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„Plasticity of Spatial Processing in Normal Hearing: Reweighting of Binaural Cues“

verfasst von / submitted by

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Abstract

Normal hearing listeners use two binaural cues, the interaural time difference (ITD) and the interaural level difference (ILD), for sound localization in the horizontal plane. They apply frequency-dependent weights when combining them to determine the perceived sound source location. Cochlear implant (CI) listeners, however, rely almost entirely on ILDs, while ITDs contribute only very little or not at all. Since current CI-systems do not reliably convey ITD information, CI listeners might learn to ignore ITDs and focus on ILDs instead. This study investigated, whether the just described reweighting of the binaural cues is generally possible. 20 normal-hearing participants, assigned to two experimental groups, completed an experiment consisting of a pretest, measuring the initial weights of ITD and ILD, a seven-day training phase, in which visual feedback was given to reinforce one of the cues, and a posttest, to measure the weights again. Participants lateralized a narrow-band noise stimulus, bandpass-filtered around a centre frequency of 2.8 kHz. In the training, various combinations of spatially inconsistent ITD and ILD were presented and participants received visual feedback at the locations corresponding to either ITD or ILD (depending on the group) through a virtual visual environment. In both groups, the root mean square error (RMSE) related to the reinforced (target) cue declined more strongly from pre- to posttest than the RMSE related to the non-target cue, suggesting that participants reweighted the binaural cues in accordance with the visual feedback. This likely is the result of increased sensitivity to the target cue, since we did not find evidence that the non-target cue was ignored.

Keywords: interaural time difference, interaural level difference, reweighting, cochlear implants

Zusammenfassung

Normalhörende verwenden zwei binaurale Orientierungsreize (Cues), die interaurale Laufzeitdifferenz (ITD) und die interaurale Pegeldifferenz (ILD), für die Schalllokalisation in der horizontalen Ebene. Wenn sie diese Cues zu einer räumlichen Wahrnehmung verbinden, um den Ort der Schallquelle zu bestimmen, gewichten sie ITD und ILD je nach Frequenz unterschiedlich stark. Cochleaimplantat (CI)-Träger hingegen verwenden fast ausschließlich ILDs, während ITDs nur wenig oder gar nicht beitragen. Da aktuelle CI-Systeme ITD-Information nicht zuverlässig übertragen, ist es möglich, dass CI-Träger lernen, ITDs zu ignorieren und sich stattdessen auf ILDs zu fokussieren. Diese Studie untersuchte, ob die eben beschriebene Umgewichtung der binauralen Cues überhaupt möglich ist. Dazu schlossen 20 normal hörende Versuchsteilnehmer, auf zwei Experimentalgruppen aufgeteilt, ein Experiment ab. Dieses bestand aus einem Pretest, in dem die anfängliche Gewichtung von ITD und ILD gemessen wurde, einer siebentägigen Trainingsphase, in der einer der beiden Cues mithilfe von visuellem Feedback verstärkt wurde, und einem Posttest, in dem die Gewichtung erneut gemessen wurde. Die Versuchsteilnehmer lokalisierten ein Schmalbandrauschen mit einer Mittenfrequenz von 2.8 kHz. In der Trainingsphase wurden verschiedene Kombinationen räumlich inkonsistenter ITD und ILD präsentiert und die Versuchsteilnehmer erhielten durch eine virtuelle visuelle Umgebung visuelles Feedback an den entsprechenden Positionen von entweder ITD oder ILD (je nach Gruppe). In beiden Gruppen sank der root mean square error (RMSE) in Bezug auf den trainierten Cue stärker von Pre- zu Posttest als der RMSE in Bezug auf den nicht-trainierten Cue, was darauf schließen lässt, dass die Versuchsteilnehmer die binauralen Cues in Einklang mit dem visuellen Feedback umgewichtet haben. Dies ist wahrscheinlich auf eine erhöhte Sensitivität für den trainierten Cue zurückzuführen, da unsere Ergebnisse keine Evidenz für das Ignorieren des nicht-trainierten Cues bieten.

Schlüsselwörter: interaurale Laufzeitdifferenz, interaurale Pegeldifferenz, Umgewichtung, Cochleaimplantate

Introduction

Spatial hearing allows us to construct an internal spatial representation of our acoustic environment and is crucial for our ability to localize sound sources, to understand speech in noisy environments, to orient in space and to enjoy music. It is, therefore, a vital part of our everyday lives, for which we use a combination of both monaural and binaural cues.

Spatial hearing within the horizontal plane

For spatial hearing within the horizontal plane, we rely on two binaural cues: the interaural time difference (ITD), which is the difference in the arrival time of the sound to each ear, and the interaural level difference (ILD), which is the difference in sound pressure level at the two ears, arising because the head attenuates the sound reaching the far ear. These two cues provide information about the azimuth, that is the lateral angle of incidence of the sound source relative to the listener. Normal-hearing (NH) listeners use both ITDs and ILDs for sound localization in the horizontal plane and apply frequency-dependent weights when combining them to determine the perceived sound source location. According to the well-known duplex theory of binaural processing (Strutt, 1907), the ITD is the dominant localization cue for pure tones with frequencies of up to approximately 1.5 kHz, whereas for higher frequencies the ILD is the dominant cue. A more recent study showed, that this finding can be extended to low-pass (0.5-2 kHz) vs. high-pass (4-16 kHz) complex sounds: ITD weights are large and ILD weights are small for low-pass stimuli, whereas the opposite pattern is observed for high-pass stimuli. For wideband stimuli (0.5-16 kHz), the ITD weight is either greater than or equal to the one given to ILDs, depending on individual listeners (Macpherson & Middlebrooks, 2002).

Weighting of binaural cues

The weighting of binaural cues, also known as the trading ratio, is traditionally measured by presenting one of the cues at fixed magnitudes and instruct the participants to adjust the other cue, until the sound is perceived centrally (e.g., Deatherage & Hirsh, 1959). However, this method leads to a greater weight of the to-be-adjusted cue in relation to the fixed cue, probably because attention is shifted towards the to-be-adjusted cue (Lang & Buchner, 2008). A different approach is to confront the participants with an inconsistent ITD/ILD-combination (an auditory stimulus consisting of an ITD corresponding to one location and an ILD corresponding to a different location) and instruct them to indicate the perceived sound source location. The weighting can then be measured as the relative proximity of the perceived location to the corresponding location of either of the two cues, as shown by Macpherson and Middlebrooks (2002) using a virtual auditory space technique or with Stecker's (2010) "open-loop" procedure. In the virtual auditory space technique used by Macpherson and Middlebrooks (2002), the participants oriented towards a centring light emitting diode (LED) inside a darkened anechoic chamber and pressed a hand-held button, which led to the extinguishment of the LED and, after a short delay, the presentation of the sound via headphones. Then, the participants oriented towards the perceived location and pressed the button again, which elicited the measurement of their head orientation by a head-mounted tracking device. The weights of ITD and ILD were measured by comparing the magnitude of the natural ITD or ILD at the perceived location with the magnitude of the bias imposed on the respective cue. If the bias had no effect (i.e., the magnitude of the natural cue at the perceived location was the same as that of the unbiased cue), the weight received the value 0. If the magnitude of the natural cue at the perceived location was equal to that of the unbiased cue plus the imposed bias, the weight received the value 1. Intermediate magnitudes of the natural cue at the perceived location led to values between 0 and 1. Thus, they used dimensionless weights rather than the classical trading ratio in units of µs/dB. Stecker's (2010) "open-loop" procedure is very similar, except that he did not use a fixed LED, but the head orientation at the first button press as a reference. He computed ITD/ILD trading ratios with multiple linear regression of the response azimuth onto the imposed ITD and ILD and reported them in units of µs/dB. These calculations are good measures of the weighting of binaural cues, but they do not provide information about localization accuracy and precision. Responses are accurate, when the average response location is close to the target location, and precise, when they are consistent and reproducible, independent of accuracy (Heffner & Heffner, 2005). Since accuracy and precision are of interest when studying sound localization, they should also be a part of studies investigating the weighting of binaural cues. A measure, which incorporates localization accuracy as well as precision, is the root mean square error (RMSE) and is therefore the most meaningful single index to describe localization performance (Hartmann, 1983). In addition, when the RMSE between the perceived location and the corresponding location of either ITD or ILD is calculated and compared, it can also provide information about the respective weights of the cues.

Spatial hearing with cochlear implants (CIs)

Hearing impairment at one or both ears often causes deterioration or even total loss of spatial hearing ability, which in turn leads to severe difficulties in the daily listening situations mentioned at the beginning. In cases of profound hearing loss or complete deafness while the auditory nerve is still intact, CIs have been shown to be successful in restoring auditory sensation. CIs are auditory prostheses that stimulate the auditory nerve electrically. While state-of-the-art CIs enable listeners to understand speech in quiet, they allow only poor performance in horizontal sound localization and speech-understanding in noise, even if they are implanted bilaterally (Nopp, Schleich, & D'Haese, 2004; Schleich, Nopp, & D'Haese, 2004; van Hoesel & Tyler, 2003). It has been shown that localization in the horizontal plane with current CI-systems is almost entirely based on ILDs, while ITDs contribute only very little or not at all (Grantham, Ashmead, Ricketts, Haynes, & Labadie, 2008; Seeber & Fastl, 2008). On the one hand, this is due to the properties of current envelope-based clinical CI-systems, which do not encode the difference in arrival time in the fine structure of the stimulus waveform (fine structure ITD) and whose envelope ITD cues (the fluctuations in the temporal envelope due to ongoing amplitude modulation) for practically-relevant low modulation rates are not very salient (Grantham et al., 2008; Laback, Pok, Baumgartner, Deutsch, & Schmid, 2004; Laback, Zimmermann, Majdak, Baumgartner, & Pok, 2011). On the other hand, the sensitivity of CI listeners to fine structure ITDs presented via a research system at a single electrode pair is lower and much more variable across listeners compared to NH listeners (Laback, Majdak, & Baumgartner, 2007; Majdak, Laback, & Baumgartner 2006; van Hoesel, 2007). In other words, even if fine structure ITD information is conveyed, CI listeners perform worse on average than NH listeners do.

Research question and hypotheses

To explain the sole reliance on ILDs of CI listeners even in laboratory situations, where fine structure ITDs are conveyed, we hypothesize that CI listeners learn to ignore ITDs and focus on ILDs instead, because current envelope-based clinical systems do not reliably convey fine structure ITD information. That is, they learn to put greater weight on ILDs than on ITDs, because ILDs consistently indicate the sound source location, whereas ITDs arise at random or are not perceived at all. This implies an increase in sensitivity to ILDs, which is in line with the finding that CI listeners are even more sensitive to ILDs than untrained NH listeners (Aronoff, Freed, Fisher, Pal, & Soli, 2012). Thus, if it is possible to change the weights NH listeners apply when combining ITDs and ILDs into a spatial percept, this will suggest that CI listeners might also use this adaptive mechanism to focus on ILDs and to ignore ITDs. If a change of weights occurs because one of the binaural cues has been reinforced, we expect the relative proximity of the perceived locations to the corresponding locations of either of the cues to change over time (hypothesis 1). Additionally, if the cue, which is not reinforced, is successfully ignored, we expect the increase in lateralization accuracy and precision related to the reinforced cue from pre- to posttest to be greater for large inconsistencies than for consistent conditions (hypothesis 2).

Reweighting of binaural cues

In an early study, Jeffress and McFadden (1971) already tried to change the respective weights of ITDs and ILDs by providing visual feedback (a light) in correct trials. They used a lateralization task, in which participants had to left/right discriminate sounds with inconsistent combinations of ITD and ILD based on the cue they were trained on. For example, if participants were trained on the ITD cue, the sound pressure level was greater at the left ear, but the sound arrived earlier at the right ear, right would have been the correct answer. In contrast, if participants were trained on the ILD cue, left would have been the correct answer. Unfortunately, the study does not provide explicit information concerning the number of trials participants were trained with. Since accuracy did not differ between the conditions favouring ITD or ILD, the authors concluded that reweighting is not possible. However, they used a within subject design, starting with a training phase reinforcing the ITD cue, followed by a testing phase. Then, participants completed a training phase reinforcing the ILD cue, again followed by a testing phase. To allow for more training, to prevent sequence effects and to avoid having to reverse the effect of the first training phase, a design with two groups is more suited for studying the reweighting of binaural cues. Additionally, they tested only four participants and the lateralization task used provides relatively little information compared to the localization task used by Macpherson and Middlebrooks (2002) or Stecker (2010). Therefore, a combination of Macpherson and Middlebrooks' (2002) and Stecker's (2010) methods for measuring the weighting of binaural cues and training with feedback to reinforce one of the cues seems to be the most promising approach. Since vision is naturally used for auditory spatial calibration in NH listeners (Recanzone, 1998) and has been extensively used in studies of auditory spatial plasticity (e.g., Kopčo, Lin, Shinn-Cunningham, & Groh, 2009; Zwiers, van Opstal, & Paige, 2003), we also used visual feedback to reinforce one of the cues. To combine the described methods, we adapted the training procedure used by Majdak, Walder and Laback (2013): Instead of using the whole space, answers were restricted to the horizontal plane and the frontal area, because binaural cues only provide information about the azimuth, and, instead of using a hand-held pointer, positions were indicated via head turn, as in Macpherson and Middlebrooks' (2002) and Stecker's (2010) studies, which additionally provided proprioceptive information. Most importantly, the auditory stimuli consisted of independent combinations of ITD and ILD, to allow for the testing of our hypotheses.

Although Jeffress and McFadden's (1971) study is to our knowledge the only one in which the reweighting of binaural cues was investigated, there are many studies investigating adaptation to altered spatial cues, mostly by using ear plugs (see Carlile, 2014, for a review). Adaptation to altered spatial cues occurs between, rather than within, daily training sessions (Kumpik, Kacelnik, & King, 2010), which demonstrates the need for training sessions across multiple days. However, how many days participants have been trained, varies considerably across studies. Since Kumpik et al. (2010) observed adaptation within a period of seven to eight days, we used a similar time frame. In Kumpik et al.'s study, participants wore a unilateral earplug and performed a free-field localization task as well as a task assessing binaural sensitivity. Since they did not observe adaptation to the altered binaural cues, they attributed the adaptation observed in the free-field localization task to a reweighting of binaural and monaural spectral cues (i.e., a stronger weighting of the unaltered monaural cues of the open ear compared to the binaural cues). Therefore, to enable exclusive re-weighting of binaural cues, participants should not have access to unaltered, informative monaural spectral localization cues for their sound localization in the horizontal plane. This is possible by pre-senting auditory stimuli, which are not filtered with (individualized) head-related transfer functions (i.e., the natural auditory filter induced by the pinna, head and torso; HRTFs), via headphones.

Methods

Design

Our design consisted of a pre-training to check for basic lateralization ability, to get accus-tomed with the task and to check for sensitivity to both binaural cues, a pretest, a training phase and a posttest. The pre-training, the pretest and the first training session were completed on the first day, days two to six consisted of one training session each and on the seventh day the last training session as well as the posttest was performed. All seven sessions were completed within a two-week interval. We used two experimental groups that were trained either by reinforcing ITD cues (group A) or ILD cues (group B). Participants were pseudo-randomly assigned to one of the groups, ensuring balanced age, sex and basic lateralization ability.

Participants

A total of 26 participants were tested. They were recruited through the subject database of the Acoustics Research Institute of the Austrian Academy of Sciences and received monetary com-pensation for their participation. All participants provided informed consent before participating in the study. One participant reported having a tinnitus, but was included nonetheless, due to good performance in the pre-training. All other participants reported normal hearing. Of these 26 participants, three had to be excluded because they experienced dizziness induced by the head-mounted display used for the presentation of the visual environment. Another two participants exercised their right to terminate the experiment prematurely and were therefore excluded. In addition, one participant was excluded due to poor ITD-sensitivity. That is, his percentage of responses at the correct side in pre-training trials with ITD only (see procedure for details) deviated more than three standard deviations from the group's mean and was at chance level. 20 participants (ten female; mean age: 26.9 years; *SD* = 4.13; range: 21-40 years) therefore completed the experiment. Ten participants (five female; mean age: 27 years; *SD* = 5.27), were assigned to group A. The other ten participants (five female; mean age: 26.8 years; *SD* = 2.86), were assigned to group B. The mean probability of responses at the correct side in pre-training trials with ITD or ILD only (see procedure for details) of all included participants was 0.896 (*SD* = 0.080) for ITDs and 0.840 (*SD* = 0.071) for ILDs. Mean RMSEs between response and stimulus location of the second half of consistent ITD/ILD-combinations in the pre-training of all included participants (as an indicator of basic lateralization ability) was 9.230° (*SD* = 2.965). The RMSE was 8.885° (*SD* = 3.547) in group A and 9.576° (*SD* = 2.391) in group B.

Apparatus and stimuli

Target locations are defined as the locations corresponding to the trained cue (i.e., the locations corresponding to the ITDs for group A and the locations corresponding to the ILDs for group B). Consequently, non-target locations are defined as the locations corresponding to the cue, which is not trained (i.e., the locations corresponding to the ILDs for group A and the locations corresponding to the ITDs for group B). The 26 target locations were distributed between -45° (left) and +45° (right) with a spacing of 3.6° between locations (figure 1). This range corresponds to the field of view of the head-mounted display. In conditions with inconsistent ITD/ILD-combinations (i.e., in the pretest, the training sessions and the posttest), the non-target cue corresponded to uniformly distributed locations +/-25.2° around each target location, also with a spacing of 3.6° between locations, resulting in a range of non-target locations from -70.2° to 70.2°.

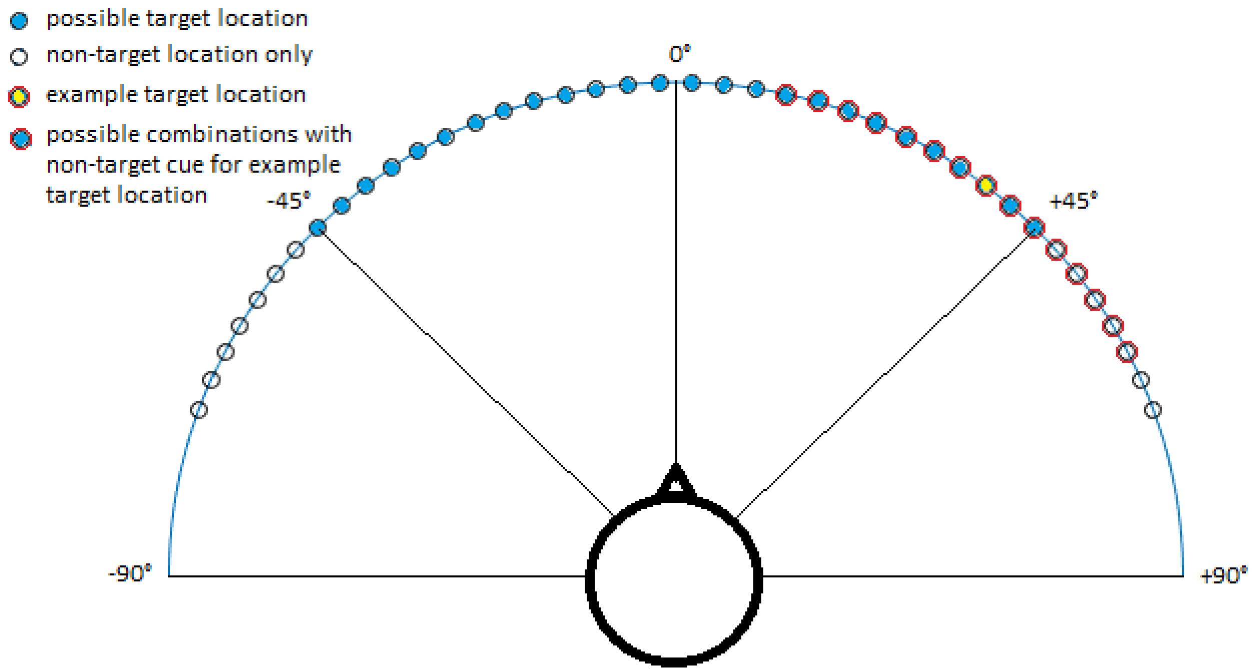

Figure 1. Possible target and non-target locations and their possible combinations.

Participants stood on a platform surrounded by a circular railing inside a semi-anechoic chamber. Stimuli were generated using a computer and output via a digital audio interface (ADI-8, RME) with a 96-kHz sampling rate. Auditory stimuli were narrow-band noise (one octave bandwidth) with a geometric centre frequency of 2.8 kHz and a duration of 500 ms, including 50 ms raised-cosine on/off ramps, presented via headphones (HD 580, Sennheiser). The overall sound pressure level varied randomly between 62.5 and 67.5 dB, to ensure that the ILDs and not absolute changes in the sound pressure level are used for lateralization. ITDs ranged from -662 to +662 µs and ILDs ranged from -19.4 to +19.4 dB, corresponding to an azimuth range from -70.2° to +70.2°, according to Xie (2013). Xie calculated ITDs and ILDs using the HRTFs of a dummy head (MIT-KEMAR with DB-61 small pinna). We used the ITD function obtained from the cross-correlation of the left and right ear head-related impulse responses (ITD_{corre}). Since ILDs are naturally dependent on frequency, we used the 2.8 kHz function. Visual feedback, a rotating cube at the target location, was provided through a virtual visual environment. This visual environment was presented binocularly via a head-mounted display (Oculus Rift) and consisted of a reference position (RP) straight ahead, a crosshair in the direction the head is oriented and a single horizontal line at 0° elevation as well as vertical lines every 15° for guidance. Additionally, the progress of the experimental session in percent was displayed and, if visual feedback was presented, an arrow pointing towards it as well as a yellow bar, whose length indicated the distance to it, were displayed. Participants' head position and orientation were tracked with a head-mounted tracking sensor (Flock of Birds, Ascension) and the visual environment was rendered accordingly in real-time. Only left/right movements led to the rendering of the visual environment, up/down movements had no effect.

Procedure

The experiments were conducted between December 1st 2016 and April 12th 2017 in the laboratory of the Acoustics Research Institute in Vienna. Firstly, the participants performed a lateralization pre-training with consistent ITD/ILD-combinations to check for basic lateralization ability and to get accustomed with the task. In addition, there were stimuli with either ITD only or ILD only, to check, whether participants were sensitive for each of the two cues. Of the 130 items, 78 were consistent ITD/ILD-combinations, 26 (each target location once) were items with ITD only and 26 (again each target location once) were items with ILD only. After 65 items, participants took a short break. The procedure, adapted from Majdak et al. (2013), was as follows (figure 2):

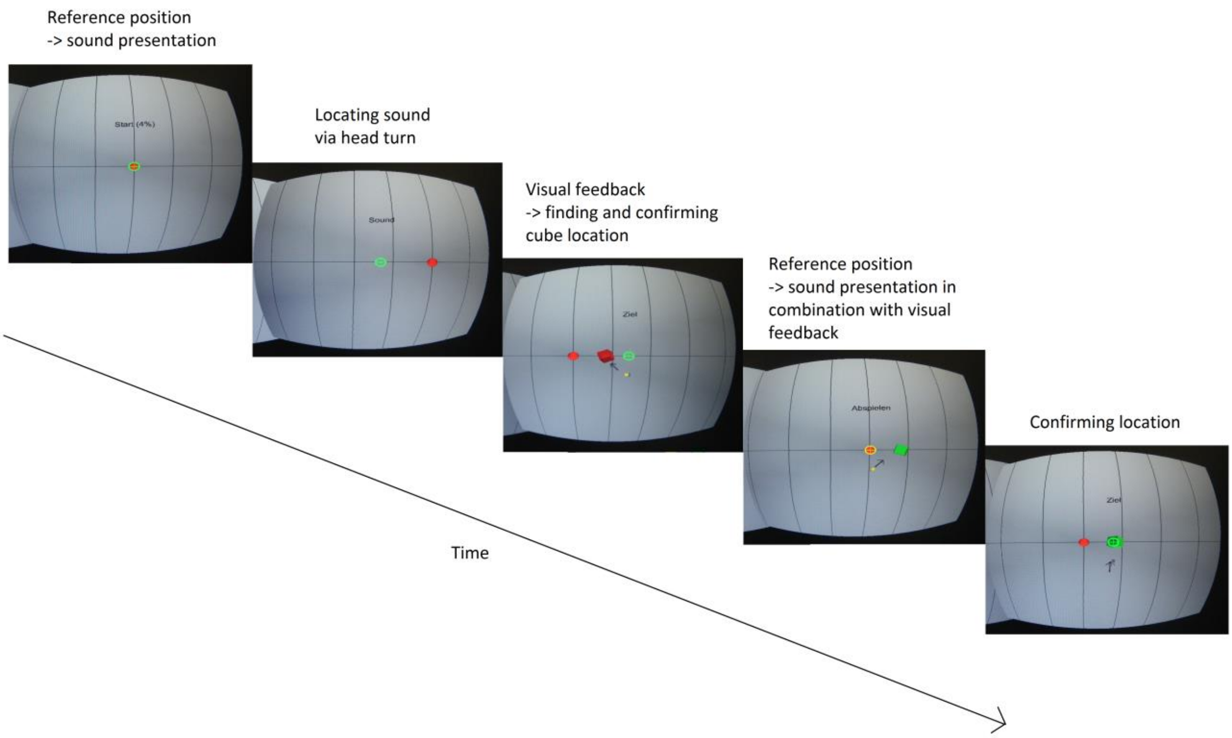

Figure 2. Procedure of a sample trial.

Participants were instructed to turn their head towards the RP. Then, they heard the acoustic stimulus and had to indicate the perceived location via head turn. When they pressed a button to indicate the location, visual feedback at the target location appeared. After the participants confirmed the target location by turning their head to the visual feedback and pressing a button, the rotating cube changed its colour from red to green and the participants were instructed to return to the RP and to press the button again. Then, the auditory stimulus was presented again, now in combination with the visual feedback. Thus, a combination of proprioceptive (due to the head turn), visual and auditory feedback was given. After the target location was confirmed again and participants returned to the RP, a new item was presented. Secondly, a pretest without the visual feedback was performed. The pretest was similar to Macpherson and Middlebrooks' (2002) virtual auditory space technique or Stecker's (2010) "open-loop" procedure, except that answers were restricted to the horizontal plane and the frontal area and a virtual visual environment was presented. Participants listened to the auditory stimulus and were instructed to indicate the perceived location via head turn and button press. After they returned to the RP and pressed the button again, a new item was presented. The auditory stimuli of the pretest consisted of all ITD/ILD-combinations possible in the subsequent training phase, 446 items in total, namely each of the 26 target cues in all 15 possible combinations with non-target cues plus the ITD/ILD combinations only possible for the other group. For example, the combination of the ILD corresponding to 70.2° azimuth and the ITD corresponding to 45° azimuth is possible for group A, for whom ITD is the target cue, but not for group B, for whom ILD is the target cue. In the pretest however, both groups listened to this combination, so that the pretest was identical for both groups. After each 150 items, participants took a short break. Thirdly, the participants were trained on seven different days within a two-week interval, with the first training session being performed on the same day as the pre-training as well as the pretest and the last training session being performed on the same day as the posttest. The training procedure was the same as that of the pre-training, except for the auditory stimuli. They consisted of inconsistent and consistent ITD/ILD-combinations, namely all possible combinations of target and non-target cues. Visual feedback appeared at the location indicated by the ITD cue for group A and at the location indicated by the ILD cue for group B. Participants completed 195 items in the first and the last training session and 390 items on days two to six. After each 65 items, participants took a short break. Fourthly, a posttest identical to the pretest was performed. The pre-training, the pretest and the posttest were identical for all participants, while the training differed in which binaural cue was the target and which was the non-target cue. Items in all tasks and conditions were presented in completely random order, whilst in the pre-training it was ensured, that the first 26 items were consistent ITD/ILD-combinations.

Analysis

As a measure of lateralization accuracy and precision, we calculated the RMSE between response and stimulus location in degrees for two conditions: On the one hand relative to the positions indicated by the ITDs ($RMSE_{ITD}$)

$$RMSE_{ITD} = \sqrt{\frac{\sum_{t=1}^{n} \left(\underset{\text{Azimuth}}{\text{ITD}} - \underset{\text{Azimuth}}{\text{Response}} \right)^2}{n}} \quad (1)$$

and on the other hand relative to the positions indicated by the ILDs ($RMSE_{ILD}$).

$$RMSE_{ILD} = \sqrt{\frac{\sum_{t=1}^{n} \left(\underset{\text{Azimuth}}{\text{ILD}} - \underset{\text{Azimuth}}{\text{Response}} \right)^2}{n}} \quad (2)$$

We excluded items, whose target location was more lateral than +/- 45°, since a uniform distribution of non-target locations is not possible for them. We then ran a mixed design ANOVA with the within-subjects factors *time* (pretest vs. posttest) as well as *cue* ($RMSE_{ITD}$ vs. $RMSE_{ILD}$) and *group* (group A vs. group B) as a between-subjects factor. We also ran two separate 2 x 2 repeated measures ANOVAs with the within-subjects factors *time* (pretest vs. posttest) and *cue* ($RMSE_{ITD}$ vs. $RMSE_{ILD}$), to test for differences between the pre- and posttest in each group separately. To examine, whether the effect of maximal inconsistency on errors related to the reinforced cue changes over time, two separate (one for each group) 2 x 2 repeated measures ANOVAs with the within-subjects factors *time* (pretest vs. posttest) and *inconsistency* (consistent vs. 25.2° inconsistency) were run, including only consistent items as well as items with the maximal inconsistency and using the RMSEs related to the reinforced cue as the dependent variable.

Results

Figure 3 shows the training progress of each group. The first training session had the strongest effect, but mean $RMSE_{ITD}$s in group A were monotonically decreasing up to the seventh training session and mean $RMSE_{ILD}$s in group B were monotonically decreasing up to the fifth training session. Since the weights of the binaural cues are usually measured without visual feedback (Macpherson & Middlebrooks, 2002; Stecker, 2010) and the auditory stimuli in the training were not identical in the two groups, only the RMSEs measured with the pre- and posttest were used for further analyses.

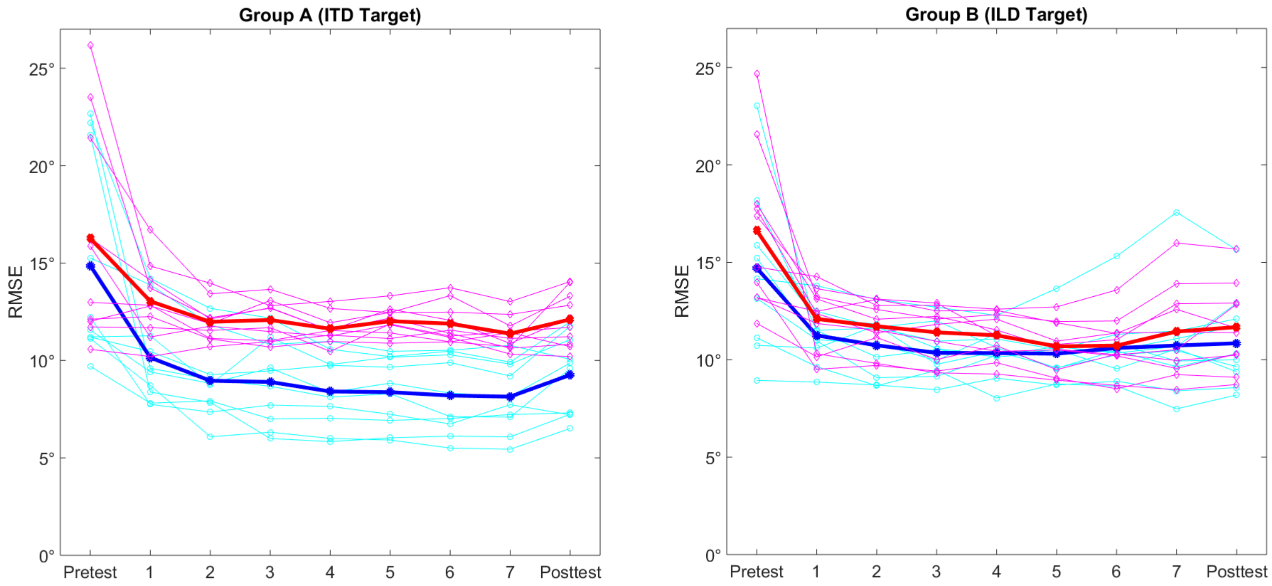

Figure 3. Training progress of group A (left) and group B (right). Mean RMSEs as well as RMSEs of each participant of the pretest, of each of the seven training sessions and of the posttest are depicted. Thicker lines are means (blue: mean $RMSE_{ITD}$; red: mean $RMSE_{ILD}$). Cyan lines are the $RMSE_{ITD}$s of each participant and magenta lines are the $RMSE_{ILD}$s of each participant.

In the pretest, mean $RMSE_{ITD}$s were 14.870 (*SD* = 5.221) in group A and 14.706 (*SD* = 4.101) in group B. Mean $RMSE_{ILD}$s were 16.265 (*SD* = 5.545) in group A and 16.634 (*SD* = 4.077) in group B. In the posttest, mean $RMSE_{ITD}$s were 9.260 (*SD* = 2.048) in group A and 10.846 (*SD* = 2.270) in group B. Mean $RMSE_{ILD}$s were 12.106 (*SD* = 1.397) in group A and 11.676 (*SD* = 2.196) in group B (table 1). Mean RMSEs as well as RMSEs of individual participants are visualized in figure 4 separately for each group. Consistent with hypothesis 1, mean $RMSE_{ITD}$s seem to decline more strongly than $RMSE_{ILD}$s in group A, whereas $RMSE_{ILD}$s seem to decline more strongly than $RMSE_{ITD}$s in group B. However, there seems to be great interpersonal variability.

Table 1

Means and standard deviations (in brackets) of the RMSEs (in degrees) of the pre- and posttest in each group

	Group A		Group B	
	$RMSE_{ITD}$	$RMSE_{ILD}$	$RMSE_{ITD}$	$RMSE_{ILD}$
Pretest	14.870 (5.221)	16.265 (5.545)	14.706 (4.101)	16.634 (4.077)
Posttest	9.260 (2.048)	12.106 (1.397)	10.846 (2.270)	11.676 (2.196)

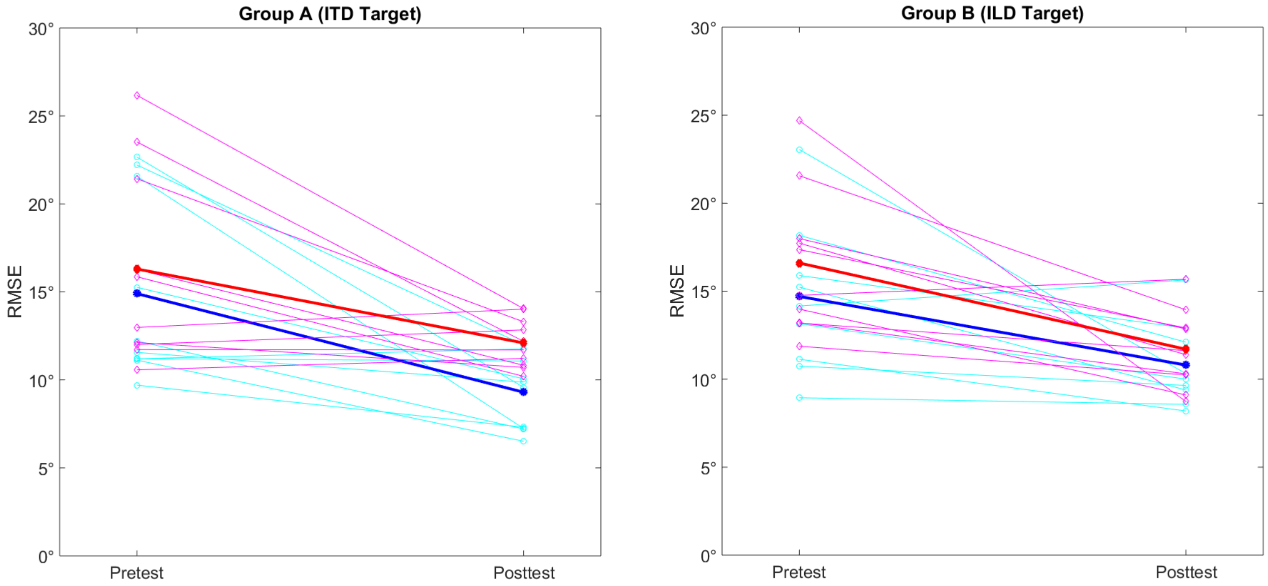

Figure 4. Mean RMSEs as well as RMSEs of each participant separately for each group. Thicker lines are means (blue: mean $RMSE_{ITD}$; red: mean $RMSE_{ILD}$). Cyan lines are the $RMSE_{ITD}$s, magenta lines are the $RMSE_{ILD}$s of each participant.

Requirements of the ANOVAs

The requirements of the ANOVA, normal distribution as well as homoscedasticity (for comparing independent groups) or sphericity (for repeated measures ANOVAs), were tested using the Shapiro-Wilk- and the Levene- (or Mauchly-) Test. Regarding the mixed-design ANOVA, only $RMSE_{ITD}$s of group A in the pretest were not normally distributed, all other *p*-values of the Shapiro-Wilk-Test were > .05. In addition, homoscedasticity can be assumed, due to the non-significant Levene-Test. Because of its robustness and because RMSEs of only one of the eight conditions were not normally distributed, the mixed design ANOVA was considered appropriate. Concerning normal distribution, the same results apply to the two *time* x *cue* repeated measures ANOVAs. In addition, with only two levels of repeated measures (as it is the case for all our repeated measures ANOVAs), sphericity can be assumed without testing. For the two *time* x *inconsistency* repeated measures ANOVAs, normal distribution was also tested. In group A, only $RMSE_{ITD}$s in inconsistent conditions in the pretest were not normally distributed, all other *p*-values of the Shapiro-Wilk-Test were > .05. In group B, normal distribution can be assumed (all *p*-values > .05). Again, because of their robustness, all 2 x 2 repeated measures ANOVAs were considered appropriate.

Mixed design ANOVA

The mixed design ANOVA yielded significant main effects of the factors *time* ($F(1, 18) = 19.619$; $p < .001$; $\eta^2_p = .522$), with larger RMSEs in the pretest ($M = 15.619$; $SD = 4.700$)

than in the posttest (*M* = 10.972; *SD* = 2.200), and *cue* (F(1,18) = 33.554; p < .001; η^2_p = .651), with smaller $RMSE_{ITD}$s (*M* = 12.421; *SD* = 4.300) than $RMSE_{ILD}$s (*M* = 14.170; *SD* = 4.200). Additionally, the three-way interaction *time* x *cue* x *group* was significant (F(1, 18) = 13.993; p = .001; η^2_p = .437). There was no significant main effect of the factor *group* and all other interactions were also non-significant (table 2).

Table 2

Results of the mixed-design ANOVA

	F	*df*	*p*	η^2_p
*Time****	19.619	1, 18	<.001	.552
*Cue****	33.554	1, 18	<.001	.651
Group	0.079	1, 18	.782	.004
Time x *Cue*	0.268	1, 18	.611	.015
Time x *Group*	0.051	1, 18	.823	.003
Cue x *Group*	1.506	1, 18	.235	.077
Time x *Cue* x *Group****	13.993	1, 18	.001	.437

* $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

***Time* x *cue* repeated measures ANOVAs**

The 2 x 2 repeated measures ANOVA of group A yielded significant main effects of the factors *time* (F(1, 9) = 9.130; p = .014; η^2_p = .504), with larger RMSEs in the pretest (*M* = 15.568; *SD* = 5.290) than in the posttest (*M* = 10.683; *SD* = 2.246), and *cue* (F(1, 9) = 18.401; p = .002; η^2_p = .672), with smaller $RMSE_{ITD}$s (*M* = 12.065; *SD* = 4.814) than $RMSE_{ILD}$s (*M* = 14.186; *SD* = 4.477). In addition, the *time* x *cue* interaction was significant (F(1, 9) = 7.784; p = .021; η^2_p = .464), showing that $RMSE_{ITD}$s declined more strongly than $RMSE_{ILD}$s from pre- to posttest.

The 2 x 2 repeated measures ANOVA of group B yielded significant main effects of the factors *time* (F(1, 9) = 10.865; p = .009; η^2_p = .547), with larger RMSEs in the pretest (*M* = 15.670; *SD* = 4.101) than in the posttest (*M* = 11.261; *SD* = 2.215), and *cue* (F(1, 9) = 15.767; p = .003; η^2_p = .637), with smaller $RMSE_{ITD}$s (*M* = 12.776; *SD* = 3.785) than $RMSE_{ILD}$s (*M* = 14.155; *SD* = 4.077). Furthermore, the *time* x *cue* interaction was significant (F(1, 9) = 6.218; p = .034; η^2_p = .409), showing that $RMSE_{ILD}$s declined more strongly than $RMSE_{ITD}$s from pre- to posttest. Figure 5 visualizes the *time* x *cue* interactions separately for each group.

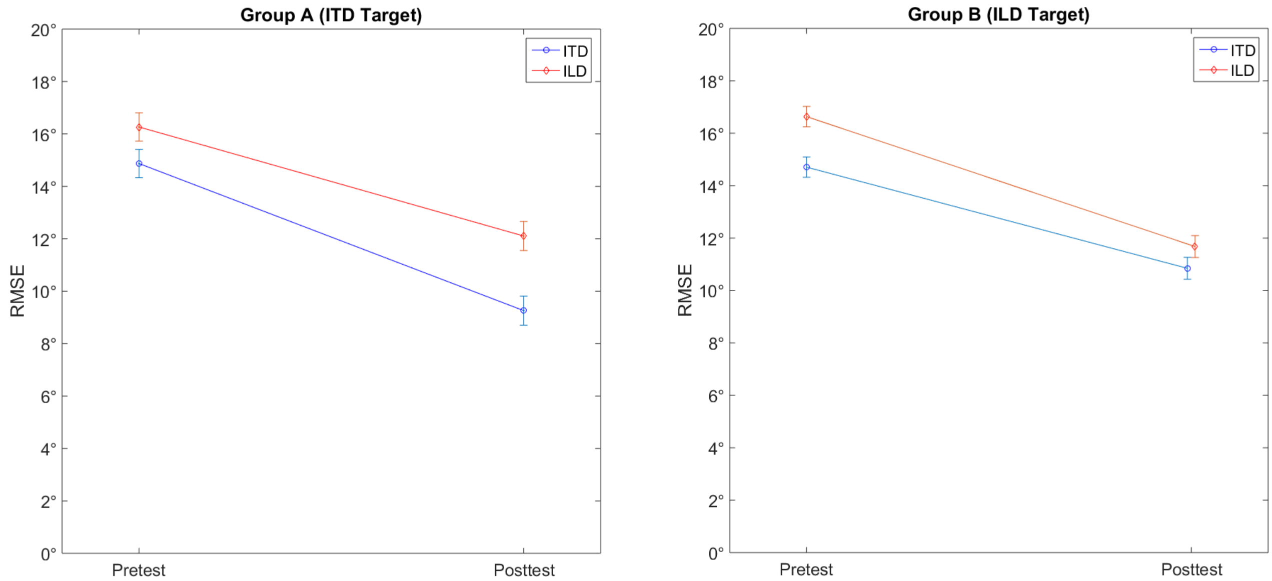

Figure 5. Time x cue interaction for each group separately. Error bars show 95% confidence intervals of the within-subject comparisons.[1]

Time **x** ***inconsistency*** **repeated measures ANOVAs**

The 2 x 2 repeated measures ANOVA of group A yielded significant main effects of the factors *time* ($F(1, 9) = 12.748$; $p = .006$; $\eta^2_p = .586$), with larger $RMSE_{ITD}$s in the pretest ($M = 15.257$; $SD = 5.506$) than in the posttest ($M = 9.267$; $SD = 1.859$), and *inconsistency* ($F(1, 9) = 57.014$; $p < .001$; $\eta^2_p = .864$), with smaller RMSEs in consistent conditions ($M = 10.029$; $SD = 3.380$) than in conditions with an inconsistency of 25.2° ($M = 14.495$; $SD = 3.074$). The *time* x *inconsistency* interaction was non-significant ($F(1, 9) = 1.718$; $p = .222$; $\eta^2_p = .160$) (figure 6).

[1] Since typically the between-subject variance does not play a role in the statistical analysis of within-subject designs, the classical confidence intervals of between-subject designs cannot be interpreted meaningfully in within-subject designs. However, standardised mean differences, whose confidence intervals can be interpreted analogously to the classical confidence intervals in between-subject designs, can be calculated (see Loftus & Masson, 1994). This and the following figures show the 95% confidence intervals calculated by using these standardised means.

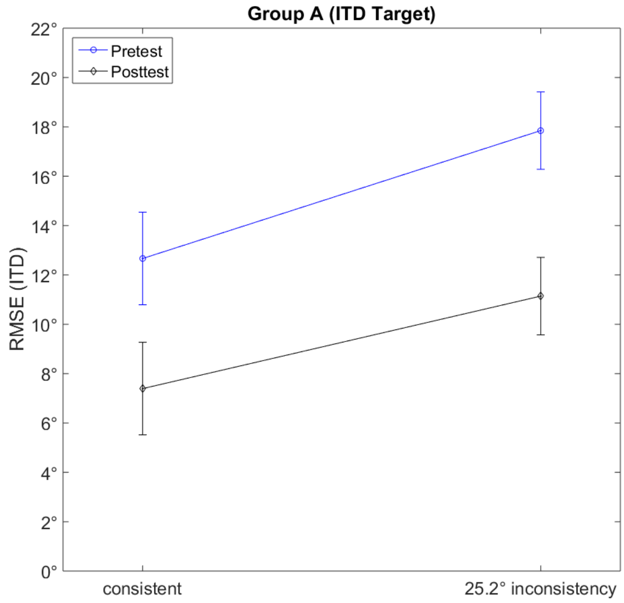

Figure 6. Non-significant time x inconsistency interaction of group A. Large inconsistencies have an equally strong impact on $RMSE_{ITD}$s in the pre- and posttest. Error bars show confidence intervals of the within-subject comparisons.

The 2 x 2 repeated measures ANOVA of group B yielded significant main effects of the factors *time* ($F(1, 9) = 11.259$; $p = .008$; $\eta^2_p = .556$), with larger RMSEs in the pretest ($M = 16.979$; $SD = 3.915$) than in the posttest (M = 12,086; $SD = 2.868$), and *inconsistency* ($F(1, 9) = 85.874$; $p < .001$; $\eta^2_p = 905$), with smaller RMSEs in consistent conditions ($M = 11.039$; $SD = 2.973$) than in conditions with an inconsistency of 25.2° ($M = 18.026$; $SD = 2.631$). The *time* x *inconsistency* interaction was non-significant ($F(1, 9) = 0.046$; $p = .835$; $\eta^2_p = .005$) (figure 7).

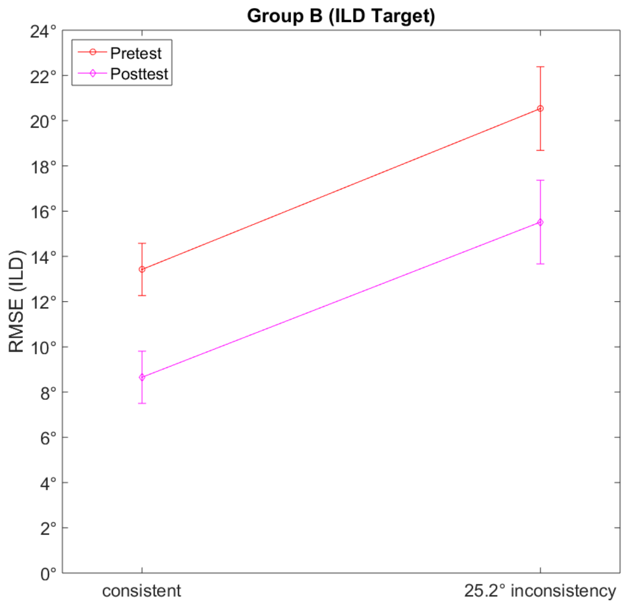

Figure 7. Non-significant time x inconsistency interaction of group B. Large inconsistencies have an equally strong impact on $RMSE_{ILD}$s in the pre- and posttest. Error bars show confidence intervals of the within-subject comparisons.

Discussion

The main effect of the factor *time* with smaller RMSEs in the posttest indicates an increase in lateralization performance related to both cues and in both groups. Thus, there was an improvement in performance from pre- to posttest independent of reweighting. Moreover, our results appear to replicate Macpherson and Middlebrooks (2002) finding that, if ITD-dominated low frequencies are available (which, given the shallow filter slopes, is also the case for the band-pass-filtered stimuli centred at 2.8 kHz we used), mean ITD weights are greater than mean ILD weights. In our study, $RMSE_{ITD}$s were smaller than $RMSE_{ILD}$s, as shown by the main effect of the factor *cue*. Most importantly, with respect to hypothesis 1, the significant three-way interaction *time* x *cue* x *group* shows, that the RMSEs changed differently over time in the two groups. Namely, $RMSE_{ITD}$s declined more strongly than $RMSE_{ILD}$s in group A, whereas in group B, $RMSE_{ILD}$s declined more strongly than $RMSE_{ITD}$s, suggesting that participants reweighted the binaural cues in accordance with the visual feedback they received. In other words, participants learned to focus on the binaural cue that was consistent with the visual feedback. This conclusion is strengthened by the fact that there was a significant *time* x *cue* interaction in both *time* x *cue* repeated measures ANOVAs, one for each group, ruling out the possibility that only one group reweighted the binaural cues, while the other group showed procedural learning only. Our results therefore do not support Jeffress and McFadden's (1971) conclusion that reweighting of binaural cues is not possible. Furthermore, since our stimuli were presented via headphones without being HRTF-filtered, they did not comprise potentially informative monaural spectral localization cues and therefore, the observed changes cannot be attributed to a stronger weighting of the monaural cues, as in Kumpik et al.'s (2010) study.

The *time* x *inconsistency* repeated measures ANOVAs yielded a main effect of *inconsistency* in addition to the main effect of *time.* This was expected, because integration across inconsistent cues necessarily results in enhanced RMSEs with respect to either cue if both cues have a weight greater than zero. With respect to hypothesis 2, the *time* x *inconsistency* interaction was of main interest, since it can indicate, whether the non-target cue was successfully ignored. That is, if the sensitivity for the reinforced cue increases, but the non-target cue cannot be ignored, RMSEs for the reinforced cue should decrease equally in consistent and inconsistent conditions from pre- to posttest. However, if the non-target cue is successfully ignored, RMSEs related to the reinforced cue should decrease more strongly in inconsistent than in consistent conditions, since the non-target cue, which is conflicting in inconsistent conditions only, would have less of an effect. Although this was the case in absolute numbers – in inconsistent conditions, mean $RMSE_{ITD}$s declined more strongly (by 1.435°) in group A and mean $RMSE_{ILD}$s declined more strongly (by 0.252°) in group B) – both *time* x *inconsistency* interactions were non-significant, showing that random fluctuations can account for these differences. We therefore do not have any evidence that the non-target cues were successfully ignored, not confirming hypothesis 2, and the observed reweighting can most likely be attributed to increased sensitivity to the reinforced cue.

Type of learning

In cognitive psychology, the existence of two distinct learning systems, implicit and explicit learning, is assumed. Implicit learning does not rely on awareness or intentionality and takes place without making demands on working memory. Explicit learning, however, heavily involves working memory and thus takes place consciously. In this case, learners are aware of and can verbalize what was learned (Ellis, 2009). Since listeners likely cannot not distinguish between ITD and ILD cues (Sand & Nilsson, 2014), it is unlikely that they were aware of the underlying manipulation and could consciously focus on one cue and ignore the other. Indeed, when asked, participants could not verbalize what they learned and mostly reported to respond intuitively. Therefore, even though participants probably had the intention to learn, the resulting effects can most likely be attributed to implicit learning. According to Reber (1993), the characteristics of implicit systems are robustness against disorders and dysfunctions, age independence, low variability between individuals, IQ independence and cross-species commonality. If indeed applicable, these characteristics would be favourable when applying our binaural cue training paradigm in cochlear implantees.

Neural pathways

The binaural cues are processed in different parts of the superior olivary complex in the brainstem. While the lateral superior olive (LSO) selectively responds to ILDs as well as envelope ITDs, the medial superior olive (MSO) selectively responds to fine structure ITDs (Joris, 1996). Given the lack of informative fine-structure ITD cues with current envelope-based CI-systems, processing of binaural cues in CI listeners wearing such systems is probably restricted to the LSO with no contribution of MSO neurons. Indeed, CI listeners' processing of fine structure ITDs presented directly via a research system is more reminiscent of envelope ITD processing in NH listeners (see van Hoesel, 2012), possibly explaining the low sensitivity of CI listeners to fine structure ITDs. Interestingly, Tirko and Ryugo (2012) observed a full recovery of inhibitory and a partial recovery of excitatory inputs to the MSO in deaf cats after a period of electrical stimulation with CIs. Even though the (partial) restoration of input to the MSO does not necessarily imply the processing of ITD cues, this plasticity of synaptic organization in the MSO is promising in terms of making fine structure ITD cues available to listeners with future CI-systems that explicitly encode carrier ITD information. Alternatively, if the properties of pulsatile electric stimulation pose general limitations on ITD processing by the MSO (Chung, Delgutte, & Colburn, 2015), reweighting of ITD cues may take place exclusively based on LSO processing.

Limitations and future directions

Due to the properties of our auditory stimuli, both, ITDs in the fine structure and in the envelope, were present in our study. We therefore cannot disentangle the individual contributions of these cues to the observed reweighting. However, this is of interest in the light of the fact that with current envelope-based CI-systems, envelope ITDs can be perceived but fine structure ITDs cannot.

The observed initial differences in the weights of ITD and ILD might have resulted in a different task difficulty between the two groups, which complicates the comparability of the groups. Future studies with NH listeners should therefore use auditory stimuli or listeners, for which or for whom the initial weights are more balanced.

Our training sessions were only one and a half hours per day, while participants listened naturally for the rest of the day. In contrast, when using CIs and in most studies using earplugs, participants constantly listened with the altered localization cues (e.g., Kumpik et al., 2010). Therefore, our results might underestimate the potential for reweighting of binaural cues.

This first indication, that reweighting of binaural cues is possible, leaves us with several open research questions, which should be addressed in future studies. First of all, since we only trained and tested with narrow-band noise centred at 2.8 kHz, it is unclear, whether the changed weights generalize to other frequency regions. Additionally, it is of interest, whether changed weights have an effect on performance in speech-understanding in noise. Since NH listeners benefit from the presence of ITDs in spatial release from speech masking (Ellinger, Jakien, & Gallun, 2017; Kidd, Mason, Best, & Marrone, 2010; Licklider, 1948) and this is a task CI listeners have difficulties with (van Hoesel & Tyler, 2003), increased ITD weights and resulting increased ITD sensitivity might improve speech-understanding in noise.

Finally, as this was, apart from Jeffress and McFadden's (1971) study, the first attempt at reweighting binaural cues, we tested NH listeners, because it is very unlikely that an effect not detectable in NH listeners can be found with CI listeners. However, since we did not test CI listeners, the results might not be generalizable to them because of listener-specific factors such as electrode position in the cochlea, survival of auditory nerve fibres or possibly even cortical asymmetries due to a long interval between the implantations of the two CIs (Jiwani, Papsin, & Gordon, 2016). Therefore, it is important to test actual CI listeners to find out if they also show reweighting of binaural cues through reinforcement and particularly whether they can benefit from increased ITD weights.

Conclusion

Binaural-cue-specific training was shown to induce cue-specific reweighting, namely a relatively larger gain in sensitivity for the reinforced cue compared to the non-reinforced cue. These results have implications concerning the development of future CI-systems. That is, since it is possible to reweight binaural cues, this might encourage the development of CI-systems that better convey ITD information, because CI listeners might be able to use the additionally provided ITD information. These results can also serve as a basis for designing training tools for improving sound localization performance with future CI-systems that explicitly encode carrier ITD information. This could speed up the training time required to acclimatize to new sensory input provided by new CI-systems or even revive ITD sensitive cells in CI listeners showing no ITD sensitivity at all before the training. If future CI-system users have rebalanced the weights they apply when combining ITDs and ILDs into a spatial percept, this might improve their sound localization and speech-understanding-in-noise performance in daily listening situations, which in turn would lead to a better quality of life.

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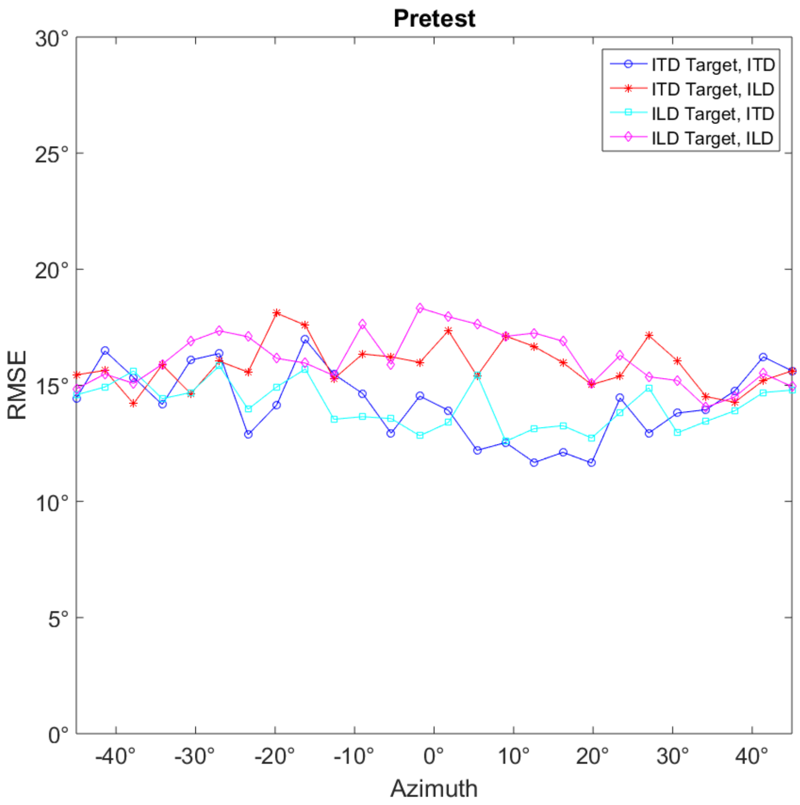
CI	cochlear implant
HRTF	head-related transfer function
ILD	interaural level difference
ITD	interaural time difference
LED	light emitting diode
LSO	lateral superior olive
MSO	medial superior olive
NH	normal-hearing
RMSE	root mean square error
RP	reference position

APPENDIX



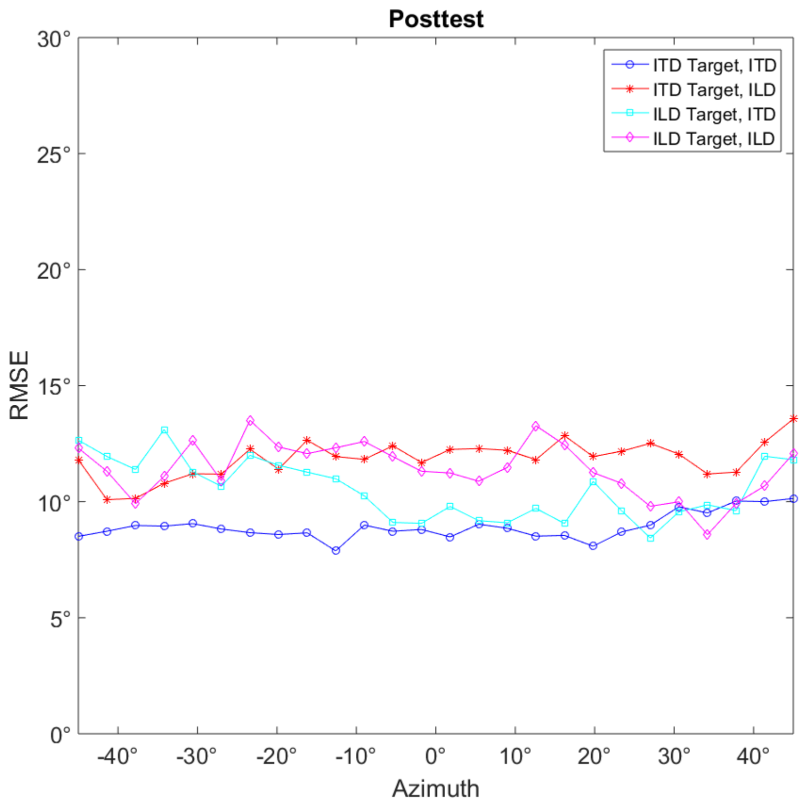


Figure 8. Mean RMSEs related to each of the target locations separately for pre- and posttest. Errors were larger and more variable in the pretest, but there was no systematic bias related to specific target locations.

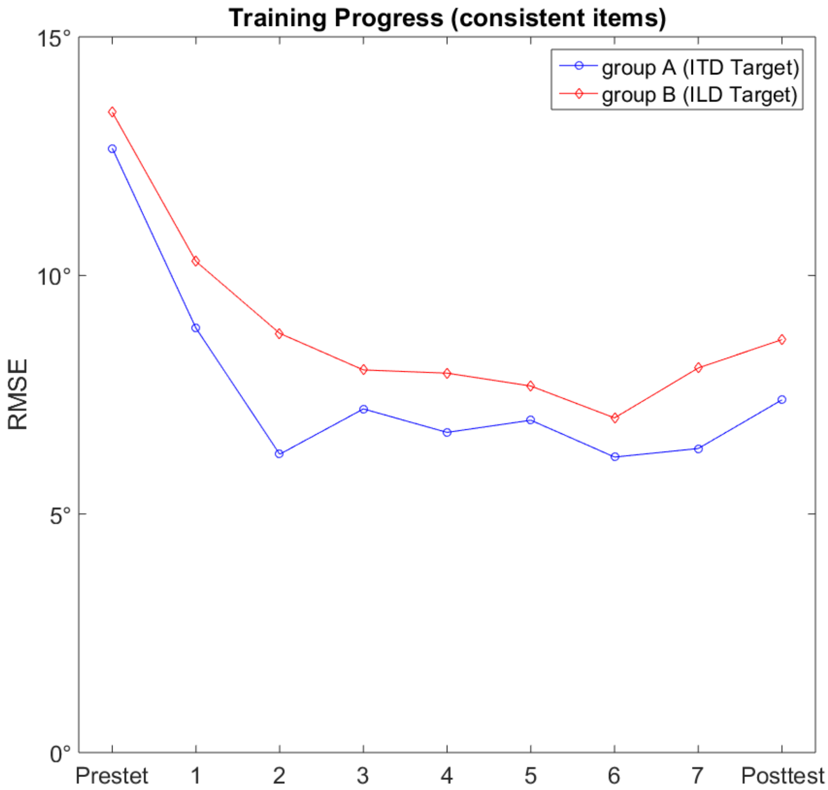


Figure 9. Training progress for the consistent items only. Mean RMSE of consistent items of the pretest, of each of the seven training sessions and of the posttest are depicted. Errors were generally smaller in group A and, except for surprisingly small errors in group A on day two, follow a similar trend in both groups.