# VERTICAL SOUND LOCALIZATION IN LEFT, MEDIAN AND RIGHT LATERAL PLANES

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## ABSTRACT

A few studies have reported better auditory localization under binaural listening for sounds presented from the left side of midline compared to the right. That asymmetry was attributed to a superior ability to resolve front/back confusions in the left hemifield. This research further investigated asymmetric effects in an experiment assessing vertical localization in three lateral planes perpendicular to the interaural axis (median, left and right). Eleven sources spaced at 18-deg intervals were arrayed around the upper half of the cone-of-confusion intersection in each plane. Subjects (15 males, 9 females) were required to identify the direction of incidence of a 250-ms band-limited white noise stimulus (250-8000 Hz). Statistical analyses performed on the proportion of correct responses and on three different angular error measures did not uncover any significant effect in performance for sources on the left versus right side of subjects. However, significant gender differences favoring male subjects were found for the variable and total error measures. This finding may be a purely physical effect due to the smaller size of female ears on average or related to cognitive effects. Results must be viewed in light of the wide distribution of response patterns from subject to subject; while most responded symmetrically and over the entire localization array, some had distinctive asymmetrical behaviors and/or systematic response biases in specific sectors of the localization array.

## SOMMAIRE

Quelques études ont rapporté une meilleure capacité de localisation lors de l'écoute binaurale pour des sons présentés à la gauche, comparativement à la droite, de la ligne médiane. Cette asymétrie a été attribuée à une capacité supérieure à résoudre les confusions avant/arrière dans le demi-champ gauche. Cette étude a examiné davantage de tels effets asymétriques lors d'une expérience portant sur la localisation verticale dans trois plans latéraux perpendiculaires à l'axe interaural (médian, gauche et droit). Onze sources sonores séparées de 18 degrés étaient réparties sur la moitié supérieure de l'intersection entre le cône de confusion de chaque plan. Les participants (15 hommes et 9 femmes) devaient identifier la provenance d'un stimulus constitué d'une bande limitée de bruit blanc (250-8000 Hz) de 250 msec. Des analyses statistiques effectuées sur la proportion de bonnes réponses ainsi que sur trois différentes mesures d'erreur angulaire n'ont pas révélé de différence significative dans les performances de localisation pour les sources à la droite et à la gauche des participants. Par contre, un effet significatif du genre favorisant les hommes a été noté pour les mesures d'erreur variable et d'erreur totale. Ce phénomène pourrait être relié au fait que les oreilles des femmes sont plus petites que celles des hommes en moyenne ou indiquer des différences cognitives. Les résultats doivent être interprétés avec prudence étant donné l'étendue interindividuelle importante de la distribution des patrons de réponse. Quoique la plupart des participants ont répondu symétriquement et sur toute l'étendue de l'arc de localisation, d'autres présentaient des réponses distinctivement asymétriques et/ou teintées d'un biais systématique pour certains secteurs de l'arc de localisation.

## 1. INTRODUCTION

It is generally recognized that accurate sound localization in three-dimensional space relies on both binaural and monaural cues. While localization in the horizontal or azimuthal plane is based mainly on binaural cues, such as the interaural time and level differences, localization in the vertical mid-sagittal plane or judgment of sound elevation is primarily dependent on monaural spectral cues from the filtering effects of the pinna, head and body (Hebrank and Wright, 1974; Asano et al., 1990; Blauert, 1997). Spectral cues have also been shown to help resolve the various locations on a cone-of-confusion, positions characterized by equivalent interaural differences, thereby reducing front/back and up/down discrimination errors in lateral planes parallel to the mid-sagittal plane (Morimoto and Aokata, 1984).

Animal studies have shown that the cerebral hemisphere contralateral to a sound source is more predominantly activated in response to the source than the ipsilateral hemisphere, suggesting that the left and right hemispheres may be important in localizing sounds in the right and left hemifields, respectively (Neff and Casseday, 1977; Jenkins and Masterton, 1982; Jenkins and Merzenich, 1984). Asymmetrical activation of the brain to sound stimuli has also been reported in several human studies (Reite et al., 1981; Pantev et al., 1986; 1998; Tiihonen et al., 1989; Makela et al., 1993; Woldorff et al, 1999; Kaiser et al., 2000; Kaiser and Lutzenberger, 2001; Richter et al., 2009). Moreover, hemispheric differences in auditory processing exist in many species, such as the rat (Fitch et al., 1993) and Mongolian gerbil (Wetzel et al., 1998) as well as in humans (Hellige, 1990; Fitch et al., 1997; Patterson et al., 2002). In a review of evidence, Zatorre et al. (2002) argue that the left hemisphere is better at resolving temporal information necessary for speech understanding whereas the right cortical areas are better at analyzing spectral information critical to music perception. The right hemisphere's greater involvement in spatial hearing is also supported by findings of many electrophysiological, magnetoencephalograpy, lesion and imaging studies (Altman et al., 1979; Ruff et al., 1981; Bisiach et al., 1984; Griffiths et al., 1998; Tanaka et al, 1999; Weeks et al., 1999; Itoh et al., 2000; Kaiser et al., 2000; Palomäki et al., 2000; Kaiser & Lutzenberger, 2001; Zatorre and Penhune, 2001; Ducommun et al., 2002, 2004; Fujiki et al., 2002; Lewald et al., 2002; Arnott et al., 2004; Krumbholz et al., 2005; DeSantis et al., 2007; Spierer et al., 2009). Fujiki et al. (2002), for example, investigated auditory space representation in the human auditory cortex to changes in the azimuth and elevation of a virtual sound source. Their findings suggest that sound azimuth is analyzed mainly in the cortex contralateral to the sound source, whereas spectral cues critical to judgments of elevation are analyzed more extensively by the right hemisphere.

Given a dominant activation in the hemisphere contralateral to the stimulated ear, a right-hemisphere specialization for spectral processing, and the importance of spectral information in spatial hearing, a left-ear advantage can be hypothesized in the ability of localize sounds. Although a left/right (L/R) asymmetry has not been demonstrated in all human studies on normal subjects or those with brain lesions (Sanchez-Longo et al., 1957; Sanchez-Longo and Forster, 1958; Fritze et al., 1973; Oldfield and Parker, 1984; Poirier et al., 1993), a right-hemisphere dominance in the analysis of spectral information has been reported in some studies, as demonstrated by a greater accuracy in localizing sounds emanating from the left hemifield or when listening with the left ear in some situations (Ivarsson et al., 1980; Duhamel et al., 1986; Butler, 1994; Burke, et al., 1994; Abel et al., 1999; 2000; Savel, 2009).

Ivarsson et al. (1980), for example, tested vertical localization of band-pass noise presented binaurally or monaurally over four loudspeakers placed in the mid-sagittal plane at 11° intervals. A foam plug (experiment 1) or masking noise (experiment 2) was used to block the left or right ear in the monaural conditions. In both experiments, performance was better in the binaural listening condition than in the monaural conditions. In the first experiment carried out with 9 subjects, left-ear monaural performance was better than the right ear despite the lack of statistical significance which could be attributed to the small number of subjects. In the second experiment with 15 subjects, mean performance was statistically higher when listening with the left ear than with the right ear. Furthermore, when dividing the subjects into two groups, males and females, the L/R difference reached statistical significance only for the group of males. The greater ability to localize with the left ear was interpreted as evidence supporting the superiority of the right hemisphere for vertical sound localization.

Butler (1994) extended the Ivarsson study by assessing the ability to localize a high-pass noise originating from eight loudspeakers in the mid-sagittal plane in 10 subjects listening with the left ear, with the right ear and with both ears. An E-A-R insert and ear muff were used to block one ear in the monaural conditions. In contrast to the Ivarsson et al. (1980) study, inactive loudspeakers were also positioned to cover a region extending to ± 90° in the horizontal plane and from -45° to +60° in the vertical plane. Given the tendency to perceive sounds toward the listening ear in monaural conditions, this experimental setup allowed quantification of the magnitude of localization errors in both vertical and horizontal dimensions. In agreement with previous studies, all subjects exhibited greater localization accuracy when listening binaurally. Moreover, sound localization was significantly more accurate and the perceived displacement from midline was less when listening with the left ear than with the right ear. Such a left-ear advantage in monaural sound localization was interpreted as a right-hemisphere superiority in processing complex spectral information.

Following up on these studies, Burke et al. (1994) investigated asymmetry under binaural listening conditions, hypothesizing that if such an L/R asymmetry exists, sounds emanating from the left hemifield would be more accurately localized by binaural listeners. Sound localization was assessed in 20 right-handed and 20 left-handed subjects using broadband noise originating from 104 loudspeakers equally spaced in the horizontal and vertical dimensions over the left or right side of the subjects. When analyzing the results with respect to the horizontal coordinates, a significantly greater accuracy in localization was found when sources were placed in the left hemifield, independently of the subjects' handedness. The L/R asymmetry was no longer significant after compensating for front/back reversal errors. Since spectral cues provide critical information for discriminating sounds from the front and back, the hemifield effect in judging the horizontal coordinates of sound sources and the lack thereof after compensating for front/back reversals were attributed to a superiority of the right hemisphere in processing spectral cues. However, no main effect of hemifield was noted when localization judgments were analyzed with respect to the vertical coordinates, for which spectral cues are also expected to be critically important. This conflicting finding was attributed to the nature of the localization task in which interaural time and level differences provided adequate cues to discriminate along the vertical dimension in their coordinate system for sources off the mid-sagittal plane, thus making vertical judgments insensitive to spectral cues. This highlights the importance of the array design, response set and choice of head-related coordinate system in analyzing sound localization data (Searle et al., 1976; Perrett and Noble, 1995).

Abel et al. (1999) assessed the ability to localize three stimuli (one-third octave bands centered at 0.5 and 4 kHz, and broadband noise) in the horizontal plane (over 360°) in 16 subjects. The broadband noise was easiest to localize while the 0.5 kHz band yielded the lowest accuracy. However, a left-advantage was evident for the low-frequency stimulus, which was largely due to a higher incidence of front/back reversals on the right side. This L/R asymmetry was later found to be evident until the fifth decade of life (Abel et al., 2000).

The sound localization studies reviewed above suggest that the processing of spectral information is better performed by the right hemisphere (left-ear advantage). However, a recent study investigating gender-specific hemispheric asymmetry in monaural localization in the vertical dimension portrays a somewhat more complex situation. Lewald (2004) assessed sound localization of a high-frequency band-pass filtered noise over 31 loudspeakers in the mid-sagittal plane for 22 right-handed males and 22 right-handed females. A monaural left-ear advantage was noted in the female group; however, a monaural right-ear advantage prevailed in the male group. When combining the two groups, no asymmetry was found, a finding consistent with other studies failing to show a L/R asymmetry in sound localization, but contrary to the Ivarsson et al. (1980) study in which a significant left-ear advantage was found in males.

Previous studies examining possible L/R asymmetry in sound localization focused on the traditional spherical coordinate system to describe sound source positions and localization responses (azimuth angle from -180 to 180° in the horizontal plane and elevation angle from -90 to 90° in vertical planes intersecting the mid-sagittal plane). However, as found in Burke et al. (1994), interaural time and level difference cues are available to discriminate among sources placed in vertical planes intersecting the mid-sagittal plane, not only spectral cues (Perrett and Noble, 1995), and this reduces the sensitivity to detect L/R asymmetries if such an asymmetry is based on spectral processing. Instead, a head-related coordinate system based on the cone-of-confusion is warranted, such as the interaural-polar-axis system (Morimoto and Aokata 1984; Middlebrooks et al., 1989; Morimoto et al. 2003). In this system (Figure 1), lateral angle $\alpha$ subtended from the vertical axis, describes the cone-of-confusion surface on the left ($-90° \leq \alpha < 0°$) or right ($0° < \alpha \leq 90°$) side of the mid-sagittal plane (defined as $\alpha = 0°$), whereas vertical angle $\beta$ determines the angular position of the sound source on the cone-of-confusion in the plane perpendicular to the interaural axis and intersecting the sound source ($-180° \leq \beta \leq 180°$ with front defined as $\beta = 0°$). Using this system, Morimoto and Aokata (1984) showed that sound localization can be explained by two mutually independent cues: binaural difference cues for resolving angle $\alpha$, and spectral cues for angle $\beta$. Abel et al. (1999; 2000) exploited this coordinate system in rescoring their data. However, the range of $\beta$ angle positions was restricted to two, front ($\beta=0°$) and back ($\beta=180°$), thereby limiting analysis of possible left/right asymmetries to front/back discrimination, instead of fine vertical localization perception.

The objective of this study is to determine if a L/R asymmetry exists when listeners are presented with many stimulus and response options for the vertical angle $\beta$, while lateral angle $\alpha$ remains fixed and the source array placed on the left or right side of subjects. A binaural open ear localization paradigm is used to reflect natural listening and avoid complications in interpreting monaural sound localization data (Wightman and Kistler, 1997). Based on previous findings, an asymmetry may be anticipated, with a greater accuracy localizing sounds in the left side, thereby supporting evidence of right-hemisphere dominance in the analysis of spatial information. Should an asymmetry exist, it must also be taken into consideration in the design and administration of sound localization tests for clinical and functional hearing assessments.

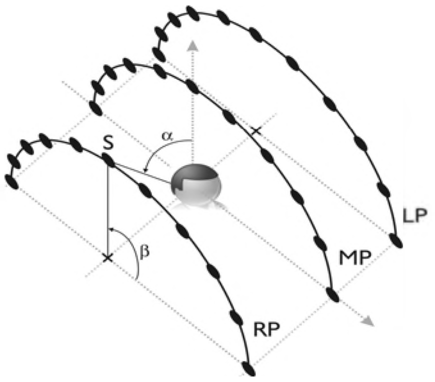

**Figure 1.** Interaural-polar-axis head-related coordinate system [adapted from Morimoto et al., 2003] ($\alpha$ = lateral angle between the source S and the vertical axis; $\beta$ = vertical angle between the source S and the horizontal plane in the direction perpendicular to the interaural axis). The three lateral positions of the 11-speaker localization array used in this study are also shown (RP = Right plane; MP = Median plane; LP = left plane).

## 2. METHOD AND MATERIALS

### 2.1 Subjects

Twenty-four subjects (15 men and 9 women) between 19 and 29 years old (average age = 24) participated in this study. All but three subjects were right-handed. In addition to having normal hearing bilaterally, as defined by pure tone thresholds no greater than 20 dB HL at 250, 500, 1000, 2000, 4000 and 8000 Hz, subjects had to meet the following inclusion criteria: (1) normal otoscopic evaluation; (2) normal tympanograms; (3) symmetrical hearing, defined as an ear-difference in thresholds no greater than 10 dB at any audiometric frequency tested; and (4) symmetrical vision, defined as a difference no greater than one line on the Snellen Chart. This last criterion ensured that visual acuity was similar for both lateral fields and would not be a confounding factor in assessing possible L/R asymmetries in sound localization.

### 2.2 Experimental Design

Sound localization was assessed using 11 miniature loudspeakers (Realistic Minimus 3.5) matched in frequency response within ± 2.5 dB for third-octave bands from 100 to 12000 Hz and mounted on a semi-circular arc with a radius of 1 m. The sources were separated by 18° along the arc to span a range of 180° in angular space. The localization arc was positioned vertically in three lateral planes perpendicular to the interaural axis, as shown in Figure 1. Thus, in each plane, the sound sources were distributed around the cone-of-confusion at vertical angles $\beta$ of 0° (front), 18°, 36°, 54°, 72°, 90° (above), 108°, 126°, 144°, 162 ° and 180° (back) in the upper hemisphere. In the median sagittal plane condition (MP), the arc was placed directly above the subjects (lateral angle $\alpha = 0°$). In the left lateral plane condition (LP), the arc was positioned to the left, 58 cm from the subjects' head, at a lateral angle $\alpha$ of -30° from the vertical axis, whereas it was positioned at the same distance to the right at a lateral angle $\alpha$ of 30° in the right lateral plane condition (RP).

The experiment was carried out in a 5.6 m × 2.9 m × 2.0 m audiometric room. Subjects were seated on an adjustable stool, about 87.5 cm from the floor, ensuring that the ears were at the same height as the boundary sources on the semi-circular arc ($\beta$=0° in front and $\beta$=180° at the back). To minimize L/R asymmetric room acoustic effects and to facilitate administration of the experimental conditions, the sound localization array remained fixed in space in the center of the room. The stool, rather than the arc, was moved from one experimental condition to the next. In the MP condition, the stool stood in the center of the room with the localization array directly above the subjects' head. In the LP condition, the stool and subjects were moved by 58 cm to the right along the interaural axis. In the RP condition, the stool and array were in the same position in the space as the LP condition, but the subjects were rotated by 180°.

The stimulus to be localized was a 250-msec sample of band-limited white noise (250-8000 Hz) with a 25-ms rise and fall time presented at a comfortable level (60 dB SPL). While important cues to vertical sound localization exist at frequencies well above 8000 Hz (Hebrank and Wright, 1974; Shaw, 1997; King and Oldfield, 1997; Blauert, 1997), a more restricted stimulus bandwidth was used in this study to better reflect the functional localization abilities of human listeners to everyday sounds such as speech, warning signals or other environmental noises (Jelonek, 1991).

### 2.3 Procedure

Subjects received no formal training prior to the start of the experiment, other than listening without feedback to a sequence of a few trials to familiarize them with the data collection system. Each subject was tested under all three experimental conditions and testing order was counterbalanced between subjects to control for potential order effects. The stimulus was presented randomly 6 times from each of the 11 speakers, for a total of 66 trials in each listening condition. Prior to each trial, subjects were required to sit still and fixate a visual target placed straight ahead on the wall of the testing chamber. Head movements were not allowed during stimulus presentation. Following each presentation, subjects were required to identify the speaker through which the stimulus was thought to originate using a tactile screen displaying the response choice in the same semi-circular arrangement as the speaker array. A maximum response time of 10 seconds was allowed, after which there was a 2-second interval for reassuming the original head position before the next stimulus. Guessing was encouraged in case of uncertainty and no feedback was provided during testing.

### 2.4 Data Analysis

Sound localization was assessed using four measures: the proportion of correctly identified sound sources, and the three angular errors proposed by Rakerd and Hartmann (1985). The latter allow the identification and quantification of the types of localization errors committed. The first of these, the mean error, consists of the signed arithmetic average of the angular error in degrees over the 6 trials for a given stimulus source, thereby indicating the size and direction of any response bias or systematic error. A negative mean error represents a tendency to respond to a source positioned at a smaller vertical angle $\beta$ than the actual target source (a bias towards the front), whereas a positive mean error indicates a tendency to respond at a larger vertical angle $\beta$ (a bias towards the back). The second type of error, the variable error, is the standard deviation of the angular errors for a given source target and represents the consistency of subject responses once response bias is eliminated. Finally, the third type of error, the total error, is the root mean square of angular errors for a given source target and represents the global error in localization without regards to the direction of the error.

The four performance measures were calculated separately for each subject, source angle $\beta$ and localization plane. Each measure was submitted to a mixed design ANOVA, with two repeated-measures variables [localization plane (3 levels) and target angle $\beta$ (11 levels)] and one between-group variable (gender).

## 3. RESULTS

### 3.1 Response Patterns

Inspection of the confusion matrices revealed that response patterns varied greatly among the 24 subjects. About half the subjects (ten males, three females) responded fairly uniformly over the entire array, without a clear evidence of bias. Others, including the majority of females, responded preferentially in specific sectors of the vertical array, often front/above (four males, four females), but sometimes frontally (one female) or in different sectors in the different localization planes (one male, one female). The response patterns for females clearly showed more variability and a greater occurrence of front/back confusions (in 23.6% trials) than males (10.8% trials), as shown in Table 1. Finally, most subjects (ten males, five females) had similar response patterns in the two lateral planes LP and RP; however, distinct asymmetrical behaviors (difference ≥10% in identification accuracy between the two lateral planes) was evident among the other subjects favoring LP (three males; two females) or RP (two males, two females).

**Table 1.** Percentage of front/back confusions by gender and plane.

| Plane | Male | Female | Total |
|---|---|---|---|
| Right | 12.3 | 24.8 | 17.0 |
| Median | 12.3 | 19.8 | 15.1 |
| Left | 7.7 | 26.1 | 14.6 |
| All planes | 10.8 | 23.6 | 15.6 |

### 3.2 Performance Measures

Figure 2 presents the localization data averaged over all subjects by vertical source angle for each of the four performance measures (percent correct and three angular errors) and three lateral planes. Figure 3 presents the summary localization data averaged over vertical source angle by gender.

3.2.1 Proportion of correct responses

The repeated-measures ANOVA revealed a significant main effect of target angle $\beta$ on the subjects' identification accuracy in localizing sources [$F(10,220) = 3.756$, $p < 0.001$]. No significant main effect of localization plane [$F(2,44) = 1.043$, $p = 0.361$] or gender [$F(1,22) = 2.843$, $p = 0.106$], or interaction among factors were found at the 0.05 confidence level.

As shown in Figure 2, the proportion of correct responses was similar overall in all three planes and shows the same pattern as a function of target angle. Averaged across the three planes, target sources were more accurately identified in the front sector (range = 0.30 to 0.36) than the above (range = 0.22 to 0.30) and back (range = 0.16-0.21, with the exception of target angle $\beta$ = 180° with a 0.30 accuracy) sectors. Repeated within-subjects contrasts, used to compare neighboring $\beta$ angles, showed a significant difference in localization between $\beta$ pairs 108-126° and 162-180°.

3.2.2 Mean error

Again, the repeated-measures ANOVA revealed a significant main effect of target angle [$F(10,220) = 46.164$, $p < 0.001$], but no significant main effect of localization plane [$F(2,44) = 0.535$, $p = 0.589$] or gender [$F(1,22) = 2.324$, $p = 0.142$], or interaction among factors at the 0.05 confidence level. As shown in Figure 2, the mean error was near zero (no response bias) for target angle $\beta$ around 54-72°, but systematically increased in absolute terms in all three planes towards the two boundary sources ($\beta$ = 0 and 180°). Target angles in the front sector were associated with positive mean errors, indicating a response bias towards the back or overhead; whereas angles within the above and back

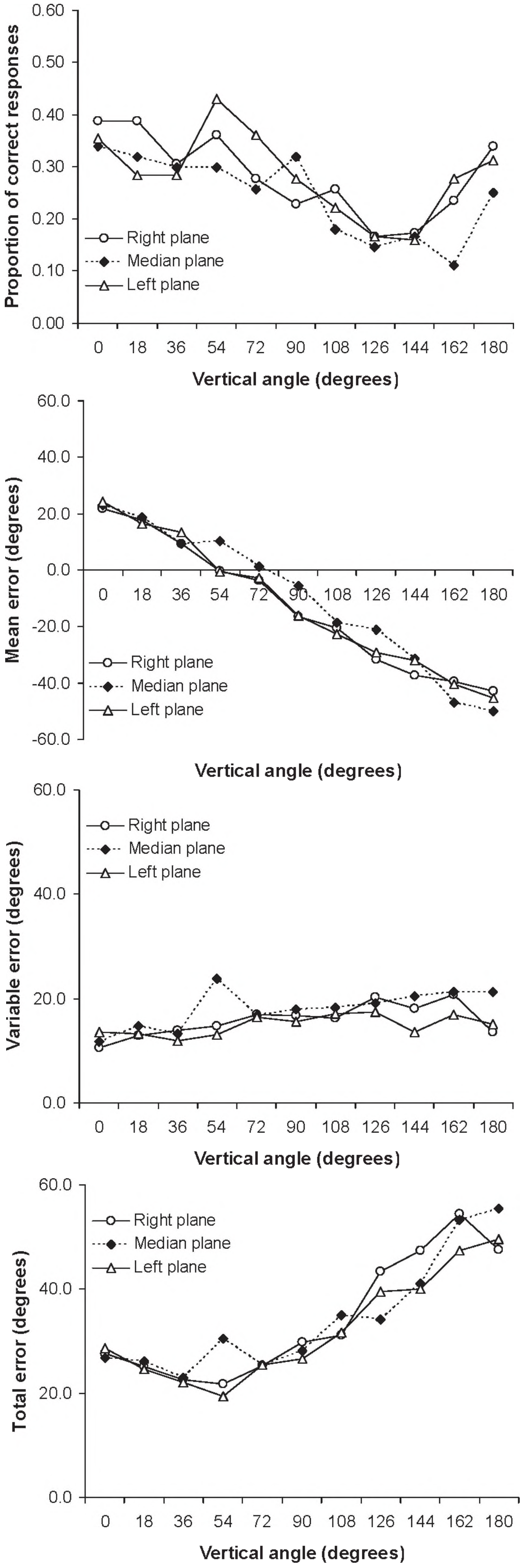

**Figure 2.** Localization performance by lateral plane (RP, MP, LP) as a function of the vertical source angle. Data averaged across all subjects. Results are shown for the proportion of correct responses and the three error types.

sectors were generally associated with negative mean errors, indicating a bias towards the front. Repeated within-subjects contrasts revealed significant differences between all pairs of adjacent angles $\beta$ (0-18°, 18-36°, 36-54°, 54-72°, 72-90°, 90-108°, 108-126°, 126-144° and 144-162°), with the exception of the most backward pair (162-180°).

### 3.2.3 Variable error

The repeated-measures ANOVA performed on the variable error revealed a significant main effect of target angle [$F(10,220) = 4.438$, $p < 0.001$], localization plane [$F(2,44) = 6.008$, $p = 0.005$] and gender [$F(1,22) = 4.289$, $p = 0.050$], but no significant interactions among factors at the 0.05 confidence level. The main effect of angle is shown in Figure 2, where the variable error tends to increase slightly in all three planes from front to back sources. Repeated within-subjects contrasts found a significant difference between only two successive target angles: 36 and 54°.

The main effects of localization plane and gender are illustrated in Figure 3. Tests of within-subjects contrasts revealed a significant difference in localization plane between MP and both RP ($p = 0.045$) and LP ($p = 0.002$), with a greater variable error committed in MP (18.1°) than RP (15.9°) or LP (14.9°). There was no significant difference between the two lateral conditions RP and LP ($p = 0.248$). Finally, male subjects performed better (smaller variable error) than female subjects by 3.1° over the three localization planes (15.1 versus 18.2°).

### 3.2.4 Total error

The repeated-measures ANOVA performed on the total error revealed a significant main effect of target angle [$F(10,220) = 10.013$, $p < 0.001$] and gender [$F(1,22) = 9.512$, $p = 0.005$], but also a significant interaction between localization plane and gender [$F(2,44) = 3.451$, $p = 0.041$]. No significant main effect of localization plane [$F(2, 44) = 0.134$, $p = 0.875$], or other interactions were found at a 0.05 confidence level. As illustrated in Figure 2, there was a general increase in total error in all three planes with increasing target angle $\beta$. Averaged over the three planes, the error was smallest for angles in the front sector (range = 22.6 to 27.7°), followed by the above sector (range = 25.4 to 32.6°) and the back sector (range = 39.0 to 51.7°) where it was the largest. Repeated within-subjects contrasts on pairs of successive source angles $\beta$ showed the following pairs to be significantly different: 18-36°, 90-108°, 108-126° and 144-162°, with a tendency of larger total errors for larger angles, except for the first pair.

Males (28.4°) performed significantly better than females (42.4°) on the total error measure, as shown in Figure 3. Finally, tests of within-subjects contrasts demonstrated an interaction between gender and localization plane, but only when MP is compared to LP ($p=0.01$). This interaction is clearly noted in Figure 3. Although males performed better in LP (24.7°) than MP (31.9°), female exhibited greater total errors in LP (44.1°) than MP (38.6°).

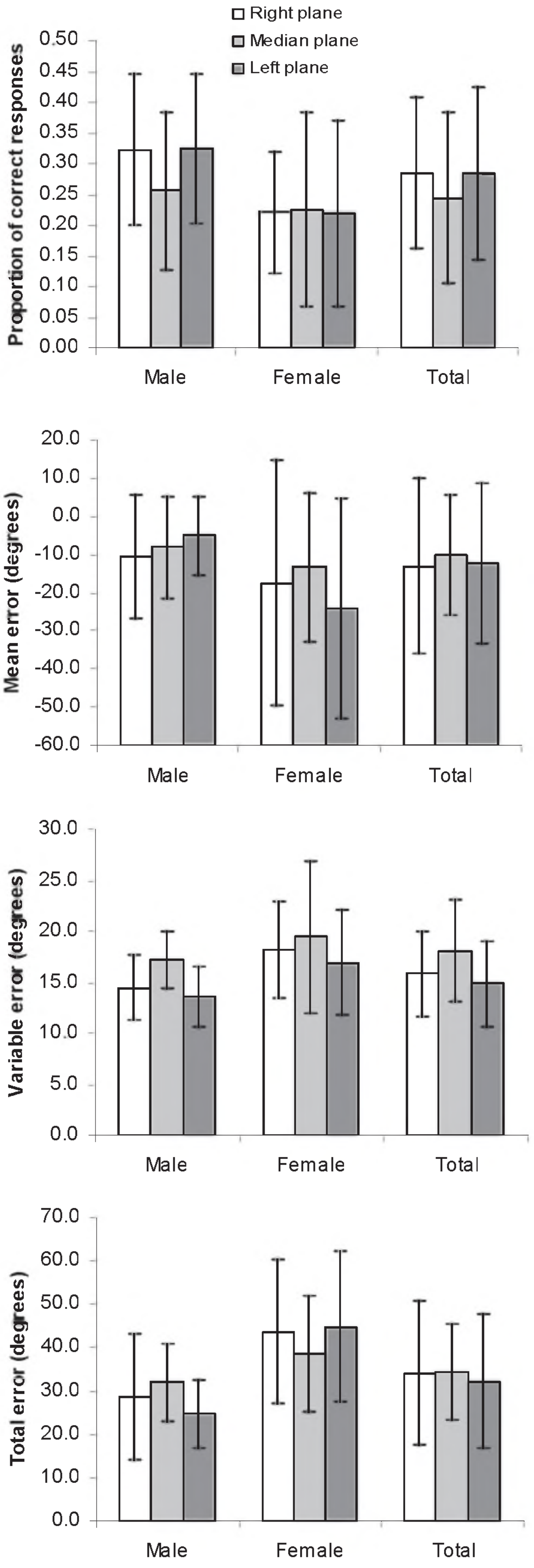

**Figure 3.** Localization performance by gender and lateral plane (RP, MP, LP). Data average across vertical source angles. Error bars represent ± one standard deviation. Results are shown for the proportion of correct responses and the three error types.

## 4. DISCUSSION

The main objective of this study was to further explore a possible asymmetry in vertical sound localization under binaural listening. A few studies (Burke et al. 1994; Abel et al., 1999; 2000) had indicated better localization for sources on the left side, particularly with respect to front/back perception, and that the asymmetry was likely related to the processing of spectral cues. Other studies had shown asymmetrical localization abilities in the median plane under left or right monaural conditions (Ivarsson et al., 1980; Butler, 1994; Lewald, 2004), possibly interacting with gender. However, previous studies were generally limited to mid-sagittal plane localization or offered confounding interaural cues that could be used to judge elevation, in addition to spectral cues. Instead, this study assessed asymmetry using a semi-circular arc positioned perpendicularly to the interaural axis, in the median plane and in left and right lateral planes. Sound sources were arrayed around the upper half of the cone-of-confusion intersection in each plane (Figure 1), thus minimizing the confounding effects of interaural cues.

The study design yielded a fairly challenging localization task, given the short duration (250 ms) and band-limited white noise stimuli used (250-8000 Hz). As shown in Figure 2, the proportion of correct responses varied from 0.11 to 0.43 (chance = 0.09) across conditions, and there were relatively large localization errors. The mean error showed a general response bias toward a neutral direction of approximately 60° in vertical elevation. This pattern was shown in all three localization planes. Mean error was largest for the boundary in the front and back, where it dominated the total error. Such edge effects were expected and had been previously noted in other studies (e.g. Rakerd and Hartmann, 1985). In contrast, mean error was smaller for source positions above, where variable error was the dominant component. The latter, while slightly increasing from front to back, showed much less variation with source positions than mean error. Overall, the size of total errors was fairly large compared to other studies (Burke et al., 1994; Makous and Middlebrooks, 1990; King and Oldfield, 1997; Best et al., 2005). Typically, a wider stimulus bandwidth is used and front/back reversals are often compensated for or screened out from the results. In this study, front/back reversal errors, which occurred in about 15.6% of trials, were not compensated for since they appear to reflect a class of errors indistinguishable from other elevation errors (Morimoto and Aokata, 1984). Best et al. found a similar proportion of reversal errors (16.4%) for speech stimuli low-pass filtered at 8000 Hz.

A main outcome of this study was that repeated-measures ANOVAs performed on the proportion of correct responses and on three different angular error measures (mean, variable, total) did not uncover any significant difference in performance for sources in the left versus right planes. Indeed, localization plane was not a main effect or an interaction effect for the proportion of correct responses and the mean error measure. While plane was a main effect for the variable error, it was the result of a slightly higher error in the median plane compared with the left or right lateral planes, not between left and right planes. Likewise, a significant interaction involving localization plane was found for the total error measure, but it only involved the median plane compared with the left plane; males had smaller total error in the left plane than the median plane and the converse for females. Observation of the pattern of errors across source angles in Figure 3 also did not show any important effect involving left versus right planes. Thus, there is little evidence in this study in support of asymmetric vertical sound localization abilities for sources positioned laterally on the left or right sides. It is important to realize, however, that there were large intersubject variations in the data and, as pointed out earlier in Section 3.1, some subjects showed distinct L/R asymmetrical behaviors that are not well accounted for in group data. Butler (1994) also observed distinct asymmetrical response patterns across subjects for vertical elevation under monaural listening conditions.

While care was taken to minimize reflections and provide the most symmetrical layout possible, the influence of asymmetrical room reflections in the audiometric testing room cannot be fully discounted. It was already noted that distinct asymmetrical behavior was found in some subjects, but not in others, despite listening to the same sound field. This, together with the main finding of a null hypothesis for left versus right localization plane, makes it unlikely that reflections contributed adversely to the study outcome. Given the study design and response variability, a mean difference in total error of about 7° (or slightly less than half the source angular spacing) was detectable between localization planes at the 95% confidence interval, whereas a mean difference of less than 2° was observed between left and right planes.

Gender, however, appeared as a significant main or interaction factor for several performance measures in this study. Gender was a main effect for the variable and total error measures, and in both cases males showed significantly less error than females in all three localization planes (Figure 3). Comparative data on gender differences for vertical sound localization is limited. Interestingly, Lewald (2004) found a trend for males to be more precise (less variable) and show less total angular error in vertical localization in the mid-sagittal plane under binaural listening conditions. Under monaural listening conditions, a significant gender difference favoring males was found when listening to the right ear. Ivarsson et al. (1980) did not find gender differences under binaural listening conditions, but their data under monaural masking also showed a male advantage. In contrast to Lewald (2004), however, the male advantage was found for the left ear, instead of the right ear.

Concerning the origin of gender differences, we can hypothesize as in Best et al. (2005) that the generally smaller size of the outer ears of females is such that important spectral features for vertical localization are encoded at higher frequencies than for males on average. Indeed, Middlebrooks (1999) found that differences in directional transfer functions between subjects could be predicted by physical attributes, particularly pinna cavity height and head width, and that the spectral features of directional transfer functions lay at higher frequencies in females than in males. Thus, poorer performance found for band-limited stimuli for females could be a purely physical effect. Gender differences have also been reported for sound localization in the frontal horizontal plane. For example, using low-frequency noise bursts, Savel (2009) reported a gender difference in sound localization in 50 adults with normal hearing, with better performance in males. A left-hemifield advantage was also noted, which interacted with handedness and gender, being more strongly observed in right-handed males.

Cross-gender differences in performance could also be explained by differences in cognitive abilities related to the structural organization of male and female brains (Cahill, 2006), with men displaying superior visuospatial abilities (see Becker et al., 2008 for a review on sex differences in brain and behavior). A male advantage in spatial hearing abilities has also been reported (Lewald, 2004; Neuhoff et al., 2009; Simon-Dack et al., 2009; Zündorfz et al. 2011). For example, in an investigation of sex differences in auditory spatial localization by Zündorfz et al. (2011), right-handed subjects with normal hearing were required to localize five environmental sounds (dog barking, baby crying, telephone ringing, man laughing and cuckoo clock) in a single source condition and in a multi-source condition simulating a "cocktail party situation". In the latter, subjects had to localize a target sound in the presence of multiple competing sound sources. Irrespective of the response modality used (verbal and manual), males outperformed females in the multi-source condition and results were attributed to sex differences in higher-order attentional mechanisms.

Vertical sound localization is highly dependent on the frequency content of the stimulus (Hebrank and Wright, 1974; Musicant and Butler, 1984; Blauert, 1997; Best et al., 2005) and the response choice provided to the subjects. In this study, a stimulus bandwidth limited to 8000 Hz was used to depict the functional localization abilities of human listeners to everyday sounds. Asymmetry and gender issues may play out differently in applications for which an extended stimulus frequency range can be made available, such as in the design of audio displays (King and Oldfield, 1997). Best et al. (2005) showed that human listeners are much better at vertical sound localization for speech stimuli low-pass filtered at 16000 Hz than at 8000 Hz, indicating an important role of high frequencies for speech localization. However, high frequencies may easily be masked in real environments or rendered inaudible due to hearing loss or hearing aid bandwidth limitations. Finally, stimuli were presented at the same level across sources in the current study; it is uncertain if the lack of rove might have provided overall level cues that would have fostered significant effects in localization performance, notable for gender differences. Until L/R asymmetrical effects and gender differences are more clearly understood, future studies need to pay particular attention to control for these factors in clinical applications.

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