaged over close (1.22–1.72 m), middle (2.44–4.88 m), and far (6.90–13.79 m) distances, following similar analyses in previous reports [21,28,42]. A mixed-model ANOVA was performed with within-subjects factors of virtual distance groups (three levels: close, middle and far), environment (two levels: anechoic and reverberant), and stimulus (three levels: speech, music and noise). Visual status was a between-subjects factor (three levels: sighted controls, early onset, late onset). The dependent variable was judged distance.

The ANOVA showed main effects of visual status ($F(2, 49) = 4.48$, $P = 0.016$, $\eta^2 p = 0.16$), reverberation ($F(1, 49) = 11.60$, $P = 0.001$, $\eta^2 p = 0.19$), distance ($F(2, 98) =$

563.65, $P = 0.001$, $\eta^2 p = 0.92$), and stimulus ($F(2, 98) = 16.42$, $P = 0.001$, $\eta^2 p = 0.25$). Significant interactions between environment and visual status ($F(2, 49) = 4.12$, $P = 0.02$, $\eta^2 p = 0.14$), distance and visual status ($F(4, 98) = 3.10$, $P = 0.02$, $\eta^2 p = 0.11$), stimulus and environment ($F(2, 98) = 7.49$, $P = 0.001$, $\eta^2 p = 0.13$), and stimulus and distance ($F(4, 196) = 5.09$, $P = 0.001$, $\eta^2 p = 0.09$) were shown. No other significant interactions were found (all $P > 0.05$). The significant interaction of distance and visual status reflects the finding that the differences across groups were greater for closer distances than for those further away. Post hoc t-tests with Bonferroni correction showed significant differences between the early-onset VI and the sighted group for closer distances for all conditions except the anechoic speech condition; at middle distances for all conditions except the reverberant speech and music conditions (table 2). Although these conditions showed significant differences in the analysis, these were not retained significant after Bonferroni correction. No significant differences were observed for any of the far distances. There were also no significant differences between the sighted controls and the late-onset VI group, or between the early-onset VI group and the late-onset VI group.

Table 2. Post hoc analysis showing significant differences between early onset and sighted controls for the different distances after Bonferroni correction. * denotes conditions that were significant in the analysis ($p<0.05$) but did not retain significance after Bonferroni correction was applied and therefore have been denoted as ns.

stimuli	Near	Mid	Far
Speech - Reverb	p=0.013	ns*	ns
Speech - Anechoic	ns*	p=0108	ns
Music - Reverb	p=0067	ns*	ns
Music - Anechoic	p=0110	p=0123	ns
Noise - Reverb	p=0.0035	p=0097	ns
Noise - Anechoic	p=0018	p=0.0027	ns

Discussion

The normally sighted controls generally gave the most veridical judgements for sounds presented at close distances, and systematically underestimated distances as the virtual source distance increased. This is consistent with reports in the literature for sound sources presented in real environments (for reviews, see [43,44]), and suggests that the virtualization methods utilized were adequate in simulating real-world environments.

It is appreciated that experimental conditions simulated in our experiment provided only limited cues to support distance judgements. In particular, for the simulated anechoic environment the only available cue was the sound level at the listener's ears. Although there was a significant effect of environment, the distance judgements were not markedly more veridical for the reverberant room than for the anechoic condition, even though the additional cue of direct-to-reverberant ratio was available for the former. This suggests that participants based their judgements largely on the level of the sounds reaching their ears. However, as data suggests the mapping of sound level to distance varied across groups, with differences across groups being greater for closer distances than further distances.

These findings can be interpreted in terms of the possible role of visual experience in calibrating auditory space. It has been shown that absolute judgments, particularly with limited acoustic cues, tend to be less accurate than body-related judgements.[45,46] For example Vercillo et al [45] showed that participants who were born blind performed much more poorly than sighted participants when they were required to localize brief auditory stimuli with respect to external acoustic landmarks or when they had to reproduce the spatial distance between two sounds. Such judgements require the calibration of auditory space using an external reference frame, which probably is much more accurate when visual information is available. In contrast, the blind participants performed similarly to sighted controls when they had to localize sounds with respect to their own hand (body-centred reference frame), or to judge the distances of sounds from their finger. Performance on these tasks may be based on calibration using tactile/haptic information rather than using visual information.

Our experiment most likely required the use of an external reference frame. None of the groups would have had much experience in judging the distance of sources that were 5 or more meters away from them, so far space was probably poorly calibrated for all groups, and this could account for the fact that differences across the groups were small (and not veridical) for the largest simulated distances. However, the sighted group would have been able to use visual information to calibrate auditory space for small to intermediate distances, and this could account for why, at these distances, the judgements of the sighted group tended to be more veridical than the judgements of the two VI groups, especially the early VI group.

Previous work has shown that early-onset blindness but not late-onset blindness leads to significant changes in auditory abilities [10,19,20]. The current results show that partial VI affects auditory distance judgements. The data are consistent with the notion that vision is required to calibrate auditory space, and that in general early-onset vision loss leads to significant changes in auditory ability, in line with the Perceptual Restructuring Hypothesis. [45] (Principle P6 from the Perceptual Restructuring Hypothesis states: Calibration requiring visual cues is important, and P9 states that Age of onset is important, respectively). P6 was based on evidence around the importance of visual calibration information for spatial tasks that relied heavily on accurate internal auditory representations of the external world in fully blind individuals [11-13], and the current results suggest that this also applies to partial visual loss. The current results are also consistent with other theoretical models, including the Crossmodal Calibration Hypothesis[16], which proposes that cross-sensory calibration occurs in the event of loss of a primary sense and that calibration is especially important in the early years of life, and the Perceptual Deficiency Hypothesis[47,48], which proposes that visual signals calibrate auditory spatial information. In general, these hypotheses have previously proposed explanations for the effects of full visual loss on the intact senses. Partial visual loss is distinct from full visual loss in a number of ways, including abnormal orienting behaviours resulting from partial visual loss, potential conflicts between auditory spatial maps obtained from peripheral vs. central vision, and deafferented brain areas not being recruited by the auditory system[4]. Despite these differences between full and partial visual loss, the current results suggest that the explanations for the effects of partial visual loss derived from the Perceptual Restructuring, Crossmodal Calibration, and Perceptual Deficiency hypotheses are also in line with the effects of partial sensory loss.

Further work is needed to investigate whether it is early onset vision loss *per se* that leads to significant changes in auditory abilities, and/or whether the overall duration of vision loss is the dominant factor. However, this would be difficult to assess, since early onset would lead to longer a duration of vision loss in a group of people with a fixed age range. Previous work using fully blind individuals showed that early age-of-onset but not duration of vision loss led to enhanced auditory abilities [18]. It is possible that a critical period in early development may play an important role in crossmodal calibration of the senses [16], and in studies of fully blind individuals, the effects of age of onset and/or duration of vision loss have been discussed in terms of the degree of crossmodal plasticity and the recruitment of visual areas of the brain to process auditory cues in the event of vision loss (for reviews, see [2,49,50]). Changes in neural processing resulting from full blindness have been reported to be dependent on whether blindness was early- or late-onset [17,51,52]. The effects of VI on crossmodal plasticity require further investigation, because existing (albeit partial) visual input may limit the recruitment of visual areas of the brain for auditory processing. Further investigation could also investigate the potential role of sex-related differences, or differences due to other demographic factors such as education, on auditory distance judgements in VI individuals. Previous work has shown sex-related differences in monaural vertical localization,[53] and target localization in the presence of a distractor sound,[54] and further work is needed to explore whether such differences extend to individuals with partial visual loss.

The effects of changing the criteria used to define early and late onset VI also warrant further investigation. In the current experiments, a cutoff of age of onset of 10 years was used to define early versus late onset loss, similar to the cutoff used in previous work investigating fully blind individuals [10,18,25]. Other studies have used an earlier cutoff age, such as 5 years [32,55]. In a study that measured performance for both congenitally blind and early-blind individuals (age of onset between 1.4 and 13 years), Wan, Wood, Reutens, Wilson [18] reported that for a frequency-discrimination task, the congenitally blind group showed better performance than matched sighted controls to a greater extent than the early-onset blind group, suggesting that loss of vision at birth may lead to greater changes in auditory ability compared to early-onset loss of vision. However, this has not yet been assessed for partially sighted individuals, and future work is needed to clarify exactly how changes in auditory abilities are affected by age of onset for this group.

In summary, the results showed that distance judgements were significantly different between early-onset VI participants and sighted controls for the close distances for all conditions except the anechoic speech condition, and at middle distances for all conditions except the reverberant speech and music conditions. This is the first study to report for absolute distance task. No significant differences between the sighted controls and the late-onset VI group were observed. Taken together, the results show that in general, early partial visual loss but not late onset visual loss leads to significant changes in auditory distance judgements.

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Figure legends

Figure 1. Estimated source distance judgements for each virtual source distance, both plotted on a logarithmic scale. Symbols show geometric mean data for normally sighted participants (green circles), early-onset VI participants (blue triangles), and late-onset VI participants (red squares). Solid lines show where the datapoints would lie if judgements were veridical. Data for speech, music, and noise are shown in the left, middle and right panels, respectively. The upper and lower panels show data for virtual reverberant and anechoic rooms, respectively. Error bars show ±1 standard error across participants.