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Auditory localization by subjects with unilateral tinnitus

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Tinnitus is associated with changes in neural activity. How such alterations impact the localization ability of subjects with tinnitus remains largely unexplored. In this study, subjects with self-reported unilateral tinnitus were compared to subjects with matching hearing loss at high frequencies and to normal-hearing subjects in horizontal and vertical plane localization tasks. Subjects were asked to localize a pink noise source either alone or over background noise. Results showed some degree of difference between subjects with tinnitus and subjects with normal hearing in horizontal plane localization, which was exacerbated by background noise. However, this difference could be explained by different hearing sensitivities between groups. In vertical plane localization there was no difference between groups in the binaural listening condition, but in monaural listening the tinnitus group localized significantly worse with the tinnitus ear. This effect remained when accounting for differences in hearing sensitivity. It is concluded that tinnitus may degrade auditory localization ability, but this effect is for the most part due to the associated levels of hearing loss. More detailed studies are needed to fully disentangle the effects of hearing loss and tinnitus. © 2016 Acoustical Society of America.

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I. INTRODUCTION

Tinnitus is the occurrence of an auditory sensation without the presence of an acoustic stimulus (Jastreboff, 1990) and is frequently described as “a ringing in the ears” (Baguley, 2002). Approximately 79% of subjects with tinnitus report that tinnitus resembles tones while 21% report that it resembles a broadband noise (Eggermont, 2003). There may be many different mechanisms causing or interacting with tinnitus, and several can be at play within one subject (Baguley, 2002). Hearing loss is a risk factor for tinnitus, and most subjects with tinnitus have some degree of hearing loss at high frequencies (König *et al.*, 2006; Nicolas-Puel *et al.*, 2002). Hearing loss is indeed considered the most common cause of tinnitus, but also other causes have been identified, such as neurologic factors, infectious diseases, medications, and temporomandibular joint dysfunction (Han *et al.*, 2009).

Tinnitus is evidenced by changes in electrophysiological measures along the auditory chain (Eggermont and Roberts, 2004), including structures that are thought to be involved in the localization of auditory events. There is evidence for increased activity in the cochlear nucleus (CN) of the brainstem in tinnitus patients and animal models of tinnitus

(Koehler and Shore, 2013; Li *et al.*, 2013; Roberts *et al.*, 2010). The CN has neurons that are sensitive to spatial attributes of sound stimuli and it is assumed to be responsible for extracting spectral cues for the localization of sounds (May, 2000; Schnupp *et al.*, 2011; Yu and Young, 2000). CN neurons affected by tinnitus have been found to increase their spontaneous activity as a result of decreased input from earlier stages of the auditory chain (Brozoski *et al.*, 2002; Kaltenbach *et al.*, 2004; Noreña, 2011; Schaette, 2014). This imbalance in activity can propagate in the auditory system and eventually be experienced as tinnitus. In subjects with chronic tinnitus, this mechanism can eventually be evidenced by reorganization of tonotopic maps in the auditory cortex (Eggermont, 2006; Muhlneckel *et al.*, 1998; Wienbruch *et al.*, 2006) although this is not always the case (Langers *et al.*, 2012). Since spectral cues are crucial for sound localization—both in the vertical plane and in the horizontal plane (Blauert, 1997; Middlebrooks and Green, 1991)—it is pertinent to question whether subjects with tinnitus have poorer sound localization abilities.

Currently, there are not enough comprehensive studies to draw clear conclusions about possible effects of tinnitus on localization ability. In a study testing minimum audible horizontal angles for noise and tone sounds, it was found that subjects with both sensorineural hearing loss and tinnitus did not differ from normal listening subjects

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(Niewiarowicz and Kaczmarek, 2011). However, subjects with tinnitus discriminated significantly worse those stimuli that consisted of sounds matched with their own tinnitus frequency. In another study on horizontal plane localization that used only pure tones as stimuli, it was found that there were significantly higher localization errors over all stimulation frequencies in subjects with tinnitus, compared to subjects with normal listening ability (An *et al.*, 2012). The current study is the first to report data on vertical plane localization in subjects with tinnitus.

Most subjects with tinnitus have some degree of hearing loss, and hearing loss itself can have an effect on sound localization [see Akeroyd (2014) for a recent review]. Age related hearing loss, known as presbycusis, is evidenced by degraded high-frequency hearing with increasing age, and has been shown to have a negative effect on sound localization abilities in both vertical and horizontal planes (Butler, 1970; Dobrev *et al.*, 2011; Lorenzi *et al.*, 1999a; Otte *et al.*, 2013; Rakerd *et al.*, 1998). Indeed, high frequencies are crucial for vertical plane localization, since most pinna-related cues are encoded above 3 kHz (Butler and Humanski, 1992; Middlebrooks and Green, 1991). In unilateral hearing loss there is great variability in localization accuracy: sometimes it is degraded, sometimes unaffected (Rothpletz *et al.*, 2012). Conductive hearing loss significantly affects horizontal plane discrimination, probably due to altered interaural cues, whereas in sensorineural hearing loss particularly vertical plane discrimination and high frequency sensitivity are correlated (Noble *et al.*, 1994).

In this study the goal was to address both horizontal and vertical plane localization accuracy, in subjects with normal hearing, high-frequency hearing loss, and tinnitus. It was hypothesized that possible alterations of the neural activity along the auditory pathway in subjects with tinnitus, coupled with typical hearing loss at high frequencies and assuming tinnitus as a distracting monaural tone, could lead to greater localization impairment in this population. In vertical plane localization, subjects were localized both binaurally and with each ear blocked. Additionally, in some horizontal and vertical localization conditions, background noise was introduced in the room. Results are presented in terms of response distribution and average localization error.

II. METHODS

A. Subjects

A total of 25 subjects took part in the experiment. The participants were divided into three groups based on their hearing: subjects with self-reported unilateral tinnitus, subjects with hearing loss in the high frequencies, and a control group with normal hearing. In the tinnitus (TI) group there were eight subjects with a mean age of 38.8 [standard deviation (SD) = 16]; in the high frequency hearing loss (HF-HL) group there were eight subjects with a mean age of 37.2 (SD = 11.4); in the normal hearing (NH) group there were nine subjects with a mean age of 24.3 (SD = 3.27). All subjects provided written informed consent. All subjects underwent extended audiometric screening, up to 16 kHz. First, an automated audiometry was conducted as a screening procedure in order to find signs of hearing loss. If hearing loss was suspected, clinical audiometry was performed to confirm the finding. All subjects in the TI group and all except one in the HF-HL group underwent clinical audiometry. For the one subject in the HF-HL group who was not available for the clinical audiometry, the audiogram was estimated based on the results from the automated audiometry. The audiograms of each group are presented in Fig. 1. A two-way analysis of variance was performed to test for differences in thresholds between groups accounting for each tested frequency (three groups $\times$ eight frequencies). In the left ear, there was a significant effect of group ($F_{(2)} = 35.897$, $p < 0.001$), which the *post hoc* Tukey test revealed to only be significant between the NH group and the remaining groups. Pairwise t-tests for differences in hearing sensitivity between the TI and HF-HL groups frequency by frequency revealed no significant effects. In the right ear, similar results were found. There was a significant effect of group ($F_{(2)} = 56.657$, $p < 0.001$) which was found to only be significant between the NH group and the remaining groups. There were no statistically significant differences in the hearing sensitivity between the TI and HF-HL groups at any frequency.

For the TI group, additional subjective measures of tinnitus were obtained in addition to audiometric data (Table I). Tinnitus pitch was assessed by comparing the tinnitus sound

FIG. 1. (Color online) Audiograms (dashed lines, separate lines for each ear) and average audiograms (full lines) of each experimental group: NH, HF-HL, and TI.

TABLE I. Tinnitus characteristics from subjects in the TI group.

Subject number	Age	Sex	Tinnitus side	Best matched frequency (average likeness score)	MML
1	64	male	left	16 kHz (8.3)	33.75 dB
4	52	male	left	12.5 kHz (9.3)	50 dB
8	59	female	left	—	—
11	32	male	left	14 kHz and 16 kHz (9.8)	47.5 dB
13	23	male	right	16 kHz (7.7)	50 dB
14	36	male	left	10 kHz (10)	27.5 dB
19	56	female	right	12.5 kHz (8.3)	45 dB
20	26	male	right	16 kHz (9.3)	52.5 dB

to tone beeps presented with the audiometer and rating the tones on a likeness scale from 0 (not at all similar to the tinnitus sound) to 10 (exactly like the tinnitus sound). Each tone was presented at least twice and the average score was used for determining the best matching frequency. Also, the minimum masking level (MML) of tinnitus was measured by presenting white noise from a loudspeaker in a listening booth and increasing the sound intensity in 5 dB steps until tinnitus was completely masked by the noise. The ascent was done three times, after which the hearing threshold for the white noise stimulus was determined and the MML calculated by subtracting the hearing threshold from the average level needed to mask tinnitus. For subject number four the determination of pitch or MML could not be done reliably, because the tinnitus sound was very broadband and noise-like itself.

B. Stimuli

There were two experimental conditions for both the horizontal and vertical localization tasks. In the no noise condition only a target sound was presented as stimulus. In the noise condition there was a continuous background noise over which the target sound was presented.

The target stimulus was a pink noise burst, randomly generated for each trial. The duration was 500 ms, including

50-ms rise and decay times, while the sound pressure level was measured to be 65 dB sound pressure level (SPL) at the listening position.

In the noise condition, uncorrelated pink noise was emitted from 16 loudspeakers around the listener. The background sound started before the beginning of the block and existed throughout the block. The sound pressure level of the background sound alone at the listening position was 50 dB SPL.

C. Experimental setup

The experiment was conducted in an anechoic chamber. The room was equipped with a multichannel loudspeaker layout, a headrest, curtains, and a touch-screen for the user interface [Fig. 2(A)].

The user interface was different in the horizontal and vertical plane blocks—there was a response bar that was horizontal in horizontal plane trials [Fig. 2(C)] and vertical in vertical trials [Fig. 2(D)], but the size of the bar remained the same. The response bar ranged continuously from -60° to $+60^\circ$ in both trial types. The bar contained one cross in the middle and two lines in the positions corresponding to -30° and $+30^\circ$. These served as cues to the cross and reference lines in the curtain. Subjects were asked to translate the perceived position of the sound to the corresponding space

FIG. 2. (Color online) Experimental setup. (A) The array of loudspeakers behind the acoustically transparent curtains. (B) A close-up of the headrest and the visual reference lines. [(C) and (D)] The response interfaces in horizontal and vertical blocks, respectively (“seuraava” in Finnish translates to “next”).

in the response interface with respect to the curtain references.

The loudspeakers that were used in the experiment to emit the target sounds were in the front of the listener. In the horizontal plane there were seven loudspeakers from -45° to 45° in azimuth with a 15° separation, all at elevation 0° . In the vertical plane there were five loudspeakers at -45° , -22.5° , 0° , 22.5° , and 45° in elevation and always at 0° azimuth. The loudspeakers were all approximately at 2.15 m from the listener's ears. The background sound presented in the noise condition was emitted simultaneously from 16 loudspeakers that were positioned also at a 2.15 m distance: eight in the horizontal plane (0° elevation; 0° , 45° , 90° , 135° , 180° , 225° , 270° , and 315° azimuth); four above the listener (45° elevation; 0° , 90° , 180° , and 270° azimuth); and four below the listener (-45° elevation; 0° , 90° , 180° , and 270° azimuth).

The headrest consisted of a chin rest and a support for the forehead and was positioned so that the head of the listener was at the center of the loudspeaker layout. In this position, the loudspeakers on the horizontal plane were at the height of the listeners' ears.

Three acoustically transparent curtains prevented visibility of the loudspeakers. There were five visible marks on the curtain: a cross in front of the listener, and four lines that were visual aids to ease the use of the response interface. The lines were placed at $\pm 30^\circ$ both in horizontal plane and vertical plane [see Fig. 2(B)]. The lighting in the room was dim to prevent possible visual cues.

D. Design and procedure

The experiment comprised eight different blocks, each with one of two experimental conditions and either of two stimuli orientations. The two experimental conditions were no noise and noise. The two stimuli orientations were horizontal and vertical plane.

Both the vertical and horizontal cases included blocks in silence and with background noise. The vertical blocks were repeated with each ear blocked with a foam earplug (3M™ E-A-R™ Classic™) at a time, the options being no blocking, right ear/tinnitus ear blocked, and left ear/non-tinnitus ear blocked. Thus, there were two horizontal blocks and six vertical plane blocks.

Each trial consisted of a single presentation of the target stimulus, emitted from one loudspeaker. The task of the test subject was to indicate the perceived location of the auditory event using a response bar on the user interface. The task was the same in each test case and block, regardless of the possible background noise or earplugs. In each test case, the procedure was as follows. Before the stimulus was presented, the test subjects fixated their eyes on the cross on the curtain. After pressing “next” on the user interface [“seuraava,” see Figs. 2(C) and 2(D)], the stimulus was presented. Then, subjects were allowed to look at the touch screen and place their answer. Having done that, they looked at the cross again and pressed “next.” The head was kept in the desired position with the headrest.

There were ten repetitions of each stimulus position in each block, resulting in a total of 50 trials in the vertical plane localization blocks and 70 in the horizontal blocks. The order of the blocks was counterbalanced between subjects. Within each block all trials were pseudo-randomized.

Prior to the first block, there was a short training session and explanation of the procedure inside the anechoic chamber. In the training, it was ensured that the test subject understood the instructions and knew how to use the user interface.

E. Response analysis and statistical testing

A mixed-effects analysis was performed in order to investigate the effects of group and condition on the localization error. Group (NH, HF-HL, and TI) and condition (noise, no noise) were included in the model as fixed effects, and by-subject and by-loudspeaker-position random intercepts were fitted in order to account for the repeated measures design (ten repetitions per loudspeaker position per subject). The analysis was conducted with R software, using the *lme4*-package for mixed linear models. Statistical testing of the models was done with the *lmerTest*-package, taking advantage of Satterthwaite's approximation in determining the significance of fixed effects.

III. RESULTS

A. Effect of background noise, group, and hemifield

1. Horizontal plane

The distributions of individual answers from blocks testing horizontal localization are shown in Fig. 3. Subjects tended to localize more accurately near the center (0°) and performed less accurately the more laterally the stimulus was presented. There are also visible differences between subject groups, with the NH group performing clearly better than the HF-HL and TI groups. The differences between groups are less obvious at -45° and 45° , but quite clear for the more medial loudspeaker positions, where answers of the NH group are focused more sharply around the true loudspeaker positions.

The average absolute localization errors (see Fig. 4) show the same pattern as the raw data. In the no noise condition, average errors in horizontal plane localization were 2.74° , 3.98° , and 4.71° for NH, HF-HL, and TI groups, respectively. In the noise condition, average errors were 2.77° (NH), 3.74° (HF-HL), and 5.36° (TI). The linear mixed-effects model showed a significant main effect for group ($F = 5.52$, $p < 0.05$) as well as for the group $\times$ condition interaction ($F = 4.55$, $p < 0.05$). *Post hoc* t-tests of main effect group revealed that the TI group had significantly higher errors overall than the NH group ($t = 3.32$, $p < 0.01$). This pattern was especially pronounced in the noise condition, where the difference between NH and TI groups was 2.6° ($t = 3.70$, $p < 0.01$). The same could be seen in the no noise condition where the difference between NH and TI groups was 2.0° ($t = 2.80$, $p < 0.01$). The difference between TI and HF-HL in the noise condition did not survive correction for multiple comparisons ($t = 2.24$, $p = 0.034$; p -value

FIG. 3. (Color online) Distribution of individual answers in horizontal localization for each of the experimental groups: NH, HF-HL, and TI. Answers from the noise and no noise condition indicated by dark and light gray circles, respectively.

threshold by Bonferroni correction for multiple comparisons: $0.05/3 = 0.017$), nor was there any statistically significant difference between TI and HF-HL groups in the no noise condition ($t = 2.03$, $p = 0.054$).

The TI group showed an increase in localization errors as a result of background noise ($t = -3.05$, $p < 0.01$), whereas the other groups were not significantly affected by the background noise.

a. Hemifield differences. In order to find out whether subjects performed differently on opposing hemifields, and especially whether the laterality of tinnitus had an effect on localization ability, the results for the TI and HF-HL groups were further analyzed taking into account the side of stimulus. A binary factor was included in the model, indicating whether or not the stimulus was presented in the tinnitus hemifield. The same was done for the HF-HL group, but for this group the factor indicated whether the sound was

coming from the side of worse hearing. Here, side of worse hearing means the side of the ear with a higher pure tone average (PTA). For the TI group, the ear with the higher PTA also coincided with the side of experienced tinnitus in all those cases where the subjects had both tinnitus and hearing loss. The loudspeaker position 0° was excluded from the analysis, and only positions truly on either hemifield were compared.

A mixed-effects model was fitted to the data in order to investigate effects of hemifield and condition on localization error. Hemifield (tinnitus/worse hemifield, non-tinnitus/better hemifield) and condition (noise, no noise) were included in the model as fixed effects, and by-subject and by-loudspeaker-position random intercepts were fitted in order to account for the repeated measures design (ten repetitions per loudspeaker position per subject). The statistical analysis revealed no significant differences between hemispheres for the TI group, but a significant *hemisphere* $\times$ *condition* interaction was found for the HF-HL group ($F = 6.10$, $p < 0.05$). *Post hoc* tests indicated that the interaction was driven by a difference between hemifields in the no noise condition; accuracy was 1° worse on the hemifield of worse hearing ($t = -3.09$, $p < 0.008$, Bonferroni-corrected for multiple comparisons: $0.05/6 = 0.008$).

FIG. 4. (Color online) Horizontal localization errors per experimental group and condition. Error bars represent the 95% confidence intervals.

2. Vertical plane

Localization errors in the vertical plane were much higher than in the horizontal plane. As can be seen in Fig. 5, the variability in answers was quite large, the TI group having the highest response variability. There is a clear difference between positions below and above 0° , with higher variability for responses to stimuli from loudspeakers above the midline. Answers also seem to be drawn towards the center, except for the loudspeaker positioned at 0° , where all groups were clearly more likely to localize the sound as coming from above the loudspeaker rather than from below

FIG. 5. (Color online) Distribution of individual answers in vertical localization for each of the experimental groups: NH, HF-HL, and TI. Answers from the noise and no noise condition, indicated by dark and light gray circles, respectively.

the actual position. It is possible that the reference marks at $\pm 30^\circ$ (illustrated in Fig. 5 by dashed lines) could also have influenced the answers. In particular, some answers of the NH group are slightly concentrated around the upper line, although subjects were instructed to use the marks only for scale.

The average localization errors (see Fig. 6) in the no noise condition were 10.52° (NH), 15.34° (HF-HL), and 16.12° (TI), compared to the condition with noise: 10.56° (NH), 14.66° (HF-HL), and 16.84° (TI). This pattern is identical to the behavior in horizontal plane localization, although in this case the mixed-effects model did not reach statistical significance for either of the main effects *group* ($F = 2.36$, $p > 0.1$) or *condition* ($F = 0.004$, $p > 0.9$) or the interaction *group* $\times$ *condition* ($F = 0.9$, $p > 0.4$). Because of a visually apparent trend for between-group differences, an explorative *post hoc* pairwise t-test was conducted. The test showed that the difference of 5.9° in overall localization

errors (no noise and noise conditions combined) between NH and TI groups was on the edge of significance ($t = 2.07$, $p = 0.05$), but did not survive correction for multiple comparisons.

B. Effect of ear blocking

Ear blocking was only applied in the vertical plane conditions

The localization task was more challenging when the subjects were listening with one ear only, which can clearly be seen from Fig. 7. Here the distribution of answers is shown for both ears separately. For the HF-HL and TI groups this means separating the answers based on the imbalance in hearing ability between ears. Worse ear means the ear with a higher PTA. For the TI group, the ear with the higher PTA also coincided with the side of experienced tinnitus in all those cases where the subjects had both tinnitus and hearing loss. The loudspeaker positions above midline were especially difficult to localize with one ear only.

Listening with the better (TI and HF-NH) or left ear (NH), the average localization errors were 11.19° (NH), 18.89° (HF-HL), and 18.17° (TI) in the no noise condition and 9.68° (NH), 18.74° (HF-HL), and 18.43° (TI) in the noise condition (Fig. 8). Statistical testing for the better ear resulted in a significant main effect of *group* ($F = 5.40$, $p < 0.05$). The *post hoc* tests for *group* revealed that both HF-HL and TI groups differed significantly from the NH group; the HF-HL performing on average 8.4° worse than the NH ($t = -2.90$, $p < 0.01$) and the TI group 7.9° worse than the NH ($t = 2.91$, $p < 0.01$). There was no significant difference in performance between noise and no noise conditions for the better ear.

Listening with the worse (TI and HF-HL) or right ear (NH) (see Fig. 8), average localization errors were 13.26° (NH), 19.33° (HF-HL), and 18.95° (TI) in the no noise condition, and 12.94° (NH), 18.16° (HF-HL), and 20.97° (TI) in

FIG. 6. (Color online) Vertical localization errors per experimental group and condition. Error bars represent the 95% confidence intervals.

FIG. 7. (Color online) Distribution of individual answers in vertical localization for each blocked ear and each of the experimental groups: NH, HF-HL, and TI. Answers from the noise and no noise conditions, indicated by dark and light gray circles, respectively.

FIG. 8. (Color online) Vertical localization error per experimental group and ear blocked. Error bars represent the 95% confidence intervals.

the noise condition. As opposed to the results for the better ear, the main effect *group* did not reach significance ($F = 3.42$, $p = 0.05$). Instead, there was a significant *group* $\times$ *condition* interaction ($F = 4.06$, $p < 0.05$). *Post hoc* tests showed significantly higher errors for the TI group compared to NH in the noise condition ($t = 2.65$, $p < 0.017$) as well as higher errors in the noise condition compared to the no noise condition for the TI group ($t = -2.48$, $p < 0.017$).

C. Explorative analysis of confounding factors in HF-HL and TI groups

Although the HF-HL and TI groups were matched with respect to hearing loss and age, an additional explorative step was taken in order to investigate the effects of interindividual variability of these factors on the observed results. The explorative analysis focused only on the differences between the HF-HL and TI groups. *Group*, *condition*, *age*, and *PTA* were included in the mixed-effects model as fixed effects along with *group* $\times$ *condition* and *PTA* $\times$ *condition* interactions, and by-subject and by-loudspeaker-position random intercepts were fitted in order to account for the repeated measures design (ten repetitions per loudspeaker position per subject). The PTA was calculated differently for

horizontal and vertical localization tasks, since it was assumed that the ability to hear higher frequencies is more important in the vertical task whereas lower frequencies play a more prominent role in horizontal localization. Thus, in horizontal tasks PTA was calculated as the average hearing threshold over the traditional audiometric frequencies from 125 Hz to 8 kHz and in vertical tasks as the average hearing threshold from 2 kHz up to 16 kHz.

For horizontal localization accuracy, there were no significant main effects, but instead a highly significant $PTA \times condition$ interaction ($F = 11.8$, $p < 0.001$), suggesting that although PTA itself may not have had an overall effect on the localization accuracy in horizontal plane, it could explain the differences between no noise and noise conditions.

Explorative analysis of the elevation tasks showed that the noise-induced decrease in localization accuracy in the TI group, when listening with the tinnitus ear, was not related to hearing loss. There was a strong $group \times condition$ interaction ($F = 8.7$, $p < 0.01$) when listening with the tinnitus/worse ear only, but no significant main effects for $group$, $condition$, PTA , or age . The $PTA \times condition$ interaction term had no significant effect on the accuracy. The analysis did not reveal any significant main effects or interactions when listening with both ears or with the non-tinnitus/better ear.

IV. DISCUSSION

The current study tested the localization of sounds by subjects with tinnitus, subjects with high-frequency hearing loss, and subjects with normal hearing. Localization accuracy was tested in the horizontal and vertical plane, with and without background noise. In the vertical localization subjects localized both monaurally and binaurally. Overall, the performance of the TI group was very similar to the HF-HL group, both of the groups showing on average worse localization accuracy than the NH group. The original hypothesis that localization errors would be higher in the TI group than in the HF-HL group could not be confirmed.

Horizontal plane localization performance of the NH group was comparable to the results of [Makous and Middlebrooks \(1990\)](#), whereas in the vertical plane the errors were higher compared to that study. This difference in vertical plane accuracy is most likely explained by the fact that in the current study the subjects were not allowed to move their head, contrary to the study by Makous and Middlebrooks, where subjects could move their head. [Perret and Noble \(1997\)](#) found that allowing head movements improved the localization in the vertical plane remarkably. The elevation localization results of the current study carry many similarities to those in the study by Perret and Noble, where head movements were also restricted. Subjects tended to localize the sound source at 0° elevation above the horizontal line, rather than evenly above and below the midline. Also, overall elevation localization accuracy was clearly higher than in the experiment by Makous and Middlebrooks.

In horizontal localization tasks the TI group localized significantly worse than the NH group. No differences were

found between the HF-HL group and the other two groups. The TI group was further negatively affected by background noise, while the other two groups were not. Explorative analysis suggested that the results in horizontal localization conditions could be explained by inter-individual differences in hearing abilities and thus were likely not related to tinnitus.

In elevation localization the TI group was more heterogeneous in accuracy than the other groups, but no significant differences were found between groups for binaural listening. For monaural listening, the TI group was the only one negatively affected by background noise and became significantly different from the NH group, but not from the HF-HL group. The tinnitus-specificity of this finding was supported by the explorative analysis step, where the confounding factors age and amount of high-frequency hearing loss had no significant effect on the observed results. It is noteworthy that the background noise degraded localization performance only when listening with the tinnitus ear, and that there was no corresponding decrease in accuracy in the worse ear of the HF-HL group. Thus, it would seem that the observed effect of background noise in the elevation localization task could be specific to tinnitus, although the results provide only limited evidence for such an interpretation. The tentative neural mechanisms for such a tinnitus-related effect can only be speculated. That the effect can only be seen in the tinnitus ear could point to structures early in the auditory chain, such as the cochlear nucleus. Tinnitus-related activity in localization-sensitive areas could interfere with localization cues and lead to degraded localization performance. Further, including a wideband background noise likely affects neural activity patterns along the auditory pathway differently in tinnitus and non-tinnitus subjects. For example, tinnitus can often be masked by wideband sounds, sometimes leading to short-lived residual inhibition of tinnitus. This could further confuse localization cues and be evidenced by increased sensitivity to background noise, as seen in our results.

[Lorenzi et al. \(1999a\)](#) found that hearing-impaired subjects localized worse in horizontal plane than normal-hearing subjects, and that adding a background noise affected the hearing-impaired subjects at higher signal-to-noise ratios than the normal-hearing. Nevertheless, even the hearing-impaired subjects did not lose accuracy in horizontal plane localization until signal-to-noise ratio was as low as 0 to 6 dB. In the current experiment, signal-to-noise ratio was 15 dB and yielded no effect for the NH and HF-HL groups, agreeing with the findings of [Lorenzi et al. \(1999a,b\)](#). Also [Good and Gilkey \(1996\)](#) found practically no effect of background noise in horizontal or vertical plane localization for normal-hearing subjects until signal-to-noise ratios of 4–8 dB or less, and that elevation localization was more affected by increasing background noise levels.

There are two previous studies—that the authors are aware of—which report the localization accuracy for tinnitus subjects in the horizontal plane and no studies for vertical plane. [An et al. \(2012\)](#) found tinnitus subjects to localize pure tones in the horizontal plane worse than the non-tinnitus control group. Further, they showed hemifield differences within the tinnitus group, indicating that localization

was deterred on the side ipsilateral to the tinnitus. They concluded that tinnitus interfered with the interaural level difference (ILD) cue, leading to degraded localization performance. It is, however, not straightforward to confirm this conclusion based on the data provided, since the results from all tinnitus subjects were pooled in the analysis, not taking into account the individual tinnitus-matched frequency. If the tinnitus sound itself would cause an imbalance in the ILD, localization should only be hindered at the tinnitus frequency and remain unaffected at other frequencies. Also, the ILD cue is dominant only at frequencies above approximately 1.5 kHz (Blauert, 1997). At the lower range of frequencies, including the 250 Hz and 1 kHz used by An *et al.*, the dominant binaural cue is the interaural phase delay (IPD). In contrast to An *et al.*, the current study found no difference between the two hemifields, most likely due to differences in stimuli and experimental setup between the two studies. On a more general level, the results are in line with those reported by An *et al.* in that TI group had a trend for higher error scores than the two control groups. In another study, Niewiarowicz and Kaczmarek (2011) determined minimum audible angles in the horizontal plane for various narrowband and broadband stimuli in tinnitus and non-tinnitus groups. While they did not find any differences between the two groups, the tinnitus subjects performed worse when presented with a tinnitus-matched stimulus as compared to other stimuli. The fact that we used only broadband noise could explain why there was no significant difference between HF-HL and TI groups in the no-noise condition of the current study.

Listening with one ear increased localization errors overall, but not dramatically. This result is in line with results from previous studies on monaural localization (Agterberg *et al.*, 2014; Slattery and Middlebrooks, 1994; Van Wanrooij and Van Opstal, 2007), which concluded that the spectral cues necessary for localization in the vertical plane are still present when listening with one ear only.

Although there were no statistically significant differences in audiograms between the TI and HF-HL groups, this does not mean that hearing abilities were identical in both groups. It is noticeable in the Fig. 1 that there were some differences in hearing pattern between the HF-HL group and the TI group, and the question arises, whether this could affect the observed results. The TI group has a larger variability between subjects and slightly elevated thresholds at the lowest frequencies, from 125 to 500 Hz. We expect these slight differences in low frequency hearing thresholds to have no significant impact on auditory localization in either the horizontal or the vertical plane. In horizontal plane localization, binaural information from the lower frequencies is mostly used in terms of ITDs—not ILDs, which might be affected by hearing loss—due to the reduced spatial information in terms of level differences found at those frequencies (e.g., Blauert, 1997; McPherson and Middlebrooks, 2001). Similarly, although spectral cues are crucial for auditory localization in the vertical plane, most of their information is encoded in frequencies above 3 kHz, due to little interaction between the head and sound at lower frequencies (Roffler and Butler, 1968; Hebrank and Wright, 1974; Algazi *et al.*,

2001). Thus, very subtle differences in hearing thresholds in frequencies below 1 kHz are unlikely to affect sound localization.

The small sample sizes in the current study limit the conclusions that can be drawn. There was a trend towards higher localization errors in the TI group, but the differences did not reach statistical significance. Also, the tinnitus characteristics of the TI group were not representative of the whole spectrum of tinnitus symptoms, so the results presented here are limited to this specific group only. Thus, the results regarding localization ability in subjects with tinnitus should be interpreted with care and considered as the starting point for further studies. Future studies could focus on the dynamic effects of background noise in tinnitus patients, e.g., by varying the level of background noise.

V. CONCLUSIONS

We studied sound localization accuracy in horizontal and vertical planes in three subject groups: normal hearing subjects, subjects with high-frequency hearing loss, and subjects with unilateral tinnitus. We were able to confirm previous findings regarding differences between normal-hearing and hearing-impaired subjects. The observed differences in overall localization accuracy between normal hearing and tinnitus subjects were largely explained by hearing loss, although limited evidence was found for more subtle differences between subjects with tinnitus and subjects with similar hearing loss profiles. The current study adds to existing data on sound localization ability of hearing-impaired subjects and suggests possible targets for more detailed experiments.

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