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Sound localization with monocular vision

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Abstract

An experiment was carried out to determine whether sudden loss of vision in one eye would result in a bias in sound localization in the direction of the viewing eye. Fifteen normal-sighted young adults were tested binocularly and with the right or left eye covered. Within each vision condition, sound localization was assessed using three different arrays of six loudspeakers, positioned frontally and on the right and left sides of space, in combination with two stimuli, a one-third octave noise band centred at 4 kHz and broadband noise. These assessed the utilization of mainly the interaural level difference cue and binaural and spectral cues in combination, respectively. One block of 90 speaker identification trials was presented for each of the 18 conditions. For the lateral arrays in combination with the broadband noise stimulus, monocular vision resulted in decreased accuracy on the contralateral side. Errors were in the direction of the viewing eye. While monocularly resulted in performance decrements with the 4-kHz stimulus, the error pattern was not consistent. These results support the hypothesis of visually guided auditory adaptation of binaural and spectral cues in combination in response to sudden deprivation of vision in one eye.

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1. Introduction

The present study was designed to evaluate the effect of sudden deprivation of vision in one eye on accuracy in horizontal plane sound localization. Monocular vision loss may result from injury or clinical pathology [1,2]. The question of interest is whether an asymmetric visual dysfunction will have an immediate impact on directional hearing ability. This may have particular relevance for military field operations. Previous research has shown that the loss of vision binocularly impacts sound localization ability in human subjects [3,4]. Abel et al. [5], for example, found that the blindfolding of normal-sighted adult subjects resulted in deficits in the short term in horizontal plane sound localization that were similar to deficits found in subjects who had been blind from birth. Unlike the early blind, blindfolded subjects were able to improve their accuracy scores to near normal levels with practice [6]. The latter effect was also evident in individuals who became blind later in life. Although they reported that the loss of sight had initially negatively impacted their sound localization ability, laboratory studies showed that when tested at least five years after onset, they were actually significantly better than normal at utilizing sound localization cues, specifically interaural differences in intensity and spectral information, to discriminate among auditory spatial targets [5,7].

To date, there have been no investigations in human subjects of the effect on sound localization of sudden blindness in one eye. Human studies have, however, documented the phenomenon of rapid visual capture (the “ventriloquism effect”). Under conditions of conflicting visual and auditory spatial information, sound is perceived to be in the direction of the visual stimulus or coming from the object viewed [8]. Animal studies also support the conclusion that vision dominates and guides audition in the localization of spatial targets. In barn owls raised with prisms that displaced the visual field, auditory localization was altered over time in the direction of the visual displacement up to a limit of about 20° in azimuth angle [9–11].

The behavioural data are in line with the results of neurophysiological studies. Single cell recordings in barn owls in the area corresponding to the human mid brain show a shift in the interaural time of arrival difference of sound to which units produce their strongest response in the direction of sounds at the perceived visual displacement [12]. Removal of one eye at birth in guinea-pigs results in reduced topographical precision of auditory cells, both ipsilateral to and contralateral to the enucleated eye [13]. The underlying mechanism for these physiological and behavioural changes in audition is thought to be a re-labeling of binaural cues that signify auditory spatial position [14,15]. This re-labeling may be related to a shift in the visual egocentre (the reference for visual direction judgments) in the direction of

the viewing eye. This effect has been documented in both children and adults following the removal of one eye when they are forced to face the true visual straight ahead [16,17]. Auditory adaptation in the direction of the viewing eye serves to bring the auditory and displaced visual straight aheads back into alignment.

The aim of this investigation was to test the hypothesis that sudden loss of vision in one eye results in a systematic bias in auditory space perception in the direction of the viewing eye. Monocularity was achieved by covering one eye in normal-sighted subjects. Differences in sound localization on the right and left sides of space for both frontal and rearward spatial quadrants were compared for binocular and right and left monocular viewing conditions. An evaluation was also made of whether deprivation of vision in one eye differentially affected the utilization of mainly interaural level differences and binaural and spectral cues in combination. These are cues that are normally used for horizontal plane sound localization [7]. If, as suggested in previous human studies, monocularity results in a shift of the visual egocentre towards the viewing eye, and if binaural and spectral cues signifying the auditory straight ahead adapt to align with the shift in the visual straight ahead [14,15], then perceived location on the side of the covered eye should shift toward more forward positions, while perceived location on the side of the viewing eye should shift toward more rearward positions.

2. Experimental design

Subjects were tested individually while seated in the centre of a sound proof booth. This facility models listening in a small office [18]. In each subject, sound localization ability was assessed using three different arrays of six loudspeakers (frontal, left lateral and right lateral). These are shown in Fig. 1. For the frontal

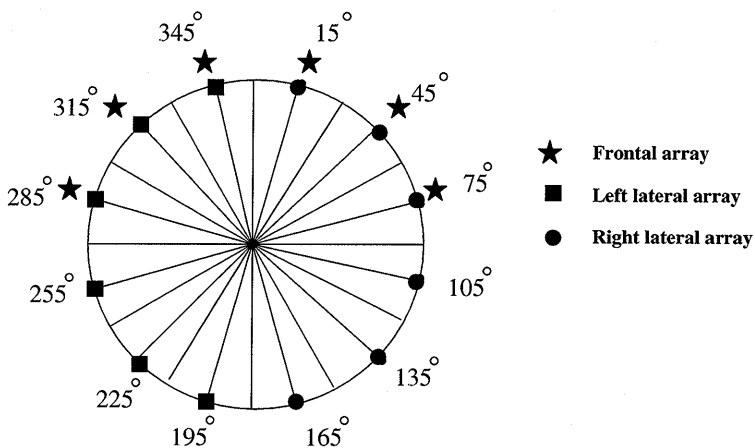


Fig. 1. The three speaker arrays.

array, the loudspeakers were positioned 30° apart at the following azimuth angles: 285° (−75°), 315° (−45°), 345° (−15°), 15°, 45° and 75° relative to the straight ahead (0°). The loudspeakers for the right lateral array were positioned in both the frontal and rearward quadrants at 15°, 45°, 75°, 105°, 135° and 165°. The loudspeakers for the left lateral array were positioned at 345° (−15°), 315° (−45°), 285° (−75°), 255° (−105°), 225° (−135°) and 195° (−165°). Previous research had shown that the ability to identify the position of a given speaker depends on the array in which it is embedded. Right–left confusions are rare. Front–back confusions are prevalent, particularly if spectral cues are unavailable [19]. Three different arrays were included in the present study to allow a separate assessment of the effect of monocularity on these two types of error, as well as on within-quadrant confusions. The speakers in each array were either right–left (frontal array) or front–back (lateral arrays) symmetric. All loudspeakers were placed at a distance of 1 m from the subject's centre head position, at the approximate height of the ears.

For each of the three arrays, accuracy in speaker identification was measured in each subject with both eyes uncovered (binocular), the left eye covered with an opaque eye patch (monocular right) and the right eye covered with the eye patch (monocular left). The eye patch was fitted by the tester. In each of the nine array by vision conditions, two stimuli were presented at a comfortable listening level of 70 dB SPL (sound pressure level): a one-third octave noise band centred at 4 kHz and broadband noise. These allowed an evaluation of the utilization of the interaural level difference cue and binaural and spectral cues in combination, respectively [7,20]. A low-frequency stimulus to evaluate the utilization of the interaural time-of-arrival difference cue was not included. Previous studies have demonstrated that blindness, actual or imposed, affects the interaural intensity cue (4 kHz), and binaural and spectral cues in combination (broadband noise) but not the interaural time-of-arrival difference cue. In both normal-sighted and blind subjects, low-frequency front–back discrimination has been shown to be close to chance [5,6].

The three arrays were presented on three different days (sessions) at least one week apart and their order was counterbalanced across subjects. The separation of arrays over time was designed to minimize the possible carry over of learning on performance. During each of the 60-min test sessions, the three vision conditions and two stimuli within each vision condition were counterbalanced across subjects to equalize fatigue and practice.

3. Methods and materials

3.1. Subjects

One group of 15 male and female subjects, aged 18–35 years, were recruited with the aid of an email sent to employees of Defence Research and Development Canada-Toronto. The upper limit on age was based on the previously reported finding of a decrease in accuracy of sound localization starting in the mid-30's, even for subjects with normal hearing [21]. All candidates were screened for a history of head

injury, severe systemic disease that might affect sustained attention and concentration, ear disease and hearing loss, as well as blindness in one or both eyes (including amblyopia). All subjects were right-handed to exclude the possible confounding effect of cerebral hemisphere dominance for processing spatial information [22].

Prospective subjects underwent a hearing screening test. Only those individuals with headphone pure tone hearing thresholds no greater than 25 dB HL in each ear at 0.5, 1, 2 and 4 kHz, in addition to an interaural difference no greater than 10 dB averaged across the four frequencies were admissible [23]. The latter requirement was designed to minimize bias in localization from asymmetrical hearing. Studies have shown that hearing loss, per se, is not a determining factor for accuracy in unoccluded sound localization, as long as the subject is able to perceive the stimulus [24].

3.2. Apparatus

The apparatus has been described previously [18,19]. The test facility was a double-walled semi-reverberant sound proof booth (IAC Series 1200) with inner dimensions of 3.5 (L) × 2.7 (W) × 2.3 (H) m. Reverberation times were 0.6 s at 0.125 and 0.25 kHz, 0.4 s from 0.5 to 4 kHz, and 0.3 s at 6.3 and 8 kHz. Ambient noise in the booth was less than the maximum allowed for audiometric testing [25]. The stimuli to be localized were generated by a noise generator (Bruel & Kjaer Type 1405) and a one-third octave bandpass filter (Bruel & Kjaer Type 1617). Stimulus envelope duration and shape (300 ms including a rise/decay time of 50 ms) and trial-by-trial loudspeaker selection were controlled by a Coulbourn Instruments modular system. Level was specified using a programmable attenuator (Coulbourn S85-08) and a set of integrated stereo amplifiers (Realistic SA-150). The stimuli were presented by a set of six loudspeakers (Radio Shack Minimus 3.5) closely balanced with respect to output levels (1.5 dB) and frequency response from 0.125 to 12 kHz (2.5 dB). Subjects signified their spatial judgments by means of a specially designed laptop response box with a set of six microswitches in the same configuration as the speaker array, both in number of elements and azimuth angles.

3.3. Procedure

One block of 90 forced-choice loudspeaker identification trials was given for each of the 18 combinations of speaker array (3), vision condition (3) and stimulus (2). A trial block comprised 15 random presentations of the stimulus through each of the six loudspeakers. The rate of presentation of trials was approximately one every seven seconds. Each trial began with 1/2 s warning light, followed by a 1/2 s delay and then the presentation of the 300-ms stimulus. The warning light was the subject's cue to sit squarely in the chair and to fixate a straight ahead visual target mounted on the wall of the booth. These measures helped to ensure the alignment between the speaker array and coordinates of the head and helped to minimize head movement, a possible confounding variable [26,27]. Peripheral visual targets mounted on both

sides of the central target were used as guides to help subjects minimize head turn towards the central target in the monocular vision conditions.

Following each stimulus presentation, the subject was required to push the micro-switch on the laptop response box corresponding to the loudspeaker that had emitted the stimulus. Guessing, if uncertain, was encouraged and no feedback was given about the correctness of the judgments. On each trial, the stimulus azimuth, the response azimuth selected and the time taken to make a judgment (from the termination of the stimulus) were automatically recorded. Response time (RT) was measured covertly so as not to compromise accuracy [28]. A set of two practice trials/loudspeaker with feedback (i.e., 12 trials) using the binocular vision and broadband stimulus combination was given at the start of the experiment to provide the subject with a spatial sense of the loudspeaker array relative to the response buttons, and to ensure that the instructions have been understood. The loudspeaker array used for the practice was the first array designated in the pre-determined order for each subject. Thus, across subjects the effect of practice was counterbalanced for the three arrays.

4. Results

Both percent correct sound localization judgments, $P(C)$, and the median response time were calculated for each block of trials. The median response time was chosen in preference to the mean because of previously demonstrated skewness in response time data [29]. The effects on sound localization of array (frontal, right lateral and left lateral), vision condition (binocular, monocular right eye and monocular left eye) and stimulus frequency (4 kHz and broadband) were assessed using repeated measures analyses of variance (ANOVA).

Table 1 shows the mean percentage correct sound localization judgments, $P(C)$, for each of the 18 array, by vision by stimulus conditions, averaged across azimuth angles and subjects. The ANOVA applied to these data [30] showed significant effects of array ($p < 0.004$), vision ($p < 0.0001$), stimulus ($p < 0.0001$), array by stimulus ($p < 0.003$) and array by vision by stimulus ($p < 0.002$). Post hoc pairwise

Table 1
Overall accuracy in horizontal plane sound localization

Speaker array	Stimulus	Vision condition		
		Binocular	Monocular right	Monocular left
Frontal	BB	98.6 (1.8)	98.2 (2.5)	97.9 (2.9)
	4 kHz	75.8 (11.3)	74.2 (11.6)	75.9 (10.9)
Right lateral	BB	92.6 (6.0)	93.9 (5.6)	87.5 (7.8)
	4 kHz	60.0 (11.6)	52.3 (13.4)	54.4 (12.3)
Left lateral	BB	90.7 (6.1)	82.9 (10.8)	87.7 (8.2)
	4 kHz	58.9 (15.0)	55.7 (16.9)	55.8 (17.6)

*Mean $P(C)$ (SD), $n = 15$.

comparisons using Fisher's LSD test ($p < 0.05$ or better) indicated that, averaged across array and vision condition, $P(C)$ was higher by 30% with broadband noise than with the 4-kHz stimulus. With the broadband noise, the vision condition had no effect for the frontal array (98%). For the right lateral array, there was a decrement in $P(C)$ of 6% for monocular left relative to binocular and monocular right vision (93%). For the left lateral array, there was a decrement of 6% for monocular right, relative to binocular and monocular left vision (89%). With the 4-kHz stimulus, again the vision condition had no effect for the frontal array (75%). For the right lateral array, the two monocular conditions resulted in decrements of 7% relative to the binocular condition (60%) but were not different from each other. For the left lateral array, the vision conditions were no different (57%).

The mean median RT for each of the 18 conditions, averaged across subjects, is shown in Table 2. An ANOVA applied to these data indicated significant effects of array ($p < 0.0001$) and stimulus ($p < 0.0001$). Vision was not a significant determinant of outcome. Averaged across array and vision, subjects took 175 ms longer to respond to the 4-kHz stimulus than the broadband noise. Averaged across stimulus and vision, subjects took 221 ms longer to respond to the lateral arrays than the frontal array.

Table 3 shows the percentage of quadrant reversal errors (right–left or front–back), averaged across the 15 subjects, for the 18 experimental conditions. These data indicate that for the frontal array the likelihood of confusing the right and left quadrants was virtually negligible, regardless of the vision condition or stimulus. For the two lateral arrays, the percentage of back given front (B/F) and front given back (F/B) errors ranged from 0.5% to 7% for the broadband noise stimulus and from 13.8% to 28.1% for the 4-kHz stimulus, across the three vision conditions. A four factor (vision, side of array, stimulus and error type) repeated measures analysis of variance (ANOVA) applied to the data for the right and left lateral arrays indicated that the only significant factor was the stimulus ($p < 0.0001$). A similar likelihood of occurrence for front–back reversal errors has been observed previously for the 4-kHz stimulus with an array of speakers surrounding the subject [5,6].

Fig. 2 shows the mean $P(C)$ as a function of azimuth angle. Results are presented in separate panels for three arrays (top, middle and bottom panels) in combination

Table 2
Overall response time in horizontal plane sound localization

Speaker array	Stimulus	Vision condition		
		Binocular	Monocular right	Monocular left
Frontal	BB	364.0 (145.2)	389.7 (166.1)	402.5 (119.4)
	4 kHz	520.4 (157.9)	544.8 (157.2)	510.3 (170.8)
Right lateral	BB	551.6 (140.1)	591.3 (141.4)	588.9 (179.4)
	4 kHz	722.7 (182.0)	848.4 (302.4)	755.7 (244.4)
Left lateral	BB	564.6 (165.8)	629.3 (174.1)	552.7 (153.8)
	4 kHz	761.1 (184.7)	791.3 (185.0)	752.1 (243.2)

*Mean RT (SD), $n = 15$.

Table 3
 Quadrant reversal errors

Vision	Stimulus	Speaker array					
		Frontal		Right lateral		Left lateral	
		R/L ^a	L/R	B/F	F/B	B/F	F/B
Binocular	BB	0.1 (0.5) ^b	0.0 (0.0)	1.5 (2.8)	1.5 (1.8)	4.7 (6.7)	3.4 (3.5)
	4 kHz	0.1 (0.5)	0.1 (0.5)	21.3 (19.3)	16.7 (24.8)	19.4 (13.9)	13.8 (18.7)
Monocular right	BB	0.0 (0.0)	0.0 (0.0)	2.5 (3.0)	0.5 (0.9)	7.0 (7.3)	6.2 (7.6)
	4 kHz	0.5 (1.8)	0.0 (0.0)	26.5 (24.6)	20.2 (23.0)	23.6 (17.7)	17.8 (19.5)
Monocular left	BB	0.0 (0.0)	0.0 (0.0)	4.8 (4.7)	3.7 (3.3)	4.5 (5.6)	3.7 (4.1)
	4 kHz	0.0 (0.0)	0.1 (0.5)	28.1 (18.1)	16.1 (12.5)	21.6 (18.1)	16.1 (23.1)

^a R/L, right response given left stimulus; L/R, left response given right stimulus; B/F, back response given front stimulus and F/B, front response given back stimulus.

^b Mean percentage of reversal errors (SD), $n = 15$.

with the two stimuli (left and right panels). The parameter within each panel is the vision condition. For each of the six array by stimulus conditions, the pattern of outcomes appears to be similar for the three vision conditions. For the frontal array (top panels), vision had no effect for either stimulus. When broadband noise was presented, subjects achieved close to 100% correct for each of the six locations on the right and left sides of space. In contrast, with the 4-kHz stimulus accuracy was higher for the midline positions, $\pm 15^\circ$, than the lateral positions, $\pm 45^\circ$ and $\pm 75^\circ$. This same outcome has been previously reported for speaker arrays surrounding the subject [6] and limited to either the frontal or lateral spatial quadrants [19]. A three-factor (vision by stimulus by azimuth) repeated measures ANOVA applied to these data indicated that stimulus, azimuth and the stimulus by azimuth interaction were significant ($p < 0.01$ or better).

When the broadband noise was combined with the lateral arrays, regardless of the vision condition, $P(C)$ was relatively greatest for positions close to the midline axis ($\pm 15^\circ$ and $\pm 165^\circ$) than the interaural axis of the head. This trend has been reported previously for arrays surrounding the subject [6]. For the right lateral array (middle left panel), $P(C)$ was relatively lowest when the right eye was covered (i.e., monocular left). For the left lateral array (bottom left panel), $P(C)$ was relatively lowest when the left eye was covered (i.e., monocular right). The difference due to the vision condition increased with azimuth angle from $\pm 45^\circ$ to $\pm 135^\circ$. No such consistent patterns emerged for the 4-kHz stimulus (middle and bottom right panels). A four-factor (vision by side of array by stimulus by azimuth) repeated measures ANOVA applied to the data for the two lateral arrays showed significant effects of vision, stimulus, azimuth, stimulus by azimuth, vision by array by stimulus, and vision by array by stimulus by azimuth ($p < 0.01$ or better). Post hoc pairwise comparisons using Fisher's LSD test indicated that for the broadband noise stimulus, with the right lateral array, at azimuth angles of 105° and 135° the $P(C)$ achieved with monocular left vision was significantly less than the $P(C)$ achieved with either binocular or monocular right vision which were no different. The reverse outcome was

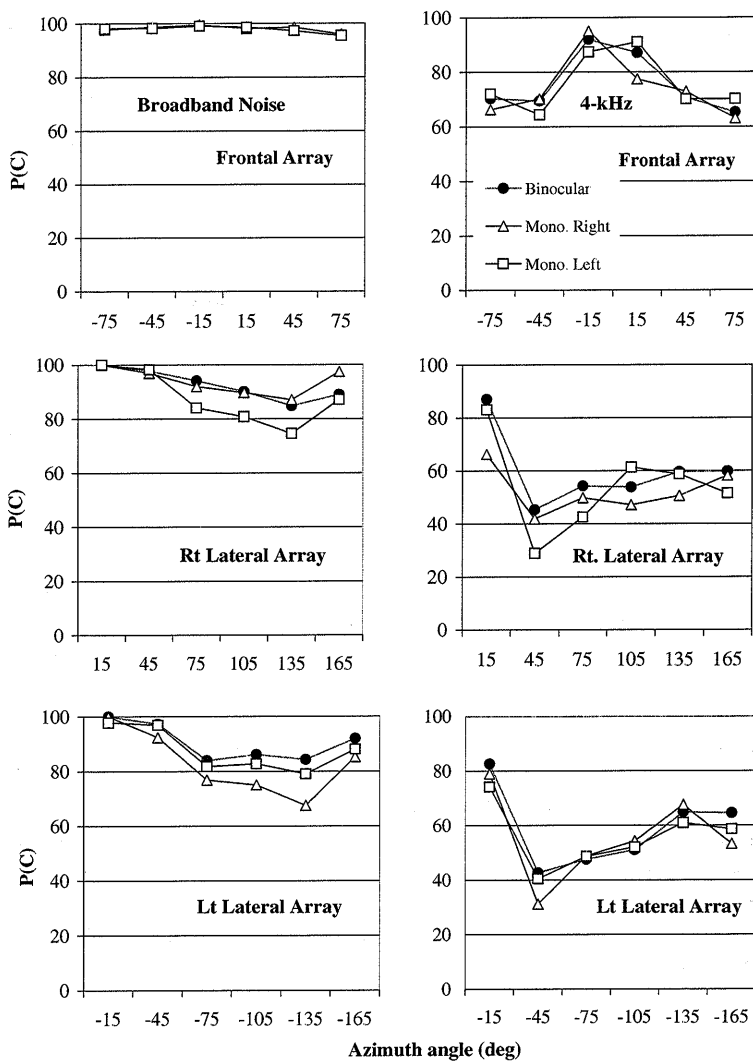


Fig. 2. Azimuthal accuracy in horizontal plane sound localization for the six array by stimulus conditions. The three vision conditions (binocular, monocular right and monocular left) are compared within panel.

observed for the left lateral array at -135° (i.e., $P(C)$ was significantly less for monocular right vision). Significant differences ranged from 9% to 14%.

Fig. 3 shows the probability of utilizing each of the six response azimuths, averaged across subjects, for the 105° and 135° azimuth angles (top and bottom panels, respectively) for the left and right arrays (left and right panels), in combination with the broadband noise stimulus. The three vision conditions are compared within each panel. These show that decrements in performance were due to subjects' perceiving

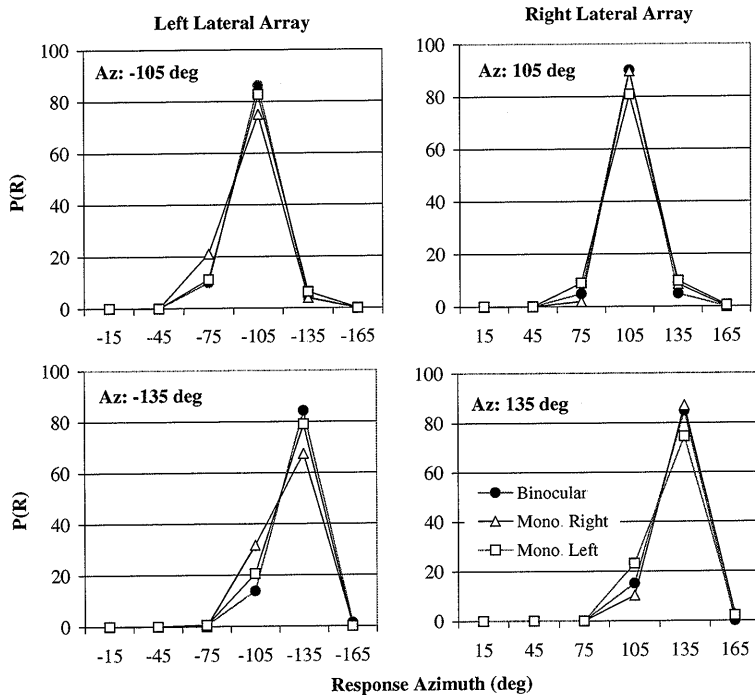


Fig. 3. The probability of utilizing each of six response azimuths, $P(R)$, for two target azimuths ($\pm 105^\circ$ and $\pm 135^\circ$) embedded in the left and right lateral arrays for the broadband noise stimulus.

the sound source in the direction of the viewing eye. Thus, for example, when the stimulus was presented from the speaker located at -135° in left lateral array (bottom left panel) and viewing was with the right eye, on 32% of the trials subjects reported that the stimulus had been presented from the speaker located at -105° . By comparison, when the stimulus was presented at $+135^\circ$ in the right lateral array (bottom right panel) and viewing was with the left eye, on 23% of the trials subjects reported that the stimulus had been presented from the speaker located at $+105^\circ$.

5. Discussion

The results of this experiment demonstrate that sudden deprivation of vision in one eye in normal-sighted adult subjects results in significantly decreased and systematic, albeit small, decrements in the accuracy of horizontal plane sound localization for the lateral arrays, for both a broadband noise stimulus and a narrowband stimulus centered at 4 kHz. Regardless of the viewing condition, accuracy was lower with the 4-kHz stimulus (availability of mainly the interaural level difference cue) than with the broadband noise stimulus (availability of both binaural and spectral cues in combination), as demonstrated previously [21]. With the broadband noise, discriminating among the six speakers on the right side of space while viewing

through the left eye or discriminating among the six speakers on the left side of space while viewing with the right eye resulted in a decrement of about 6% compared with viewing either with both eyes or the eye on the side of the array. With the 4-kHz stimulus, monocular viewing with either eye resulted in a decrease of about 7% in judging the right lateral array. Monocular viewing did not, however, affect response time, suggesting that the level of difficulty of the task had not changed. This result contrasts with Abel and Paik's [6] finding of longer response times in blindfolded than normal-sighted subjects. The difference may be due to greater difficulty in finding the response keys by subjects totally without vision.

For the broadband noise stimulus in combination with the lateral arrays, the probability of correctly localizing azimuth decreased systematically as the target speaker location moved toward the rearward quadrants (e.g., from $\pm 45^\circ$ to $\pm 135^\circ$) when the viewing eye was on the side contralateral to the array. For two azimuthal positions (105° and 135°), for which this decrement was significant relative to both binaural vision and viewing with the ipsilateral eye, it was possible to demonstrate that decreased accuracy was due to a greater likelihood of judging sounds as coming from the more forward speaker. This finding is in line with the premise of rapid short-term auditory adaptation which serves to bring the auditory and displaced visual straight aheads into alignment [8]. Contrary to the prediction, a bias toward rearward positions on the side of the viewing eye was not demonstrable. This outcome along with the absence of a difference in the pattern of quadrant reversal errors suggest that auditory adaptation was limited to the immediate vicinity of the target speaker, i.e., no more than the interspeaker distance of 30° . Auditory adaptive shifts of up to 5° have been previously been documented for shifts of flashing lights in the order of 20° [8].

The results taken together support the conclusion that a systematic auditory bias in localization directed by visual impairment can occur in the short term in adult human subjects, without an extended period of adaptation. Although decrements in accuracy were found for both stimuli, the systematic bias observed for the broadband noise stimulus and the absence of an effect for the frontal array suggests that adaptation involves a re-labeling of spectral information provided by the pinnae of the ears in the front-back dimension. The inability to demonstrate significant directional biases for all six azimuths in the lateral arrays may have been due to: (1) the small number of presentations of the stimulus from each speaker, (2) the unavailability of response azimuths in addition to those in the speaker set, and (3) small head movements which might have negated the shift of the visual egocentre [16,17]. In addition to addressing these possible contributors to outcome, future research should investigate the effects of long-term practice on auditory adaptation to asymmetric visual handicap.

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