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Effects of sex and age on auditory spatial scene analysis

Jörg Lewald[a,b,*] and Markus Hausmann[c]

[a] Department of Cognitive Psychology, Faculty of Psychology, Ruhr University Bochum, D-44780 Bochum, Germany

[b] Leibniz Research Centre for Working Environment and Human Factors, Ardeystr. 67, D-44139 Dortmund, Germany

[c] Department of Psychology, University of Durham, Durham DH1 3LE, United Kingdom

[*] *Correspondence:*

PD Dr. Jörg Lewald
Fakultät für Psychologie
Ruhr-Universität Bochum
D-44780 Bochum, Germany
Tel.: +49 234 32 28670
Fax: +49 234 32 14308
e-mail: joerg.lewald@rub.de

Abstract

Recently, it has been demonstrated that men outperform women in spatial analysis of complex auditory scenes (Zündorf et al., 2011). The present study investigated the relation between the effects of ageing and sex on the spatial segregation of concurrent sounds in younger and middle-aged adults. The experimental design allowed simultaneous presentation of target and distractor sound sources at different locations. The resulting spatial "pulling" effect (that is, the bias of target localization toward that of the distractor) was used as a measure of performance. The pulling effect was stronger in middle-aged than younger subjects, and female than male subjects. This indicates lower performance of the middle-aged women in the sensory and attentional mechanisms extracting spatial information about the acoustic event of interest from the auditory scene than both younger and male subjects. Moreover, age-specific differences were most prominent for conditions with targets in right hemispace and distractors in left hemispace, suggesting bilateral asymmetries underlying the effect of ageing.

Keywords: Sound localization; Sex differences; Ageing; Space perception; Auditory scene analysis; Cocktail party effect

1. Introduction

One of the most intriguing capabilities of human perception is the analysis of complex auditory scenes, that is, the discrimination between different sound sources that are simultaneously present in a noisy environment, in order to detect and selectively attend to one particular source (Bregman, 1994). This ability, which has also been referred to as the "cocktail party phenomenon" (Cherry, 1953), may be related to higher-order attentional mechanisms extracting spatial information about one event of interest from a complex scene with various distractors, in addition to the more basic, sensory, mechanisms of space perception. At present, there is growing evidence indicating that spatial abilities in general also apply to the specific situation of the cocktail party phenomenon. In particular, it has recently been demonstrated that sex differences exist in the auditory domain that may be comparable to those demonstrated in visual spatial attention (e.g., Hausmann et al., 2003). Namely, men showed higher performance than women for localizing target sounds in a multi-source sound environment (Zündorf et al., 2011). If one combines this result with the body of evidence indicating higher performance of men in specific visuospatial abilities, such as mental spatial transformation and visualization (for review, see Kimura, 1992), the question arises of whether this sex difference may be supramodal, rather than being specific to the visual modality. The visual spatial attention of women appeared to be more susceptible to influences by irrelevant events than that of men (e.g., Stoet, 2010). Electrophysiological and neuroimaging findings from both the visual and the auditory modalities indicated that different neural networks were recruited in the two sexes to perform spatial tasks, which has been discussed in terms of a simplified model of male bottom-up and female top-down strategies in spatial processing (e.g., Hugdahl et al., 2006; Simon-Dack et al., 2009).

Despite the well-documented sex differences in specific spatial abilities, the course of such sex differences across the life span is largely unclear, in particular with respect to the auditory modality (cf. Kimura, 1992). As concluded by Lacreuse et al. (2005), the results of studies focusing on the relation of sex- and age-related differences to cognitive decline are inconsistent. While some investigations suggest that sex differences remain largely constant up to old age (Herlitz et al., 1997; Larrabee and Crook, 1993), others concluded that sex differences disappear at older age (Dollinger, 1995; Herman and Bruce, 1983; Robert and Tanguay, 1990). Also, there are reports suggesting that the typical age-related cognitive decline is greater in men than in women (Barrett-Connor and Kritz-Silverstein, 1999; Elias et al., 1997; Van Exel et al., 2001), or the opposite (Brayne et al., 1995; Elias and Kinsbourne, 1974; Meinz and Salthouse, 1998), or equal in the two sexes (Barnes et al., 2003; Maitland et al., 2000; Singer et al., 2003). Maylor et al. (2007) tested a large sample of subjects (almost 200,000) with various tasks, and found a generally steeper age-related decline in response accuracy for males than females, while the opposite was found for response speed. The study of Lacreuse et al. (2005) in non-human primates showed higher male performance in spatial working memory at a young age and a greater decline with age for males than for females.

The aim of the present study was to investigate the influences of ageing and sex on auditory spatial performance. We were interested in the processes of auditory spatial segregation with minimum interference of effects resulting from more complex non-spatial functions, such as speech or semantic analyses, which may involve age- or sex-specific top-down processes (Liederman et al., 2010). For this purpose, we used a very simple auditory scene. Subjects simultaneously heard a target source and a distractor source, at different locations in the free sound field. Subjects had to localize the target by performing a manual pointing task. This approach is a simplified and more standardized version of the multi-source task used in a preceding study (Zündorf et al., 2011). This design was focussed on the shift in the perceived target location relative to its physical location, while estimates of general precision in target localization were used by Zündorf et al. (2011). In several previous studies that used simultaneous presentation of target and distractor sounds, a perceptual attraction between target and distractor was observed, the so-called spatial pulling effect (e.g., Best et al., 2007; Butler and Naunton, 1962; Gardner, 1969). This effect may reflect an important element of spatial analysis in complex auditory scenes. As stated by Lee et al. (2009), pulling describes a displacement of the perceived spatial location of a target sound toward the location at which a competing element would be perceived if it were presented in isolation. Best et al. (2007) suggested that pulling reflects perceptual integration as a result of the obligatory grouping of spatial information from different sound sources that occurs when there are no cues indicating the presence of two distinct sound sources, other than the spatial cues themselves (for detailed discussion, see Lee et al., 2009). In the present study, the magnitude of the pulling effect was taken as a measure of the degree of interference between the target and the distractor. We assume that the stronger the pulling effect, the stronger was the tendency to integrate the two sounds. While natural sounds were used for stimulation in the preceding demonstration of a sex difference (Zündorf et al., 2011), in the present investigation noise stimuli (band-pass-filtered noise; bandwidth 0.8-3 kHz) were used, to avoid variability related to stimulus properties. The use of stimuli with a spectrum limited to the midfrequency range of hearing was intended to minimize potential effects of presbycusis (age-related hearing loss) on performance at higher frequencies (cf. Mills et al., 2006; Willott, 1991), since the goal was to investigate phenomena of cognitive ageing, related to the central, rather than peripheral, auditory system. Finally, this experiment was conducted under ideal acoustical conditions of an anechoic environment. In addition, left/right asymmetries in localization performance were analysed, as these have been found for single target sound sources (Abel et al., 2000; Ocklenburg et al., 2010).

2. Method

2.1 Subjects

Fifty-four adult subjects (27 women) participated. Their age ranged from 22 to 67 years. Using a median-split procedure, the sample was divided into two age groups: (1) younger (range: 22-42 years; mean: 30 years, SE 1.3; 14 women, 13 men); and (2) middle aged (range: 44-67 years; mean: 56 years, SE 1.3; 13 women, 14 men). All subjects were right-handed, as indicated by the hand subscale of the Laterality Questionnaire of Siefer et al. (2003). Subjects in both age groups had levels of education ranging from secondary school to university degree. There were no professional musicians among the subjects. None of the subjects wore hearing aids. The experiments were carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

Prior to experimentation, standard audiometry (125-8000 Hz) was performed. Individual mean thresholds across frequencies and ears indicated normal hearing or slight hearing loss (≤ 25 dB HL) in all younger and 18 middle-aged subjects, while the remaining 9 middle-aged subjects showed a mild hearing loss (26-40 dB HL). Twenty-one subjects of the younger group and 6 middle-aged subjects showed normal hearing (≤ 25 dB HL) for all of the eleven frequencies tested within this range for both ears. For at least one of these frequencies, a mild hearing loss (26-40 dB HL) was found for 6 younger and 12 middle-aged subjects, a moderate hearing loss (41-55 dB HL) for 5 middle-aged subjects, a moderately severe hearing loss (56-70 dB HL) for 3 middle-aged subjects, and a severe hearing loss (71-90 dB HL) for one middle-aged subject. However, more severe degrees of hearing loss observed at specific frequencies were related to high-frequency decline or dips that did not overlap the spectrum of the band-pass filtered noise used for acoustic stimulation. All subjects had hearing thresholds better than 30 dB HL in both ears for at least one of the following frequencies: 1, 1.5, 2, or 3 kHz. These frequencies approximately cover the spectrum of the stimuli (0.8-3 kHz; see below). Mean thresholds across frequencies of 1, 1.5, 2, or 3 kHz and both ears were at most 27 dB HL, except for two subjects showing a mild to moderate hearing loss (32 and 40 dB HL). A statistically significant, but only slight (mean 2 dB, SE 0.8), difference in thresholds between age groups was found for the right ear at 1 kHz (*t*-test; $t_{(52)} = 2.88$, $p = 0.046$, Bonferroni corrected). No such difference was found for the left ear or for the remaining frequencies between 1 and 3 kHz. No significant differences in threshold were present between male and female groups for the same range of frequencies ($t_{(52)} \leq 2.06$).

2.2. Apparatus and Stimuli

The experiments took place in a sound-proof, anechoic room (5.4 × 4.4 × 2.1 m^3), with 40 cm (height) × 40 cm (depth) × 15 cm (width at base) fiberglass wedges on each of the six sides. A suspended mat of steel wires served as the floor. The ambient background noise level was below 20 dB(A) SPL. Experiments were conducted in total darkness.

Stimuli were generated digitally and converted to analogue form via a computer-controlled external soundcard (Sound Blaster Audigy 2 NX, Creative Labs, Singapore) at a sampling rate of 96 kHz. In the single-sound condition, a target sound source to be localized was presented in isolation. In the distractor-sound condition, a distractor sound at a location different from the target sound source was presented simultaneously with the target. The target was identical in the two conditions. The target was a band-pass-filtered noise (lower cut-off frequency 0.8 kHz; upper cut-off frequency 3 kHz) with a maximum duration of 12 s (rise/fall time 100 ms) and was presented with a sound-pressure level of 70 dB(A). The distractor stimulus was identical to the target stimulus, with two exceptions: (1) The carrier signals of the target and distractor were incoherent (i.e., independently generated, uncorrelated noise waveforms) and (2) the carrier noise of the distractor stimulus was amplitude-modulated by a low-frequency (40 Hz) sinusoidal signal (modulation depth

100%). Even though such a task is difficult, perceptual segregation of similar concurrent sound sources has been shown to be possible (see Blauert, 1983).

Subjects sat on a comfortable chair with the head fixed by a custom-made framework and stabilizing rests for the chin, forehead and occiput (see Lewald, 1997). Stimuli were delivered via a semicircular loudspeaker system (Fig. 1). An array of 91 broadband loudspeakers (5×9 cm^2, Visaton SC 5.9, Visaton, Haan, Germany) was mounted in the subject's horizontal plane, at a constant distance of 1.5 m from the centre of the head in front of the subject. The azimuth of the loudspeakers ranged from -90° (left) to 90° (right), in steps of 2°, with the centre loudspeaker at 0°. Target stimuli were presented from 21 loudspeaker positions: straight ahead of the subject (0°), 10 positions on the left and 10 positions on the right, with constant angular separation of 4°, thus covering an angular range from -40° to the left to 40° to the right. Distractor stimuli were presented from various loudspeaker positions (see below).

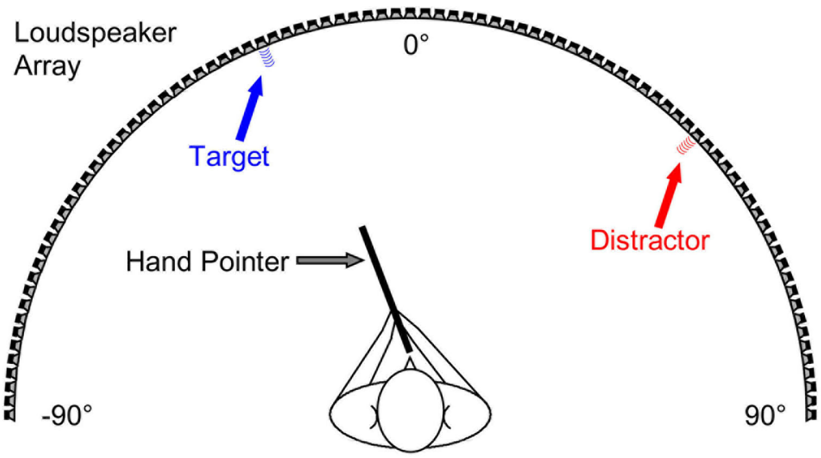

Figure. 1. Experimental paradigm for the distractor-sound condition. Two sound sources, the target and the distractor, were presented simultaneously via separate loudspeakers. The target and distractor locations were varied between trials. The perceived target location was assessed using a swivel-mounted hand pointer.

2.3. Procedure

The main experiment was comprised of two parts, following a fixed sequence: the single-sound condition was conducted in the first part and the distractor-sound condition in the second part. Subjects used a swivel-mounted hand pointer (for details, see Lewald et al., 2000). The pointer was mounted in front of the subject and consisted of a metal rod that the subject could rotate in the horizontal plane. A response key was mounted on the upper side of the rod. The azimuthal angle of the pointer was recorded by a potentiometer when subjects pressed this response key.

In both conditions, each trial began with the onset of the target sound stimulus at one of the 21 positions. The target position changed in a fixed, quasi-random order between trials without identical target location in consecutive trials. The order of trials was identical for all subjects. Subjects were instructed to direct the pointer as accurately as possible toward the target sound source and to press the response key when they were convinced that the pointer pointed exactly toward the sound source. Immediately after pressing the response key, the stimulus disappeared. The next trial followed with a delay of 2 s. If the response key was not pressed within 12 s after stimulus onset, the trial was repeated at the end of the experimental block. The timing of the stimuli as well as the switching of the loudspeakers were controlled by custom-written software, which also recorded the time of the key press and the pointer position at this point in time. For each condition, a minimum of 20 practice trials was conducted prior to data collection.

In the single-sound condition, each target position was presented six times (plus repetitions), resulting in 126 trials within one block. In the distractor-sound condition, the position of the distractor was varied in two ways: (1) The distractor source was located at a fixed position, either at -46° or at 46°, while the target was varied between -40° and 40°. (2) The distractor source was located at a constant azimuth relative to the target, 22° or 46° to the left or right of the target, and the target was varied between -40° and 40° (thus resulting in a variation of absolute position of the distractor from -86° to 86°). Types of variation were presented in an intermixed manner, thus preventing any potential side effects of long-term adaptation. Each target-distractor combination was presented six times, resulting in 624 trials that were presented in three blocks (each comprising 208 trials). Subjects were allowed to rest for about 5 min between blocks.

2.4. Data analysis

In the initial analysis of the data, subjects' individual pointing responses were determined as a function of target position and a regression line was fitted. In the second analysis, the mean of the signed deviations of the responses from the physical target locations (mean constant error) was analysed for each subject. For statistical analyses, mixed-factor analyses of variance (ANOVAs) were conducted to compare performance across subjects. For all computations, F-statistics were based on ε-corrected degrees of freedom (Greenhouse-Geisser). Post-hoc testing was performed using t-tests for homogeneous or, if necessary, inhomogeneous variances. The Bonferroni procedure to account for multiple comparisons was used.

3. Results

3.1. Demonstration of the spatial pulling effect

In the single-sound condition, all subjects performed quite accurately, with significant linear correlation between pointing responses and target azimuth (range of Pearson's r across all subjects from 0.90 to 0.99, $p < 0.0001$). Mean values of the pointing responses as a function of target azimuth are shown in Fig. 2. All subgroups of subjects showed high performance when the target was presented in isolation. When a distractor was presented simultaneously with the target, localization worsened, as indicated by a bias toward the location of the distractor sound, although correlations between pointing responses and target positions remained significant (r from 0.62 to 0.99, $p < 0.0001$).

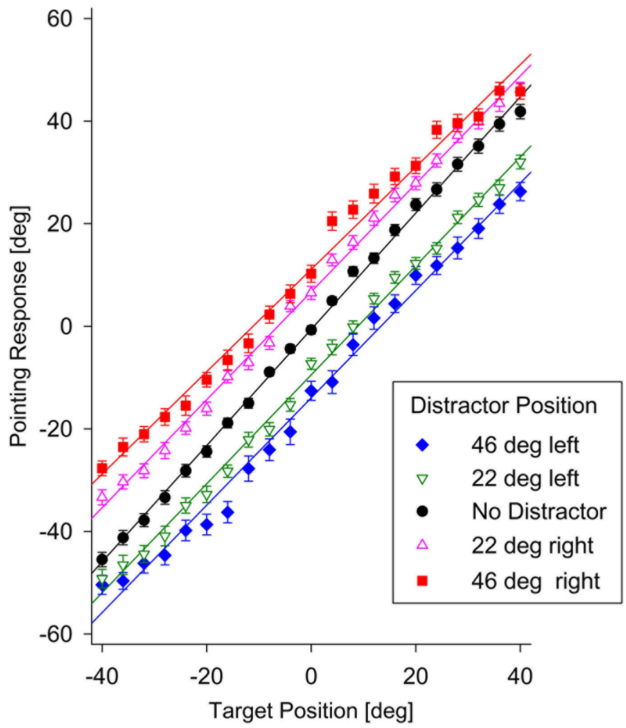

Figure 2. Pointing responses plotted as a function of target location. Mean values across all subjects (error bars, standard error) and regression lines are shown for five conditions: distractor always 46° or 22° to the left of the target; distractor always 46 or 22 deg to the right of the target; and with no distractor.

The initial analysis of data for the distractor-sound condition was focussed on the amount by which the distractor induced mislocalization of the target. A subset of data was analysed, in which the distractor was presented 22° or 46° to the left or right of the target. Individual pointing responses were determined as a function of target position, and a regression line was fitted. The y-intercept (offset) resulting from the fit was used as a measure of constant error. Individual y-intercepts were normalized such that negative values indicated a bias toward the target location and positive values a bias toward the distractor location. Statistical comparisons were conducted using a two-factor (2 × 2) ANOVA, with target-distractor separation (22°, 46°) and distractor side relative to the target (distractor to the left of the target, distractor to the right of the target) as within-subjects factors. The ANOVA revealed a main effect of target-distractor separation ($F_{(1, 53)} = 26.46$, $p < 0.0001$, $\eta_p^2 = 0.333$), indicating a stronger bias toward the distractor with larger (46°), than with smaller (22°) separations. There was a non-significant tendency for a stronger bias when the target was to the right than when it was to the left of the distractor ($F_{(1, 53)} = 3.28$, $p = 0.076$, $\eta_p^2 = 0.058$). The interaction was not significant ($F_{(1, 53)} = 0.03$).

3.2. Effects of age and sex on the pulling effect in left and right hemispaces

The main statistical analysis compared the effect of the distractor for the left and right hemispaces. For this purpose, a subset of the combinations of target and distractor positions was analysed: for the distractor-sound condition, pointing responses to 10 target positions in either hemispace (from 4° to 40° eccentricity) were included with the distractor always at 46° in contralateral hemispace. These results were compared to pointing responses to single target sources located at identical positions in the same hemispace. For each subject, the mean constant error (across target ecentricities) was computed. Mean constant errors were submitted to a four-factor (2 × 2 × 2 × 2) mixed ANOVA, with condition (absence vs. presence of the distractor sound source) and hemispace of target presentation (left vs. right) as within-subjects factors, and sex and age group (younger, middle-age) as between-subjects factors.

For both conditions, the constant error was normalized such that negative values indicated a shift toward the side of presentation of the target sound and positive values a shift toward the opposite side (Fig. 3A, B). Thus, in the distractor-sound condition, positive values indicated a shift toward the distractor source. As expected, there was an effect of condition ($F_{(1, 50)} = 41.27$, $p < 0.0001$, $\eta_p^2 = 0.452$). The direction of the bias was toward the position of the distractor, confirming the occurrence of the pulling effect.

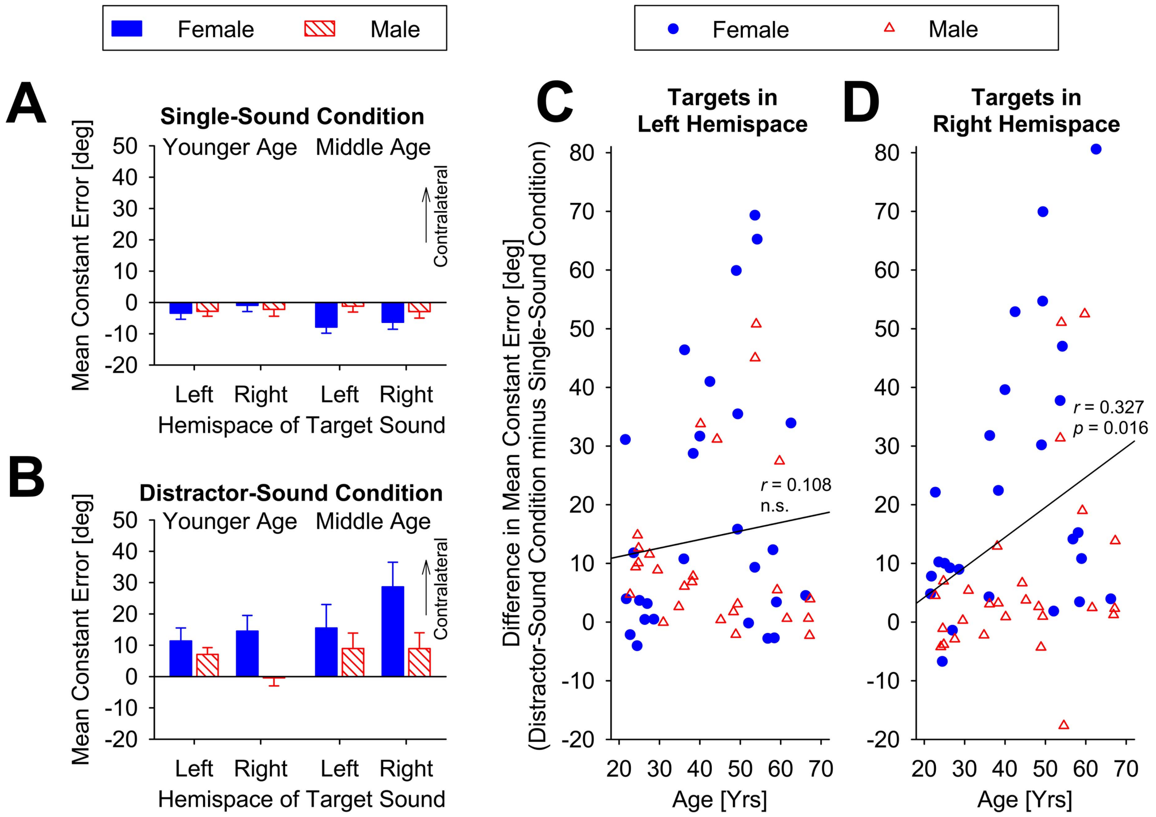

Figure 3. Mean constant errors (error bars, standard error) in pointing to targets in left and right hemispaces are shown for the different groups of subjects in the single-sound condition (A) and with a distractor sound at 46° to the left or right of the median plane (B). Positive constant errors indicate a bias toward the side contralateral to the target. Individual constant errors of males and females are plotted as a function of the subjects' age for targets in left (C) and right hemispaces (D). Black lines indicate regression lines across data from males and females.

There was a significant condition × sex interaction ($F_{(1, 50)} = 8.31$, $p = 0.005$, $\eta_p^2 = 0.143$), indicating that the pulling effect was sex-specific. Post-hoc *t*-tests indicated that both women (mean 17.3°, SE 3.6; $t_{(26)} = 4.77$, $p < 0.0001$) and men (mean 6.2°, SE 2.5; $t_{(26)} = 2.46$, $p = 0.021$) showed a significant constant error toward the distractor position, which was significantly larger for women than for men ($t_{(52)} = 2.50$, $p = 0.016$). No significant differences between women and men were found for the constant error in the single-sound condition ($t_{(52)} = 1.50$). Most importantly, the difference in constant error between conditions was significantly larger for women (mean 21.9°, SE 4.0) than for men (mean 8.5°, SE 2.8; $t_{(52)} = 2.74$, $p = 0.009$). The main effect of sex was not significant ($F_{(1, 50)} = 4.01$, $p = 0.051$, $\eta_p^2 = 0.074$), indicating that an influence of sex was not demonstrable when data were collapsed across the two conditions. The interactions of hemispace × sex ($F_{(1, 50)} = 3.79$, $p = 0.057$, $\eta_p^2 = 0.070$) and condition × hemispace × sex ($F_{(1, 50)} = 3.57$, $p = 0.065$, $\eta_p^2 = 0.067$) were not significant. Taken together, these analyses indicate that a significant influence of sex was present in the spatial pulling effect, but not for localization of single targets. The influence of sex on the pulling effect did not differ with targets in left and right hemispaces.

There were significant interactions of condition × age group ($F_{(1, 50)} = 4.06$, $p = 0.049$, $\eta_p^2 = 0.075$) and condition × hemispace × age group ($F_{(1, 50)} = 4.42$, $p = 0.041$, $\eta_p^2 = 0.081$). Post-hoc *t*-tests showed significantly smaller constant error in the single-sound, than in the distractor-sound conditions for each hemispace for each age group ($t_{(26)} \geq 3.28$, $p \leq 0.003$), thus indicating that the pulling effect always occurred. More importantly, compared with the younger group, the middle-age group showed a significantly larger pulling effect for targets in right hemispace ($t_{(52)} = 2.37$, $p = 0.023$), but not in left hemispace ($t_{(52)} = 0.76$). The main effect of age group was not significant ($F_{(1,50)} = 1.30$, $p = 0.26$). The main effect of hemispace ($F_{(1,50)} = 0.62$, $p = 0.44$) and all other interactions (all $F \leq 0.91$, $p \geq 0.34$) were not significant. In sum, these analyses demonstrate a significant influence of age on the pulling effect for targets in right hemispace, but not for targets in left hemispace. The localization of single sources did not depend on age.

Further analyses of the mean constant errors as a function of age revealed a significant increase of the difference in constant error between the two conditions with age for women for targets in the right hemispace ($r = 0.413$, $p = 0.032$), but not for the left hemispace, nor for men ($r \leq 0.351$; Fig. 3C, D). However, statistical comparisons failed to confirm any significant differences between correlation coefficients (resulting from the plot of the differences in constant error between the two conditions as a function of age) for men and women and between correlation coefficients for left and right hemispaces ($p \geq 0.1$). Correlations between the data for left (Fig. 3C) and right hemispaces (Fig. 3D) indicated that women ($r = 0.529$, $p = 0.005$) and men ($r = 0.745$, $p < 0.0001$) with lower performance in one hemispace also performed lower in the other hemispace. There was no correlation between age and constant error in the single-sound condition ($r \leq 0.364$; not shown).

There was no correlation between hearing threshold and constant error in the distractor-sound condition ($r \leq 0.270$) for any of the frequencies used in the audiometric test (125-8000 Hz), suggesting that the pulling effect was independent of hearing thresholds. Also, the absence of correlation between hearing threshold and constant error in the single-sound condition ($r \leq 0.239$) suggested an independence of target localization from hearing thresholds.

4. Discussion

Across all groups, a synchronous distractor resulted in a bias in perceived target location toward the location of the distractor (Fig. 2). This pulling effect may reflect an important element of the subject's performance in spatial analysis of auditory scenes. The magnitude of the pulling effect depended on both age and sex: The localization of the target sound was more biased by the distractor for older than younger and female than male subjects (Fig. 3). The localization of single sounds did not depend on age or sex.

4.1. Age-related differences

The pulling effect increased with age. Thus, there may be an age-related decline in the ability to segregate two concurrent sounds. The lack of an age effect for single-sound localization may be explained by relatively low task difficulty, and the fact that the older group included mainly middle-aged subjects. In seeming opposition to this, Abel et al. (2000) have shown that correct single-source identification judgments decreased as early as in the third decade of life. However, the proportion of correct identifications analysed by these authors may involve factors different from the constant error used here as a measure of performance. Also, an anechoic environment was used here, while the experiments of Abel et al. (2000) were conducted in a semireverberant environment, thus involving phenomena such as echo suppression (Cranford et al., 1990). Because echoes could have been distracting, the approach of Abel et al. (2000) may be comparable with the present distractor-sound condition, in which deterioration in performance was obtained at middle age (cf. Lee et al., 2009; Litovsky and Shinn-Cunningham, 2001).

The origin of this age-related increase of the pulling effect remains unclear. As age groups did not substantially differ in hearing thresholds for the frequency range of the stimuli used and correlations between hearing thresholds and the pulling effect were absent, one may assume that age-related changes in auditory central processing and cognition may be more relevant for this finding than peripheral hearing loss. However, some of the middle-aged subjects showed some degree of severe hearing loss for mid to high frequencies (see 2.1.). It is possible that these changes in peripheral sensory input could trigger processes of brain reorganization at a higher-order level over the course of aging (for review, see Li and Lindenberger, 2002).

The pulling effect for the middle-age group was significantly stronger with targets to the right than to the left, whereas the effect was roughly symmetrical for the younger group (see Fig. 3B). This result left the question of whether in the middle-age group distractors to the left were more effective than distractors to right, or targets to the right were more resistant to the pulling effect than targets to the left. The latter assumption can be related to the well-documented contralaterality of auditory cortical processing (Woldorff et al., 1999), which is also relevant for free-field sound sources presented in one hemispace: spatial analysis of the target sound might be related to the cortical hemisphere contralateral to this hemispace. Thus, at first glance, the lower performance in right hemispace found for middle-aged subjects might indicate that the left hemisphere is more susceptible to effects of ageing than the right hemisphere. However, the analyses shown in Fig. 3 were based on data obtained with two sound sources, each in one hemispace, thus supplying approximately equal sound energy to the two ears and similar auditory input to the two cerebral hemispheres. As a consequence of this experimental design, it may have been the task of attending to a specific sound source that was relevant for the emergence of the asymmetry. If so, the asymmetry should be interpreted in terms of higher-order spatial attention. Studies using young adults that employed audiospatial tasks with single sound sources have revealed a left-hemispace advantage, e.g., for localization (Abel et al., 2000; Burke et al., 1994) or motion perception (Hirnstein et al., 2007). Such asymmetries have been related to the superiority of the right cortical hemisphere in auditory spatial processing (Griffiths et al., 1998; Kaiser et al., 2000; Kreitewolf et al., 2011). Using single sources, Abel et al. (2000) found such a left-hemispace advantage for subjects up to 50 years old, but not for older subjects. However, on the basis of the present results, the question remains of whether age-related deteriorative processes in spatial audition are specifically related to a decline in right-hemispheric functions, to a more global decline of both hemispheres, or to a decline of interhemispheric communication (Daselaar and Cabeza, 2004). Also, left/right asymmetries in auditory performance may depend substantially on the stimuli and tasks used. In particular, the age-related decline in central processing of speech is known to be greater for left-ear than for right-ear input (e.g., Jerger et al., 1994). Because of this stimulus and task specifity of bilateral asymmetry in auditory processing, it seems unlikely that the present results obtained with localization of simple noise stimuli can be generalized. Future studies using a greater variety of stimuli including speech may help to elucidate this problem.

4.2. Sex differences

While men and women showed similar performance in the single-sound condition, men revealed consistently higher performance than women in target localization with the distractor sound. These findings are consistent with the higher precision of sound localization in men than women, as recently reported by Zündorf et al. (2011), who used a task of localization of non-verbal natural sounds in a multi-source environment with five simultaneously active loudspeakers and a younger group of subjects. The present study, combined with previous studies, shows that sex has a substantial influence on the perceptual integration of different sound sources. This effect of sex seems to occur independently of whether the target and distractor stimuli consist of natural sounds or more artificial noise stimuli.

As pointed out by Zündorf et al. (2011), the higher performance of men can be interpreted in more general terms of audiospatial attention, since the task required extraction of auditory information about the target sound in the presence of a competing sound. The higher male performance in this task may parallel findings of men outperforming women in right-monaural vertical sound localization, auditory motion perception of looming sounds, and auditory spatial attention (Lewald, 2004; Neuhoff et al., 2009; Simon-Dack et al., 2009), as well as men outperforming women in visuospatial attention (e.g., Kimura, 1992; Stoet, 2010; for a detailed discussion, see Zündorf et al., 2011). These sex-related differences in spatial attention and the effect of sex demonstrated here are possibly of similar origin. It has been proposed that such sex differences could be associated with the stronger brain asymmetry in men, resulting in a more effective use of the right hemisphere, which is specialized for spatial functions (Halpern, 1996; Hausmann and Güntürkün, 1999; Hiscock et al., 1995; McGlone, 1980). This view predicts a sex-specific asymmetry in performance, which was not established by the present analyses. However, if one considers the large interindivual variability of the data (see also below), this negative finding is far from being conclusive and future studies may focus on this issue.

4.3. Sex differences across the life span

The trend shown in Fig. 3B suggests an age-related decline in performance that was stronger for women than for men. However, the statistical analyses did not reveal a significant interaction between sex and age for the pulling effect. The failure to find an interaction between sex and age may be a consequence of large interindividual variability. In particular, there were individual male and female subjects who performed well even in the middle-age group, suggesting that neither sex nor age always affect performance. The difference between groups was mainly caused by an increase in the portion of low performers in the middle-aged female group compared with younger women or men.

Independently of age and sex, interindividual variability was remarkably high, with constant errors ranging from zero to more than 30° in each group of subjects (Fig. 3C, D). Dramatic variability in performance between subjects has been previously reported using auditory selective attention tasks. Recently, Ruggles et al. (2012) showed that these interindividual differences correlated with physiological differences in temporal coding precision in the auditory brainstem. Since brainstem encoding of sound has been related to several factors involving experience (e.g., musical training and reading proficiency; for a recent review, see Hornickel and Kraus, 2012), it remains an open question whether individual experience could be more relevant to differences in auditory selective attention than sex and age, as were investigated here.

As mentioned in the Introduction (1.), the literature on age-related decline in cognitive abilities of women and men is quite heterogenous, suggesting that relations between the factors of age and sex are highly task and stimulus specific. As in the present study, the meta-analysis of Meinz and Salthouse (1998) on sex- and age-related differences in spatial attention also failed to demonstrate an interaction of age and sex for spatial tasks. However, there were some hints of greater age-related decline in cognitive abilities for women than for men. Maylor et al. (2007) found interactions of age and sex for visuospatial performance that, although significant, were extremely small. It is possible that the present results reflect general, supramodal characteristics of the effects of sex and age on spatial performance, rather than a peculiarity of the auditory modality. However, it is important to note that the segregation of target and distractor in the task used here involved auditory spectrotemporal analyses for the discrimination of two concurrent stimuli with different amplitude modulation. It is conceivable that age and sex had different influences on these two aspects of the task, which would provide an alternative explanation for the absence of an interaction of age and sex.

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