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Research paper

Sound localization in noise and sensitivity to spectral shape

Guillaume Andéol[a,*], Ewan A. Macpherson[b], Andrew T. Sabin[c]

[a] Institut de Recherche Biomédicale des Armées, Département Action et Cognition en Situation Opérationnelle, BP 73, 91223 Brétigny sur Orge Cedex, France
[b] School of Communication Sciences and Disorders & National Centre for Audiology, Western University, London, Ontario, Canada N6G1H1
[c] Hearing Aid Laboratory, Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL 60208, United States

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ABSTRACT

Individual differences exist in sound localization performance even for normal-hearing listeners. Some of these differences might be related to acoustical differences in localization cues carried by the head related transfer functions (HRTF). Recent data suggest that individual differences in sound localization performance could also have a perceptual origin. The localization of an auditory target in the up/down and front/back dimensions requires the analysis of the spectral shape of the stimulus. In the present study, we investigated the role of an acoustic factor, the prominence of the spectral shape ("spectral strength") and the role of a perceptual factor, the listener's sensitivity to spectral shape, in individual differences observed in sound localization performance. Spectral strength was computed as the spectral distance between the magnitude spectrum of the HRTFs and a flat spectrum. Sensitivity to spectral shape was evaluated using spectral-modulation thresholds measured with a broadband (0.2–12.8 kHz) or high-frequency (4–16 kHz) carrier and for different spectral modulation frequencies (below 1 cycle/octave, between 1 and 2 cycles/octave, above 2 cycles/octave). Data obtained from 19 young normal-hearing listeners showed that low thresholds for spectral modulation frequency below 1 cycle/octave with a high-frequency carrier were associated with better sound localization performance. No correlation was found between sound localization performance and the spectral strength of the HRTFs. These results suggest that differences in perceptual ability, rather than acoustical differences, contribute to individual differences in sound localization performance in noise.

1. Introduction

Although audition allows us to accurately localize a sound's origin, the auditory sensory epithelium is not spatially organized. Instead, the auditory system must "rebuild" the auditory space based on acoustic cues, specifically: binaural cues for the left/right dimension and spectral cues for the up/down and front/back dimensions. As indicated by large individual differences in sound localization performance, the quality of these cues and/or the ability to process them could differ among normal hearing listeners. To date, there have been few direct examinations of the factors responsible for such individual differences. Here we tested the role of sensitivity to spectral shape in individual differences in sound localization performance.

Sound localization ability is partially determined by spectral cues, arising from the acoustic filtering of the outer ears, head and upper torso, that shape the spectrum of the incoming sound wave according to the sound source direction (Shaw, 1974, 1997). The function that describes this spectral shaping is called the head related transfer function (HRTF)(Wightman and Kistler, 1989a). The spectral cues in the HRTFs are responsible for front/back as well as up/down localization (Shaw, 1974, 1997). These cues are assumed to be particularly affected by background noise, given the increasing of localization errors in the front/back and up/down dimensions with signal-to-noise ratio degradation (Good and Gilkey, 1996).

Large individual differences are regularly observed in localization in front/back and up/down dimensions (Wenzel et al., 1993; Wightman and Kistler, 1989b; Zahorik et al., 2006). For instance, the proportion of localization trials on which listeners judge that a sound is behind them when it is actually in front of them (or vice versa) can vary by a factor of 20 (from 2% to 40%) among naïve listeners in free field conditions (Wenzel et al., 1993), and the mean localization error in the up/down dimension can range from as little

Abbreviations: DTF, directional transfer function; HRTF, head related transfer function; SLT, sound localization threshold; SMF, spectral modulation frequency; SMT, spectral modulation threshold; SNR, signal-to-noise ratio

* Corresponding author. Tel.: +33 607411905.
E-mail addresses: guillaume.andeol@irba.fr, guillaume.andeol@gmail.com (G. Andéol), ewan.macpherson@nca.uwo.ca (E.A. Macpherson), a-sabin@northwestern.edu (A.T. Sabin).

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as 5° to as much as 40°, depending on the listener (Wenzel et al., 1993). Moreover, in a noisy environment, individual differences are even larger (Best et al., 2005). One potential explanation for the individual differences in localization performance might be the variations in the features of spectral cues across listeners, due to diversity in outer ear size and/or shape. Some outer ears might thus provide more prominent cues than others.

Consistent with this hypothesis, Butler and Belendiuk (1977) found that a listener with poor localization performance could improve when listening through recordings made using somebody else's ears. Wenzel et al. (1988) argued that sound localization performance can be predicted by the analysis of acoustical properties of the outer ears. They showed that two listeners initially differing in performance, could reach the same performance level if they both individual listened through the same HRTFs (Wenzel et al., 1988). However, these findings were not confirmed in subsequent studies. Using large groups of listeners, Møller et al. (1996) and Middlebrooks (1999b) found that listening through somebody else's ears always resulted in worse performance. Interestingly, Middlebrooks demonstrated that the pattern of localization errors of a listener listening through another listener's HRTFs did not directly depend on the latter's HRTFs, but that it was highly correlated with the magnitudes of the differences between the HRTFs of the latter and the former (Middlebrooks, 1999a,b). Finally, Wightman and Kistler (1999) observed that listeners with similar "spectral detail" (as determined by visual inspection) in their HRTFs strongly differed in their sound localization performance. Nevertheless, to our knowledge, no study has investigated the relationship between a quantification of HRTF spectral detail and sound-localization performance.

Based on findings of Møller et al. (1996), Middlebrooks (1999b) and Wightman and Kistler (1999), we hypothesized another origin for individual differences in sound localization performance than the acoustical characteristics of the outer ear; as suggested by Wightman and Kistler (1999), it is possible that differences in the ability to detect spectral cues (Drennan and Watson, 2001; Eddins and Bero, 2007), also contribute to individual differences in sound localization ability. One approach to testing this possibility would be to examine the correlation between performance in a non-spatial spectral-shape perception task and performance in a spatial hearing task. A similar approach has been used successfully for speech perception studies: for instance, Saoji et al. (2009) found a strong relationship between spectral modulation threshold and vowel/consonant identification performance in cochlear implant listeners.

A correlation between sensitivity to spectral shape and sound localization ability would likely be restricted to those aspects of the spectral shape that convey spatial cues. Because of the limited physical dimensions of the outer ears, spatial cues introduced by outer ear filtering are mainly restricted to the high-frequency part of the spectrum (above 4 kHz). Therefore, assessing sensitivity to spectral shape above 4 kHz could be of particular interest. Likewise, a limited scale of details of the spectral shape seems to be relevant for localization. The results of studies by Macpherson and Middlebrooks (2003) and Qian and Eddins (2008) suggest that spectral details finer than 2 c/o (cycles per octave) do not influence sound localization. Therefore, it appears that spectral localization cues are conveyed by variations in the spectral shape above 4 kHz and at spectral modulation frequencies (SMFs) lower than 2 c/o.

In this study, we explored the extent to which individual variability in sound localization performance was attributable to differences in sensitivity to spectral envelope (the perceptual hypothesis) and/or to differences in HRTF acoustics (the acoustical hypothesis). To maximize individual differences in spatial sensitivity, the spatial task was conducted in noise (Best et al., 2005). Based on previous work, we reasoned that listeners' performance in this spatial task would reflect primarily the detection of spectral cues because these cues are assumed to be more strongly disrupted by noise than are binaural cues (Good and Gilkey, 1996).

To measure sensitivity to spectral shape in a non-spatial context, we used a spectral modulation detection task (Eddins and Bero, 2007). This task allowed us to determine the minimal modulation depth required to discriminate a flat spectrum stimulus from a stimulus with a sinusoidally modulated spectrum. This minimal modulation depth is called the spectral modulation threshold (SMT). We tested spectral modulation detection at different SMFs and audio frequencies because the spectral localization cues vary across these dimensions as do the SMTs. We chose to determine the SMT of stimuli whose carriers were in two different audio frequencies regions: one restricted to spectral region conveying localization cues (4–16 kHz) and one including a larger part of the audible spectrum (0.2–12.8 kHz).

We hypothesized that the relationship between SMT and sound localization performance would be stronger for the high-frequency (4–16 kHz) carrier. We also hypothesized that the correlation would be strongest at the SMFs that are critical for localization. Based on the results of Macpherson and Middlebrooks (2003), correlations should be stronger for SMFs below 2 c/o, and strongest for SMFs around 1 c/o. Significant correlations might also be observed for high-SMF stimuli if the sensitivity to spectral localization cues is related to general ability to detect spectral modulation regardless of the SMF. Finally, to separate the contribution of acoustic factors (spectral details of HRTFs) and perceptual factors (spectral shape sensitivity), we measured the spectral strength of listeners' HRTFs. The spectral strength of individual HRTFs was quantified using the spectral distance, as defined by Middlebrooks (1999a), between the magnitude spectrum of the HRTFs and a flat spectrum.

2. Methods

2.1. Participants

Nineteen participants (nine females; mean age, 30.7 ± 8 years) participated in the study. All had normal hearing (defined as thresholds of 20 dB HL or less at octave frequencies between 0.125 and 8 kHz) and no history of auditory pathology. Otoscopy was also normal. The spectral resolution ability of each participant was checked by a ripple reversal test for a 0.1–5-kHz bandwidth and 30-dB modulation-depth stimulus (Henry et al., 2005). Each participant had a ripple reversal threshold better than 2 c/o. The average ripple reversal threshold was 4.33 c/o and the range was 2.05–7.05 c/o. These results were very close to those obtained by Henry et al. (2005) with a similar population of normal-hearing participants ($n = 12$; mean = 4.84 c/o; range = 2.03–7.55 c/o).

In agreement with the guidelines of the Declaration of Helsinki and of the Huriet law regulating biomedical research in humans in France, participants provided written informed consent before inclusion in the study. All participants were paid (10 €/h) for their services.

2.2. Sound localization task

2.2.1. Task and procedure

The experimental design was similar to that of a previous study (Andeol et al., 2011). The sound localization task was conducted in a semi-anechoic room (Illsonic Sonex Audio). Listeners were seated on an elevated chair whose position was adjusted so that the listener's head was 2.5 m away from each one of eight surrounding loudspeakers (Fig. 1A). The loudspeakers were mounted on the vertices of a cuboid frame (height, 2.76 m; length, 2.94 m; depth, 2.94 m). The loudspeakers' coordinates (azimuth, elevation) were