Relative influence of interaural time and intensity differences on lateralization is modulated by attention to one or the other cue: 500-Hz sine tones

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When interaural time differences and interaural intensity differences are set into opposition, the measured trading ratio depends on which cue is adjusted by the listener. In an earlier article [Lang, A.-G., and Buchner, A., J. Acoust. Soc. Am. **124**, 3120–3131 (2008)], four experiments showed that the perceived localization of a broad band sound for which differences in one cue were compensated by differences in the other cue such that the sound seemed to originate from a central position shifted back toward the location from which the sound appeared to originate before the adjustment. It was argued that attention shifted toward the effect of the to-be-adjusted cue during the compensation task, leading to an increased weighting of the to-be-adjusted cue. The use of broadband stimuli raises the question whether the "shift-back effect" was caused by attentional shifts to the effect of the to-be-adjusted binaural cue or by attention shifts to the particular frequency range which is most important for localizations based on the to-be-adjusted cue. Two experiments are reported in which sine tones of 500 Hz were used instead of broadband sounds. The shift-back effect could still be observed, supporting our original hypothesis. A control experiment showed that participants had accurate representations of the critical central position.

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I. INTRODUCTION

In an earlier article (Lang and Buchner, 2008), we reported four experiments showing that the equivalence relation[1] between interaural time differences (ITDs) and interaural intensity differences (IIDs) varies as a function of the task participants have to perform. The experiments consisted of two phases. In the *compensation phase*, participants canceled out the effect of one preset binaural cue on localization by adjusting a compensatory value of the other cue until the sound was located in a central position. In the *localization phase*, participants assessed the virtual position of the sound, using the preset value of the fixed cue and using the same value of the complementary cue as previously adjusted. The sounds were no longer perceived as originating from the center. Instead, their perceived location was shifted back toward the location from which they appeared to originate before the adjustment. This "shift-back effect" suggests that the to-be-adjusted cue received a larger weight than the other cue during the compensation task.

Specifically, while adjusting one binaural cue in order to compensate for the effect of the other cue participants moved a control element and simultaneously received feedback about the effects of their adjustments in terms of immediate changes in the virtual location of the sound source. Given that participants were instructed to find an adjustment value that led to a certain localization (at the central position), they had to carefully observe the relation between their adjustments and the perceived changes in the sound source location. We presumed that this led to an increased attention to the effect of participants' adjustments on perceived location which, in turn, led to an increased perceptual weight of the adjusted cue in relation to the complementary cue. Let us take a closer look at the mechanism that we assume to be responsible for the effect. Attention—in terms of a resource that can be used strategically—can be directed only to stimulus features that participants can distinguish and that they could report if they were asked to. Attention, in this sense, was directed toward the effects of participants' adjustments of the control element on the virtual location of the sound source. This focusing of attention is assumed to have led to an increased weighting of the binaural cue associated with the control element in the process of ITD and IID information integration. Thus, directed attention led to a shift in the relative weighting of the binaural cues which then automatically affected sound source location. Note that there is some evidence in the literature that setting both binaural cues into opposition may lead to the occurrence of two images, a time image and a time/intensity image (e.g., see Whitworth and Jeffress, 1961; Hafter and Jeffress, 1968). A possible variant of our attentional explanation of the shift-back effect would thus be that participants attend to the image whose position was effected by their adjustments.

A plausible alternative explanation of the shift-back effect starts by noting that we (Lang and Buchner, 2008) previously used wideband stimuli (a female voice) even though in most studies 500-Hz sine tones were used (for an overview, see Trahiotis and Kappauf, 1978). By using broadband stimuli, we expected more precise localization judgments (e.g., see Stevens and Newman, 1936) and, hence, an increased chance of finding a possible shift-back effect. Nevertheless, the trading ratios found in our experiments were

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quite similar to those of the trading experiments reported by Young and Levine (1977) where 500-Hz sine tones were used. When ITD was the preset cue that was to be compensated by a complementary IID, we found a trading ratio of 80.1 μs/dB for a preset ITD of 600 μs which compares nicely with a ratio of 79.4 μs/dB for a preset ITD of 500 μs in Young and Levine (1977). When the roles of ITD and IID were interchanged, we found a trading ratio of 27.7 μs/dB for a preset IID of 7.5 dB which again seems to fit with a ratio of 40.4 μs/dB for a preset IID of 8 dB in Young and Levine (1977).

According to Rayleigh's "Duplex Theory" of sound localization (Strutt, 1907) IIDs are the more important interaural cue for sound localization of high-frequency sounds while ITDs are more important for low-frequency sounds. In spite of the considerable age of Rayleigh's theory, it is still in good agreement with actual findings (e.g., see Macpherson and Middlebrooks, 2002). This "specificity" of the binaural cues to high- or low-frequency ranges poses an alternative explanation of the shift-back effect in the experiments reported by Lang and Buchner (2008). It may be hypothesized that the compensation task did not lead to a shift of attention to the effect of one of the two binaural cues on localization but to a shift of attention to one of two *frequency ranges*. ITDs can only be evaluated at lower frequencies because of a loss of phase-locking in the auditory nerve at high frequencies (Macpherson and Middlebrooks, 2002). In natural hearing situations, IIDs mainly occur with high frequencies since low frequencies become deflected around the listener's head. Thus, life-long learning experience of IID-based sound localization could have lead to a stronger association between high frequencies and IIDs than between low frequencies and IIDs. This stronger association may influence localization judgments even in a situation where low-frequency IIDs are available (as is the case in our headphone-based experiments). In our experiments, listeners had to adjust the IID of a broadband sound in order to compensate for an ITD. To do so they moved a control element and simultaneously received feedback in terms of a change in the virtual sound source location. Present during decades of sound localization experience, the ubiquitous association between IIDs and high-frequency sound components could have led to a shift of attention toward the high-frequency components of the sounds in our experiments in order to receive the best feedback about the relation between their adjustments and the changes in the sound source position. Similarly, while adjusting the ITD in order to compensate for an IID listeners' attention could have shifted toward the low-frequency components of the sounds.

If this assumption were correct, then the shift-back effect found in the experiments reported by Lang and Buchner (2008) should no longer be observed if pure tones are used instead of broadband stimuli. However, if our original hypothesis were correct that shifts of attention between the binaural cues *themselves* (more precisely: the effect of either cue on localization) caused the shift-back effect, then the shift-back effect should also emerge when pure tones are used. Two experiments were conducted to test these predictions of the two alternative explanations of the shift-back effect. In experiment 1, participants compensated preset ITDs by complementary IIDs. In experiment 2, the roles of ITDs and IIDs were interchanged.

II. EXPERIMENT 1

A. Method

1. Participants

Participants were 12 female and 6 male persons, most of whom were students at Heinrich-Heine-Universität Düsseldorf. Their age ranged from 19 to 42 years ($M=26.0$, $SD=5.9$). All participants reported normal hearing. They were paid for participating or received course credit.

2. Apparatus, stimuli, and procedure

The experiment was a replication of experiment 1a of Lang and Buchner (2008) with the only difference being that 500-Hz sine tones were used as stimuli instead of natural speech sounds. In order to maximize the precision with which ITDs could be regulated the tones were sampled at a resolution of 32 bits at 96 kHz. During the experiment, the sounds were presented via headphones (AKG K-501) at a sound level of about 60 dB_{SPL} (*A*-weighted).

The experiment consisted of two phases, a compensation phase in which participants compensated a preset ITD by an IID of inverse sign and a localization phase that consisted of pure localization judgments. Each trial of the compensation phase started with a continuous loop in which the sine tone was presented for 1000 ms alternating with 1250 ms of silence. In order to avoid steep transients squared cosine ramps of 50 ms rise and fall time were used at the beginning and at the end of the tones. The tones were presented with one of seven preset ITDs (−600, −400, −200, 0, 200, 400, or 600 μs)^2; each preset ITD was presented in five trials, such that there were $7\times5=35$ compensation trials. The control element that was used by participants to choose a compensatory IID was a vertical slider displayed on a computer monitor which controlled the level difference between the left and right headphone within a range of ±15 dB. Each trial began at a randomly chosen starting position of the slider. When participants had finished the adjustment they clicked on a "Continue" button in order to start the next trial.

The *localization phase* consisted of 35 critical and 35 control trials. Each trial was presented with a preset ITD (−600, −400, −200, 0, 200, 400, or 600 μs). The IID was set to 0 dB in all control trials; in the critical trials the IID was identical with the IID, the participant had chosen during the parallel trial of the compensation phase. On the computer monitor, a sketch of a human head wearing headphones was displayed as seen from behind such that the left side of the sketch paralleled the left side of the participant's head. A red dot could be moved to angles between −90° and +90° on the upper hemicycle of the displayed head using the computer mouse.

3. Design

The independent variable was the ITD, which was manipulated within-subject in seven steps (−600, −400, −200, 0,

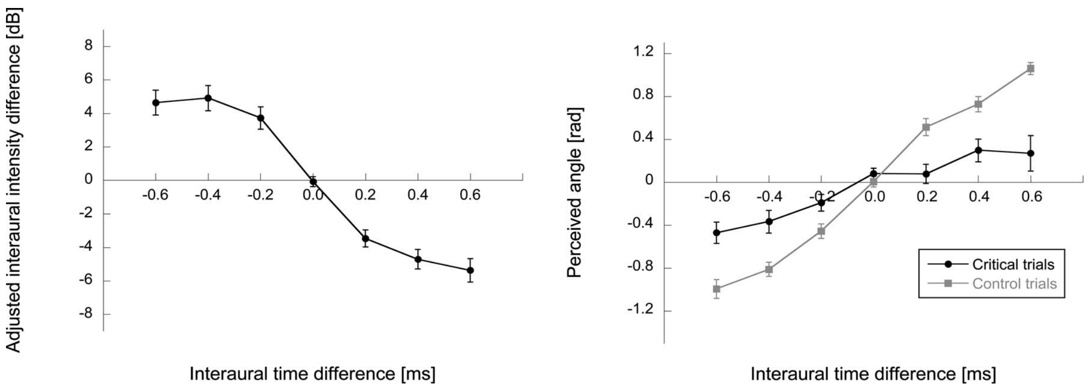

FIG. 1. Left panel: IIDs chosen to compensate for preset ITDs during the compensation phase of experiment 1 (error bars denote standard errors of the means). Right panel: Relation between the preset ITD and the perceived location during the critical trials and the control trials of the localization phase of experiment 1 (error bars denote standard errors of the means).

200, 400, and 600 μs). Dependent variables were the IID chosen during the compensation phase and the perceived location during the localization phase. A multivariate analysis of variance approach (MANOVA) was used for within-participant comparisons. Polynomial contrasts were evaluated from order 1 to order 4. Partial η^2 is reported as an effect size measure.

B. Results

Figure 1 (left panel) illustrates the relation between the preset ITD and the IID chosen to compensate for the effect of the ITD during the compensation phase. A MANOVA showed that the effect of the preset ITD (−600, −400, −200, 0, 200, 400, and 600 μs) on the chosen IID was statistically significant [$F(6,12)=7.89$, $p=0.001$, $\eta^2=0.80$]. An analysis of the polynomial contrasts revealed statistically significant first and third order trends [$F(1,17)=60.04$, $p<0.001$, $\eta^2=0.78$; $F(1,17)=35.08$, $p<0.001$, $\eta^2=0.67$, respectively].

Figure 1 (right panel) shows the relation between the preset ITD and the perceived location during the localization phase. A MANOVA for the control trials showed a significant effect of the preset ITD on perceived sound source location [$F(6,12)=74.0$, $p<0.001$, $\eta^2=0.97$].

A more interesting analysis concerns the perceived sound source locations of the critical trials. If there were no shift-back effect, then all localization judgments of the critical trials should be at zero; that is, the graph of the critical trials should lie on the abscissa. However, the fact that the slope of the graph of the critical trials is positive indicates that localization judgments were dependent on the preset ITD and hence, that the shift-back effect is present. A MANOVA for the critical trials showed that the effect of the ITD was indeed significant [$F(6,12)=3.62$, $p=0.028$, $\eta^2=0.64$]. An analysis of the polynomial contrasts showed that only the linear component was statistically significant [$F(1,17)=18.21$, $p=0.001$, $\eta^2=0.52$].

C. Discussion

The central result of experiment 1 is that our earlier findings could be replicated: The shift-back effect demonstrated in experiment 1a of Lang and Buchner (2008) with natural speech sounds also emerged in the current experiment with 500-Hz sine tones.

As a side note, in the critical trials of the localization phase of the current experiment 1, the effect of the preset ITD on perceived localization angle ($\eta^2=0.64$) was somewhat smaller than the effect in experiment 1a of Lang and Buchner (2008) ($\eta^2=0.85$). The relevant data are displayed in the right panel of Fig. 2. Of course, this may just represent random variation between experiments with different samples of participants so that we cannot be sure that the difference observed here warrants a substantive interpretation. That being said, the left panel of Fig. 2 shows another difference between these experiments in terms of the IIDs chosen by participants to compensate for preset ITDs during the compensation phases. In the current experiment 1, the chosen IIDs were smaller than in experiment 1a of Lang and Buchner (2008). It appears as if smaller IIDs were perceived as being sufficient to compensate for the effects of preset ITDs when 500-Hz sine tones were used rather than natural speech sounds. This may imply that in the compensation phase of the current experiment 1, ITDs received a smaller perceptual weight than in experiment 1a of Lang and Buchner (2008), or alternatively, that IIDs received a larger perceptual weight in the current experiment, or both.

III. EXPERIMENT 2

A. Method

1. Participants

Participants were 43 female and 4 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 18 to 48 years ($M=24.4$, $SD=7.3$). All participants reported normal hearing. They were paid for participating or received course credit.

2. Apparatus, stimuli, and procedure

Experiment 2 was a replication of experiment 2 in Lang and Buchner (2008) with 500-Hz sine tones as stimuli and is identical to experiment 1 except for the fact that the roles of ITDs and IIDs were interchanged. Each trial was presented with a preset IID of −7.5, −5.0, −2.5, 0, 2.5, 5.0, or 7.5 dB.

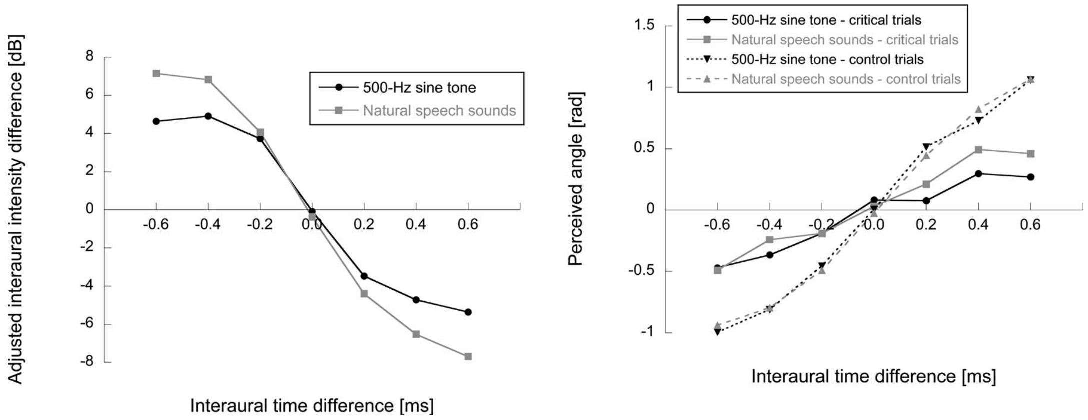

FIG. 2. Left panel: IIDs chosen to compensate for given ITDs during the compensation phase of experiment 1 (500-Hz sine tone) and the compensation phase of experiment 1a of Lang and Buchner (2008)(natural speech sounds). Right panel: Relation between the preset ITD and perceived location during the critical trials and the control trials of the localization phases of both experiments.

The slider that was used during the compensation trials allowed adjustments of the ITD between −600 and +600 μs. As in experiment 1, a sampling resolution of 32 bits/96 kHz was used.

During a pilot study prior to experiment 2 in Lang and Buchner (2008), the subjective impression was noted that for some trials even an ITD of $\pm$600 μs would not seem to compensate the given IID. For this reason, a checkbox labeled “Not enough” was displayed next to the slider, just as in experiment 2 of Lang and Buchner (2008). Participants were instructed to check the box if they had the impression that even the most extreme slider position was not sufficient to achieve a sound localization on the midline. These trials were excluded from all further analyses since the occurrence of a shift-back effect would have been a trivial finding in these trials.

3. Design

The independent variable was the preset IID, which was manipulated within-subject in seven steps (−7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB). Dependent variables were (a) the ITD chosen during the compensation phase and (b) the perceived location during the localization phase of the experiment.

B. Results

Eleven participants were excluded because for one or more preset IIDs, they chose the “Not enough” checkbox in all trials (i.e., none of the five trials with a specific preset IID could be compensated for localization in the center). For the remaining participants in 7.7% of all trials the “Not enough” checkbox was chosen. “Not enough” was chosen most frequently when the preset IID was $\pm$7.5 dB. Of all “Not enough” trials of all participants (including the 11 excluded participants) 73.8% occurred with $\pm$7.5 dB; 20.1%, 3.5%, 2.5%, and 1.99% of the “Not enough” choices were associated with a preset IID of $\pm$5, $\pm$2.5, and 0 dB, respectively.

The left panel of Fig. 3 illustrates the relation between the preset IID and the ITD chosen to compensate for the effect of the IID during the compensation phase. A MANOVA showed that the effect of the preset IID (−7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB) on the chosen ITD was statistically significant [$F(6,30)=17.1$, $p<0.001$, $\eta^2=0.77$]. An analysis of the polynomial contrasts showed that the linear and the cubic components were statistically significant [$F(1,35)=63.32$, $p<0.001$, $\eta^2=0.64$ and $F(1,35)=6.35$, $p=0.016$, $\eta^2=0.15$].

Figure 3 (right panel) shows the relation between the

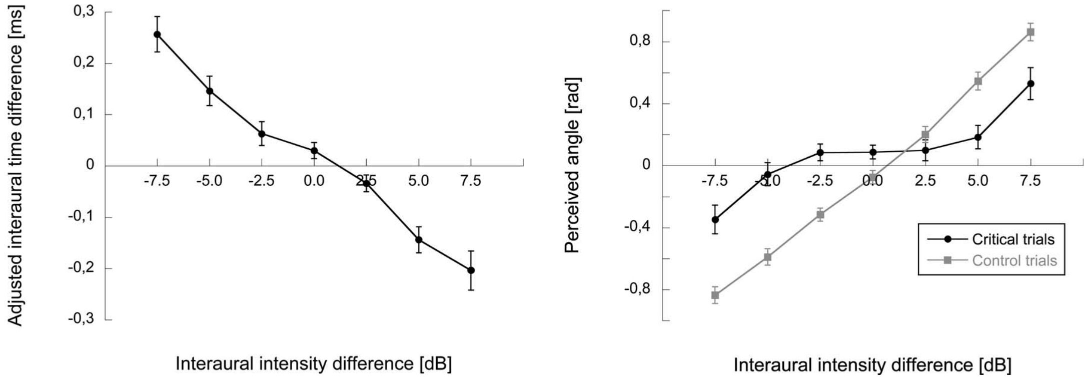

FIG. 3. Left panel: ITDs adjusted by participants in order to compensate for preset IIDs during the compensation phase of experiment 2 (error bars denote standard errors of the means). Right panel: Relation between the preset IID and perceived location during the critical trials and the control trials of the localization phase of experiment 2 (error bars denote standard errors of the means).

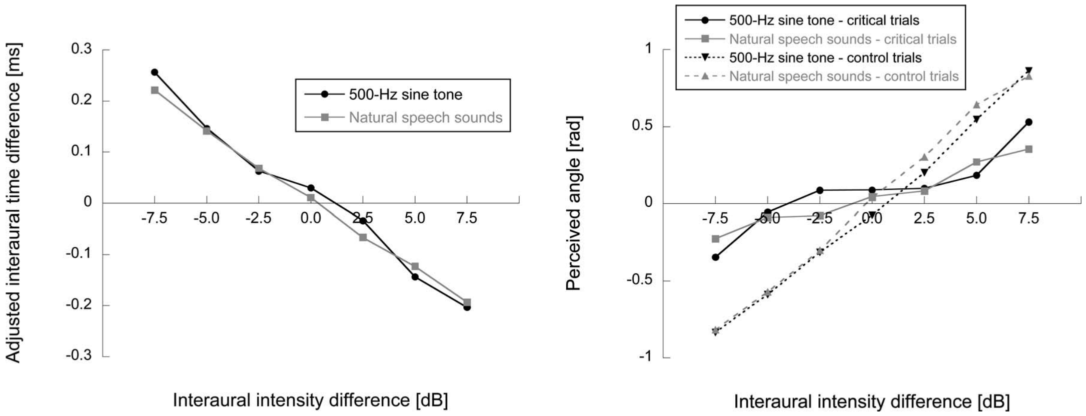

FIG. 4. Left panel: ITDs chosen to compensate for given IIDs during the compensation phase of the current experiment 2 (500-Hz sine tone) and during the compensation phase of experiment 2 of Lang and Buchner (2008) (natural speech sounds). Right panel: Relation between the preset IID and perceived location during the critical trials and the control trials of the localization phases of both experiments.

preset IID and the perceived location during the localization phase. A MANOVA for the control trials showed a significant effect of the IID on perceived sound source location $[F(6,30)=67.5,\ p<0.001,\ \eta^2=0.93]$.

As in experiment 1, the most interesting analysis concerns the critical trials since an effect of the preset IID on sound source location would indicate the presence of a shift-back effect. A MANOVA for the critical trials showed that the effect of the preset IID was statistically significant $[F(6,30)=5.29,\ p=0.001,\ \eta^2=0.51]$. An analysis of the polynomial contrasts showed that the linear and the cubic components were statistically significant $[F(1,35)=20.96,\ p<0.001,\ \eta^2=0.38$ and $F(1,35)=17.12,\ p<0.001,\ \eta^2=0.33$, respectively].

C. Discussion

The central finding of experiment 2 is that, again, the shift-back effect found in experiment 2 of Lang and Buchner (2008) also emerged when 500-Hz sine tones were used instead of natural speech sounds. Even the size of the shift-back effect was almost identical in both of these experiments ($\eta^2=0.51$ and $\eta^2=0.48$, respectively).

Figure 4 shows that, in contrast to experiment 1, there was no obvious difference as to the compensation values chosen by participants between this experiment and the analogous experiment 2 of Lang and Buchner (2008) with natural speech sounds. Thus, the current experiment very nicely replicates those earlier results, showing that the shift-back effect is not tied to the use of broadband natural speech sounds.

There was, however, a more subtle difference between these experiments. In the present experiment 2, the number of trials in which the "Not enough" checkbox was chosen was clearly larger than in experiment 2 of Lang and Buchner (2008) (12.3% versus 3.1%, respectively[3]). It is not quite clear how this should be explained. Again, this may represent just random variation between experiments. However, a plausible explanation could be that the present sine tones were more difficult to localize in general than the natural speech sounds used in our previous study (e.g., see Stevens and Newman, 1936), and that the "Not enough" response category also reflects cases in which participants felt that they had not enough information about the sound source location, such that they found it impossible to adjust a "correct" value. This would also explain why the "Not Enough" checkbox was occasionally selected with small preset IIDs and even an IID of zero.

As already mentioned in Lang and Buchner, 2008, a possible problem of not presenting a reference tone that indicates the central position is that participants' internal representation of the central position might be incorrect and thus lead to a deviation from the central position during the compensation phase as compared to the localization phase where a pointing device poses a reference to the center. However, it was also noted that a systematic deviation of participants' representation of the central position seemed very implausible because preset interaural cues with an ITD of 0 μs or an IID of 0 dB had been "compensated" by values very close to zero of the other cue (see Figs. 2 and 4). Another way to test whether participants' representation of the central position is correct is a "compensation phase" in which a preset IID has to be compensated by an IID (instead of an ITD) while the ITD is 0 μs. If participants choose a mean IID of 0 dB (while the ITD is fixed at 0 μs) it is even more plausible to assume that participants' representation of the central position was correct. Experiment 3 was conducted in order to test this prediction.

IV. EXPERIMENT 3

A. Method

1. Participants

Participants were 13 female and 2 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 20 to 50 years ($M=24.8$, $SD=7.3$). All participants reported normal hearing. They were paid for participating or received course credit.

2. Apparatus, stimuli, and procedure

The experiment consisted of a single phase which was similar to the compensation phases of the former experiments. A sine tone identical to that of experiments 1 and 2 was presented with one of seven preset intensity differences (−7.5, −5.0, −2.5, 0, 2.5, 5.0, or 7.5 dB). Participants were instructed to move a control element such that the tone appeared to originate from a central position. In contrast to the compensation tasks of our former experiments, the control element was not associated with the complementary interaural cue (ITD, in this case); rather, the control element regulated the preset cue (IID). ITDs were set to 0 μs during all trials.

The control element covered a range of 30 dB. In order to prevent participants from simply adjusting the control element to its middle position by visual control (i.e., choosing the middle position of the slider regardless of the position of the sound source), the range of the slider was shifted randomly on a trial-by-trial basis according to the following algorithm: The standard range was between −15 and +15 dB (identical to our previous experiments). A random number between −15 and +15 (at a resolution of 0.01) was chosen and the standard range as a whole was shifted by this value; that is, the random number was added to the low end of the range (−15 dB) and to the high end (+15 dB). Thus, the low end varied between −30 and 0 dB, and the high end varied between 0 and +30 dB while the magnitude of the range was constant at 30 dB. By applying this algorithm, it was achieved that the correct value to adjust (0 dB) could be at any position of the slider with the same probability. The mapping of the slider (low values—bottom, high values—top, or vice versa) was counterbalanced across participants. The starting position of the slider at the beginning of each trial matched the preset IID in the actual slider range. 35 trials were presented such that every preset IID appeared five times.

3. Design

The independent variable was the preset IID that was manipulated within-subject in seven steps (−7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB). Dependent variable was the IID chosen by participants to accomplish localization at the central position. A repeated-measures ANOVA was used in order to test the chosen IIDs against zero.

B. Results

Figure 5 shows the relation between the preset IIDs and the IIDs chosen by participants. A repeated-measures ANOVA revealed that the IIDs chosen by participants did not differ significantly from zero [$F(1,14)=1.75$, $p=0.207$, $\eta^2=0.11$].

C. Discussion

The IIDs chosen by participants in order to accomplish localization in the center are very close to zero. Given that the preset ITD was 0 μs in all trials, participants chose the correct value for the IIDs in order to localize the tones in the center. The control trials of experiment 1 for which the preset ITD was 0 μs show that trials with both interaural cues set to zero were located very close to the center during the localization phase (see Fig. 2—right panel). If there were a systematic deviation of participants' representation of the central position during the compensation phase as compared to the localization phase, one would expect that the IIDs chosen during the compensation phase would not lead to a localization in the center during the localization phase. This was not the case. Taken together with the finding from previous experiments that preset interaural cues with an ITD of 0 μs or an IID of 0 dB are reliably compensated by values very close to zero of the other cue (see Figs. 2 and 4), the results of experiment 3 let us confidently conclude that the shift-back effect found cannot be ascribed to an invalid internal representation of the central position during the compensation phases.

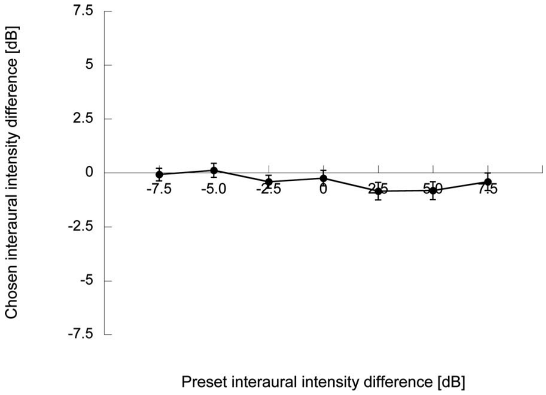

FIG. 5. Relation between preset IIDs and the IIDs chosen by participants in order to achieve a localization in the center (error bars denote standard errors of the means).

V. GENERAL DISCUSSION

The main purpose of experiments 1 and 2 was to answer the question whether the shift-back effect found with natural speech (Lang and Buchner, 2008) could be replicated with tones that had only one frequency component. The important result thus is that the shift-back effect occurs with both natural speech and 500-Hz sine tones. If there were no shift-back effect when 500-Hz sine tones were used instead of natural speech sounds, then the shift-back effect could be explained by assuming shifts of attention between different frequency ranges. However, the fact that the shift-back effect was replicated in the current experiments supports the original explanation according to which attention is shifted toward the effect of the to-be-adjusted binaural cue during the compensation phase, thereby increasing the perceptual weight of this cue above the level with which this cue affects "neutral" localization judgments. During the localization, phase attention is distributed more evenly across the binaural cues and thus, the previously adjusted cue (IIDs in experiment 1 and ITDs in experiment 2) was not large enough to compensate for the effects of the other cue on sound source localization.

Experiment 3 tested whether participants' representation of the central position underlies a systematical error if no reference tone is present. The results suggest that this is not the case, a finding that is perfectly consistent with the fact that preset interaural cues with an ITD of 0 μs or an IID of 0 dB were reliably compensated by values very close to zero of the other cue in our previous experiments (see Figs. 2 and 4).

In more general terms, these results confirm our earlier conclusions that equivalence relations of ITDs and IIDs depend in part on states of the observer. Thus the method used to obtain equivalence relations must be taken into account when interpreting them. Specifically, relations found by setting both binaural cues into opposition must not be compared with relations found in experiments where only one cue was present at a time (such as the control trials in our experiments).

[1] The more common term "trading ratio" suggests a linear relationship between time and intensity differences. In the following, the term "trading ratio" is used either when a linear relationship is assumed or when the relation at a distinct point is reported (e.g., 80.1 μs/dB, given a time difference of 600 μs). In all other cases, the more general term "equivalence relation" is used.

[2] In the rest of the article, negative ITDs or IIDs denote that a sound was earlier or more intense, respectively, on the left channel whereas positive values indicate that it was earlier or more intense, respectively, on the right channel.

[3] Note that these values also include the trials of participants that had been excluded since they chose the checkbox for all trials of one or more preset IIDs.

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