# Relative influence of interaural time and intensity differences on lateralization is modulated by attention to one or the other cue

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When setting interaural time differences and interaural intensity differences into opposition the measured trading ratio depends on which of the cues is adjusted by the listener. This paper provides some evidence that the different trading ratios may be an effect of a shift of attention toward the to-be-adjusted cue. The experiments consisted of two phases. In the compensation phase, participants canceled out the effect of one preset binaural cue by adjusting a compensatory value of the other cue until the sound was located in the center. In the localization phase participants assessed the virtual location of the sounds, again using the preset values of the fixed cue, but using the values of the other 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. These findings suggest that during the compensation task the to-be-adjusted sound localization cue received an increased weight compared to the other cue. We propose shifts of attention between the cues as a mechanism that could account for this finding. © *2008 Acoustical Society of America.* [DOI: 10.1121/1.2981041]

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## I. INTRODUCTION

Sound localization on the horizontal plane is largely determined by two physical parameters: interaural time differences (ITDs) and interaural intensity differences (IIDs). If experimenters or audio engineers want to manipulate the perceived location of a virtual sound source, they may specify a certain ITD, an IID, or a combination of both. The question arises which ITD has the same effect on localization as a certain IID (and vice versa). Many experiments have been conducted to find a trading ratio or an equivalence relation[1] between both interaural cues (e.g., see Leakey and Cherry, 1957, Deatherage and Hirsh, 1959, Whitworth and Jeffress, 1961, Colburn and Durlach, 1965, Hafter and Jeffress, 1968, Jeffress and McFadden, 1971, McFadden *et al.*, 1971, Hafter and Carrier, 1972, McFadden *et al.*, 1972, McFadden *et al.*, 1973, Algom *et al.*, 1988, Hafter *et al.*, 1990, Wightman and Kistler, 1992, Gaik, 1993, Wightman and Kistler, 1997, Breebaart *et al.*, 1999, Shinn Cunningham *et al.*, 2000).

Setting the binaural cues into opposition such that their effects cancel each other out is a frequently used paradigm to find an equivalence relation. An early study is that of Leakey and Cherry (1957). In this study, words spoken by a female voice were presented over two loudspeakers set up outdoors in order to avoid disturbing reflections. ITDs were implemented by placing one loudspeaker more distant from the participant than the other loudspeaker while keeping the angle between the two loudspeakers constant relative to the listener. The IIDs caused by the unequal distances between the loudspeakers and the listener were compensated by increasing the volume of the more distant speaker. Participants' task was to judge the apparent location of the virtual sound source for different combinations of ITDs and IIDs. The trials of interest were those in which the listener located the sound source exactly on the midline between the two loudspeakers. In these trials an ITD between the sound waves arriving from the two loudspeakers apparently had been compensated for by an IID of inverse sign, that is, the sound waves arrived earlier at one ear but at higher level at the other ear. It was found that the trading ratio increased with the preset ITD. For example, the ratio was 59 $\mu$s/dB with the ITD set to 450 $\mu$s, but 218 $\mu$s/dB with the ITD set to 2270 $\mu$s. However, the presentation of sounds over loudspeakers has the shortcoming that the experimenter has insufficient control over the ITDs and IIDs that arrive at the listener's ears. For this reason presentation via headphones has established as the standard procedure for ITD-IID trading experiments.

The search for an equivalence relation is complicated by experimental results that show that there are different moderator variables. For example, the ratios found by Leakey and Cherry (1957) increased with the sound level of an additionally inserted source of white noise. Deatherage and Hirsh (1959) presented low-pass-filtered clicks at 40, 60, and 80 $dB_{SPL}$ with preset IIDs via headphones. Participants adjusted the ITD so that they located the clicks in the middle of their heads. The ratio between ITDs and IIDs was not constant over the three listening levels. The ITD required to compensate for the given IID decreased with increasing sound pressure levels. Wightman and Kistler (1992) used either wideband or high-pass-filtered noise stimuli with conflicting ITD and IID cues. In the wideband condition the listeners located the sounds solely on the basis of ITDs. Wightman and Kistler (1992) interpreted this result as evi-

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dence for the dominance of low-frequency ITDs in the localization of sounds; when low-frequency ITDs were present they dominated IIDs at all frequencies.

Mills (1972) suggested that the localization judgment on the basis of the ITD limits the possible locus of a sound source to a so called "cone of confusion," that is, a cone-shaped volume of hypothetical positions of the sound source that are consistent with the perceived ITD. The IID may pose additional constraints to the location of the sound source. Shinn Cunningham *et al.* (2000) described the intersection of iso-ITD and iso-IID volumes as torus-shaped volume ("tori of confusion").

Besides the observation that the effects of opposing ITDs and IIDs cancel each other out, experiments have been reported in which setting both binaural cues into opposition leads to the perception of either of *two images*. One image is largely determined by the ITD ("time image"), while the other is determined to a much greater extent by the IID ("time/intensity image"). The trading ratios are very different: For the time image the range is about 0 to 10 $\mu$s/dB while for the time/intensity image values between 20 and 50 $\mu$s/dB have been reported. Extremely experienced listeners or participants that have completed huge amounts of practice trials over a period of several days may be able to hear both images (e.g., see Whitworth and Jeffress, 1961, Hafter and Jeffress, 1968).

Individual differences constitute another important set of moderator variables. For example, McFadden and co-workers (Jeffress and McFadden, 1971, McFadden *et al.*, 1971, McFadden *et al.*, 1972, McFadden *et al.*, 1973) used an experimental design that is known from the measurement of masking level differences. The output of a noise generator was bandpass filtered and then sent to a variable phase shifter. The fixed output (N) and the variable output (S) of the phase shifter were mixed on both earphones where S was inverted in phase on one side in relation to the other side ($N0S\pi$). The ITD and IID between the resultants on both ears ($SN_L$ and $SN_R$) could be manipulated by adjusting the phase angle between the fixed and the variable output of the phase shifter. Among other things, they found that there were interindividual differences in participants' weighting of ITDs and IIDs when both cues were set into opposition. This was true for both detection of the signal (S) that was turned on after N and for lateralization judgments. Herman *et al.* (1977) compared the ability of older participants (aged between 60 and 72 years) with the ability of younger participants (aged between 20 and 32 years) in lateralizing a train of clicks either solely based on ITDs or solely based on IIDs. They found that the older participants needed larger ITDs to give correct lateralization judgments compared to the younger participants, but that there was no difference between the groups when IIDs were the only binaural cue.

To summarize, previous investigations of the moderators of equivalence relations concentrated on stable properties of the stimuli (overall sound level, sound level of additionally inserted noise, and dominance of low-frequency ITDs) and on traitlike interindividual differences (extreme experience, age, and individual preferences for the weighting of the cues). There are relatively few studies that investigated momentary states of the observer. Jeffress and McFadden (1971) tried to manipulate the individual weighting of ITDs and IIDs by selective feedback. They asked participants to give lateralization judgments to sound stimuli with conflicting ITD and IID information. The critical trials were preceded by practice trials in which feedback about the correctness of the lateralization judgments was either provided solely on the basis of the ITD of the two ear signals or solely on the basis of the IID. Comparing the lateralization judgments in the critical trials that followed these two types of practice trials showed no systematic differences. Thus, selective feedback did not seem to change the processing of ITDs or IIDs.

Comparisons between experiments in which participants had to compensate ITDs by the adjustment of IIDs and experiments with converse roles of both cues showed different trading ratios (for an overview, see Trahiotis and Kappauf, 1978). For example, Young and Levine (1977) conducted two experiments in which the position of a pure tone of 250, 500, or 1000 Hz had to be aligned to the position of a diotic noise marker. The test tones were either presented with a fixed ITD or with a fixed IID. Participants' task was to adjust the other binaural cue so that the perceived position of the test tone was identical to that of the noise marker. The trading ratios more strongly favored the IID when IIDs had to be adjusted in order to compensate for ITDs than in the converse case. For example, with the test tone of 500 Hz the trading ratios were 79.4 and 40.4 $\mu$s/dB, respectively. Young and Levine (1977) interpreted this result as evidence for two-image lateralization. Trahiotis and Kappauf (1978) disagreed with the assumption that the different trading ratios obtained by Young and Levine (1977) could be accounted for by a time image and a time/intensity image. As mentioned above, the time image is almost solely determined by the ITD and only to a very small degree by the IID, which leads to very small trading ratios (e.g., 3 $\mu$s/dB as reported by Whitworth and Jeffress, 1961). Since the trading ratios found by Young and Levine (1977) were relatively large in *both* experiments, Trahiotis and Kappauf (1978) considered both ratios as more characteristic of time/intensity images. They proposed that the data could be described in terms of a "regression" to the features of the reference stimulus. In order to clarify the regression interpretation Trahiotis and Kappauf (1978) discussed a study by Sheldon (1973) in which participants were asked to adjust the abruptness or "surge" of a vibrotactile stimulus in relation to a reference stimulus. The abruptness was determined by two physical parameters: the rise time and the final amplitude. The test stimulus differed from the reference stimulus either in rise time or in amplitude. When the stimuli differed in rise time, participants had to adjust the amplitude until the stimuli had the same perceived abruptness; when the stimuli differed in amplitude the rise time was the parameter to be adjusted. It was found that the "equal-surge contours" were different in both conditions; when the amplitude was to be adjusted the chosen amplitude was closer to the amplitude of the reference stimulus than predicted by the contour of the condition where the rise time was the to-be-adjusted parameter. Analogous results were found when the rise time was to be adjusted. Trahiotis and

Kappauf (1978) assumed that an analogous effect occurred in the study by Young and Levine (1977) when subjects were asked to adjust one binaural localization cue such that a test tone was localized at the same position as a reference tone. In the case of the study reported by Young and Levine (1977) the reference stimulus was presented diotically (i.e., with an ITD of 0 $\mu$s and an IID of 0 dB). Consider a trial in which the test stimulus was presented with a fixed ITD and the participant had to adjust the IID to match the location of the reference tone; since the IID of the reference tone was 0 dB, a regression to the features of the reference stimulus would mean that the chosen compensatory IID was shifted toward 0 dB, that is, its absolute value was reduced. If the roles of ITD and IID were interchanged an analog regression toward an ITD of 0 $\mu$s would occur. Trahiotis and Kappauf (1978) were clear about the fact that the term regression only describes the data they discussed, but that it does not explain the observed phenomena in terms of the cognitive processes involved.

We suggest shifts of attention as a possible explanation of equivalence relations that differ as a function of which interaural cue is adjusted. Consider that while adjusting one binaural cue in order to compensate for the other cue, participants move a control element and simultaneously receive feedback about the effects of their manipulations in terms of an immediate change in the virtual location of the sound source. Given that participants are instructed to find an adjustment value that leads to a certain localization (e.g., in a central position), they must carefully observe the relation between their adjustments and the perceived change in the location of the sound source. This could lead to an increased attention to the effect of the to-be-adjusted cue on perceived location which in turn could lead to an increased perceptual weight of this cue in relation to the other cue.

If this assumption were correct, then one would expect differences in perceived sound source location between compensation and localization tasks even for identical pairs of ITDs and IIDs. In the compensation task, attention is focused on the to-be-adjusted cue (e.g., the IID), amplifying the weight of this cue relative to the fixed cue (e.g., the ITD). In the localization task, attention is distributed more evenly between both binaural cues. Then the previously chosen compensatory value (e.g., of the IID) would no longer receive the amplified weight and thus the image would no longer appear centered; instead it would be shifted away from the adjusted cue (IID) and toward the preset cue (ITD). Furthermore, if attention shifts induced by the compensation task caused the observed differences in trading ratios depending on which binaural cue is adjusted, these trading ratio differences are also expected to occur if no reference stimulus is presented that can act as an "anchor" for regression.

Four experiments were conducted to test these predictions. In experiments 1a–1c IIDs were adjusted in order to compensate for ITDs. In experiment 2 ITDs were adjusted in order to compensate for IIDs. Each experiment consisted of two phases: During the first phase ("compensation phase") the adjustment of the IID or ITD took place; the second phase ("localization phase") consisted of pure localization judgments.

## II. EXPERIMENT 1a

### A. Method

#### *1. Participants*

Participants were 12 female and 4 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 24 to 45 years ($M=28$, SD $=8.3$). All participants reported normal hearing. They were paid for participating or received course credit.

#### *2. Apparatus and stimuli*

Five meaningless words ("adaxal," "eferel," "inibis," "odobol," and "urubut," pronounced according to German pronunciation rules) were spoken by a female speaker and recorded in an anechoic chamber in order to avoid disturbing reflections which would have posed additional cues for spatial hearing. The signal of the microphone (Sennheiser MD-421) was amplified by one channel of a low-noise mixing console and recorded by a digital audio tape (DAT) recorder.

In order to familiarize participants with sound localization via headphones, a special set of stimuli was created. Head-related impulse responses (HRIRs) were recorded in order to be able to present practice trials in which the five sounds had natural ITD to IID ratios. The HRIRs were recorded for lateral angles between −90° and 90° in steps of 10°.

The stimuli were presented by a program written in C++ on an Intel-based personal computer. The Microsoft "Direct Sound" programming interface was used for playing the sounds and for manipulating ITDs and IIDs of the nonpractice trials. In order to assess the accuracy of Direct Sound when delaying one channel in relation to the other, the delay times were measured in the range relevant for the experiment (−600–600 $\mu$s) using a two-channel oscilloscope. This measurement revealed that Direct Sound changes the delay in steps of integer samples (22.68 $\mu$s at 44.1 kHz).

When Direct Sound receives the instruction to change the relative level between the left and the right channel, it attenuates the weaker channel so that the desired ratio is obtained. By this approach the overall sound level varies against the chosen intensity difference. In order to keep the overall sound level constant, the level was corrected by a modified version of a formula proposed by Gaik (1993) such that

$$L_{\mathrm{L}} = 20 \log \frac{10^{(L_{\mathrm{ref}}+6\mathrm{dB})/20}}{1+10^{\Delta L/20}} \tag{1}$$

and

$$L_{\mathrm{R}} = L_{\mathrm{L}} + \Delta L, \tag{2}$$

where $L_{\mathrm{ref}}$ denotes the reference level, that is, the level of a sound with no intensity difference between the channels that has the same perceived loudness as the actual sound, and $L_{\mathrm{L}}$ and $L_{\mathrm{R}}$ denote the left and right sound levels, respectively; $\Delta L$ is the difference between the left and right sound levels.

During the experiment, the sounds were presented via headphones (AKG K-400) at a sound level of about 60 $\mathrm{dB_{SPL}}$ ($A$ weighted). The ITD was varied in seven steps: −600,

−400, −200, 0, 200, 400, and 600 $\mu$s.[2] There were two types of (nonpractice) trials: During the critical trials participants had to assess the direction of a sound whose ITD they had compensated for by a certain IID in an earlier phase of the experiment. The control trials were identical to the critical trials, but their ITD had not been compensated for by the participants, that is, the IID was 0 dB. Each of the five words was presented once with each of the ITDs, resulting in 35 critical trials and 35 control trials.

### *3. Procedure*

The experiment took place in an anechoic chamber. In an initial *demonstration phase*, the computer monitor in front of the participants showed a sketch of a head wearing headphones as seen from behind. The recorded voice of a narrator spoke to the participants with the recordings of the voice being convolved with the same impulse responses as the words of the subsequent practice trials. A red dot in the drawing showed the "actual location" of the voice, that is, it appeared at an angle relative to the head sketch that matched the lateral angle employed during HRIR recordings. Different locations were demonstrated while the narrator spoke sentences such as "It sounds like this when I talk to you from the rightmost location." Subsequently, the narrator asked the participants to use the computer mouse to move the red dot to the correct position while he said "From where do you hear me now?" This sentence was repeated with 1000 ms of silence between two repetitions. After participants had made a decision and clicked on a button labeled "continue," the playback of the sentence was stopped and a green dot indicating the correct location was displayed for 2000 ms.

The demonstration was followed by a *practice phase* of 20 trials, each of which started with playing one of the five meaningless words in a loop with 500 ms of silence between two repetitions. The lateral angle of the virtual sound source was chosen randomly (between −90° and 90° in steps of 10°). As in the demonstration, participants' task was to move the red dot to the correct location and subsequently to press the continue button after which the green dot indicating the correct position was displayed for 2000 ms. 500 ms ($\pm$100 ms random variation) after the green dot had disappeared the next trial started. Every ten trials participants were offered to take a break for as long as they wished. After the second block of practice trials performance was evaluated for the last ten trials. A location judgment was classified as incorrect if the angular deviation from the correct location was larger than 22.5°. If four or more trials were incorrect, then ten more trials were presented together with the request to concentrate on giving more precise judgments. This was repeated if necessary.

For the next two phases of the experiment (compensation phase and localization phase) unfiltered sounds were used, that is, no HRIR filter was used here; the ITDs and IIDs were manipulated directly with Direct Sound as described above.

The *compensation phase* consisted of 35 trials. Each trial started with the continuous playback of one of the five meaningless words in a loop with 500 ms of silence between two word repetitions. The sound on one ear was delayed in relation to the sound on the other ear by −600, −400, −200, 0, 200, 400, or 600 $\mu$s. The computer monitor displayed a vertical slider that was used to control the relative sound level of the left and the right channels within a range of $\pm$15 dB. The mapping of the slider's position (top versus bottom) onto the sign of the level ratio (higher level on the left versus on the right channel) was counterbalanced across participants. The slider's initial position was chosen randomly for each trial. Participants were instructed to move the slider so that they localized the sound source in the center. Participants received no further information about the physical properties of the sound or the physical property that was changed by the slider. 500 ms ($\pm$100 ms random variation) after the continue button had been clicked the next trial started. Participants were asked to take a rest in intervals of ten trials.

During the *localization phase* each trial again started with the continuous playback of one of the five meaningless words in a loop with 500 ms of silence between two word repetitions. Participants assessed the apparent sound location of (a) the previously presented trials for which participants had compensated the preset ITD by an IID such that the sound appeared to originate from a central location (critical trials; the IIDs were constant at the final value selected by the participant during the compensation phase such that the sound appeared to originate from a central location) and (b) trials with only ITDs but no IIDs (control trials). On the monitor the same drawing of a head and red dot was presented as in the demonstration and practice phasess. The 70 localization trials (35 critical and 35 control trials) were set up in a new randomly chosen sequence. The participants' task was to move the red dot to the corresponding position at which they located the sound. All other aspects of the localization trials (such as intertrial and break intervals) were parallel to those of the compensation trials.

### *4. Design*

The independent variable was the ITD, which was manipulated within subject in seven steps (−600, −400, −200, 0, 200, 400, and 600 $\mu$s). The dependent variables were (a) the chosen IID during the compensation phase and (b) the perceived location during the localization phase of the experiment. A multivariate approach (MANOVA) was used for the within-participant comparisons. Polynomial contrasts were evaluated from orders 1 to 4. Partial $\eta^2$ is reported as an effect size measure. A statistical power analysis using G*Power3 (Faul *et al.*, 2007) showed that in order to detect effects of $\eta^2=0.75$ (determined in a pilot study) of the independent variable given $\alpha=\beta=0.05$, $N=9$ participants were needed.

## B. Results

Figure 1 (left panel) illustrates the relation between the preset ITD and the IID chosen to compensate for the effects of the ITD during the compensation phase. A MANOVA showed that the obvious effect of the preset ITD (−600, −400, −200, 0, 200, 400, and 600 $\mu$s) on the chosen IID was statistically significant [$F(6,10)=15.25$, $p<0.001$,

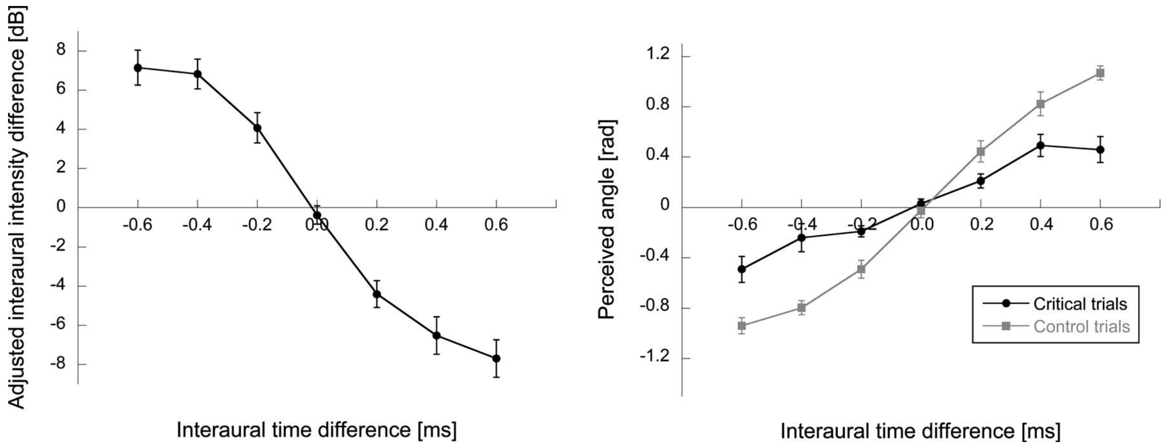


FIG. 1. Left panel: IIDs chosen to compensate for given ITDs during the compensation phase of experiment 1a (error bars denote the standard errors of the means). Right panel: Relation between the preset ITD and the perceived location during the critical trials and the control trials of the localization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

$\eta^2=0.90$]. An analysis of the polynomial contrasts revealed statistically significant first and third order trends [$F(1,15)=87.13$, $p<0.001$, $\eta^2=0.85$; $F(1,15)=26.58$, $p<0.001$, $\eta^2=0.64$, respectively].

Figure 1 (right panel) shows the relation between the ITD and the perceived location during the localization phase. A MANOVA for the control trials showed a significant effect of the ITD on the perceived sound source location [$F(6,10)=49.05$, $p<0.001$, $\eta^2=0.97$].

A more interesting analysis concerns the perceived sound source locations for the critical trials. For these trials participants had compensated ITDs by appropriate IIDs during the compensation phase. Thus, one should expect, for all levels of the ITD variable, a perceived location at the midline (i.e., a perceived angle of zero) if the processes operating during the compensation and localization phase were identical. However, this does not appear to be the case. Instead, the perceived location of the critical trials is shifted toward the location predicted by the ITD, albeit not completely. A MANOVA for the critical trials showed that the effect of the ITD was indeed significant [$F(6,10)=9.63$, $p=0.001$, $\eta^2=0.85$]. An analysis of the polynomial contrasts showed that only the linear component was statistically significant [$F(1,15)=37.31$, $p<0.001$, $\eta^2=0.71$].

### C. Discussion

The analysis of the compensation phase data showed that participants had understood the task of canceling out the preset ITDs by appropriate IIDs.

However, the data from the localization phase showed that the processes operating while manipulating IIDs to compensate for ITDs cannot be considered equivalent to the processes operating when sounds are located in a normal listening situation. The same sounds that had been adjusted to be perceived as originating from the midline were perceived off midline and, on average, shifted toward the location predicted by the ITDs during the localization phase. This shift-back effect is consistent with the assumption that when participants compensate for ITDs by manipulating IIDs, attention is focused on the (to-be-manipulated) IIDs. The result is that more weight is given to the IIDs than would be the case in a more neutral listening situation. During the localization phase, attention is distributed more evenly across the binaural cues and thus, the adjusted IID is not large enough to compensate for the ITD.

However, an alternative explanation for these findings is possible based on the fact that during the localization phase ITDs were over-represented. The critical trials were presented with a combination of ITDs and IIDs whereas the control trials were implemented only in terms of ITDs (i.e., the IID was 0 dB). This over-representation of ITDs could have led to an increased weighting of this cue. In order to test this hypothesis, experiment 1b was conducted with additional control trials that had only IIDs while ITDs were 0 $\mu$s.

## III. EXPERIMENT 1b

### A. Method

#### *1. Participants*

Participants were 12 female and 9 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 18 to 40 years ($M=27$, SD $=7.4$). All participants reported normal hearing. They were paid for participating or received course credit.

#### *2. Apparatus and stimuli*

Apparatus and stimuli were identical to those of experiment 1a except for the following: In addition to the 35 control trials that only had ITDs (−600, −400, −200, 0, 200, 400, and 600 $\mu$s), further 35 additional trials were inserted that only had IIDs (−7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB).

#### *3. Procedure*

The procedure was identical to that of experiment 1a.

#### *4. Design*

The design was identical to that of experiment 1a except for the additional independent variable of IIDs for the added control trials.

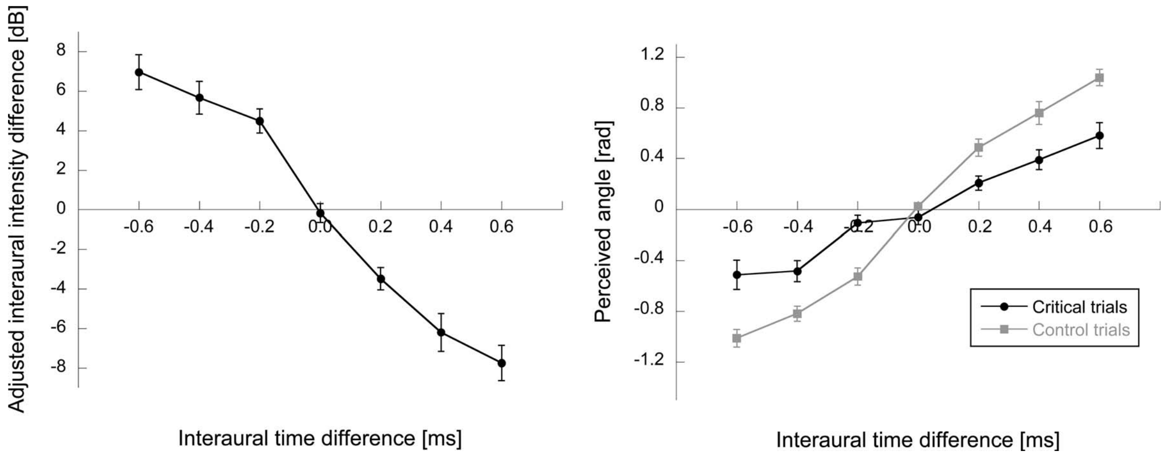


FIG. 2. Left panel: IIDs chosen to compensate for given ITDs during the compensation phase of experiment 1b (error bars denote the standard errors of the means). Right panel: Relation between the preset ITD and the perceived location during the critical trials and the (ITD) control trials of the localization phase of experiment 1b (error bars denote the standard errors of the means).

## B. Results

Figure 2 (left panel) illustrates the relation between the preset ITD and the IID chosen to compensate for the effects of the ITD during the compensation phase. A MANOVA showed that the effect of the preset ITD on the chosen IID was statistically significant [$F(6,15)=18.63$, $p<0.001$, $\eta^2=0.88$].

An analysis of the polynomial contrasts showed statistically significant trends of orders 1–3 [$F(1,20)=73.76$, $p<0.001$, $\eta^2=0.79$; $F(1,20)=8.88$, $p=0.007$, $\eta^2=0.31$; $F(1,20)=15.89$, $p=0.001$, $\eta^2=0.44$].

Figure 2 (right panel) shows the relation between the ITD and the perceived location during the localization phase. A MANOVA for the (ITD) control trials showed a significant effect of the ITD on the perceived sound source location [$F(6,15)=58.86$, $p<0.001$, $\eta^2=0.96$]. A MANOVA for the control trials that had only IIDs (Fig. 3) revealed a significant effect of the IID on the perceived location of the sound source [$F(6,15)=14.94$, $p<0.001$, $\eta^2=0.86$].

A MANOVA for the critical trials showed a statistically significant effect of the ITD [$F(6,15)=7.93$, $p=0.001$, $\eta^2=0.76$]. An analysis of the polynomial contrasts revealed that only the linear component was statistically significant [$F(1,20)=44.14$, $p<0.001$, $\eta^2=0.69$].

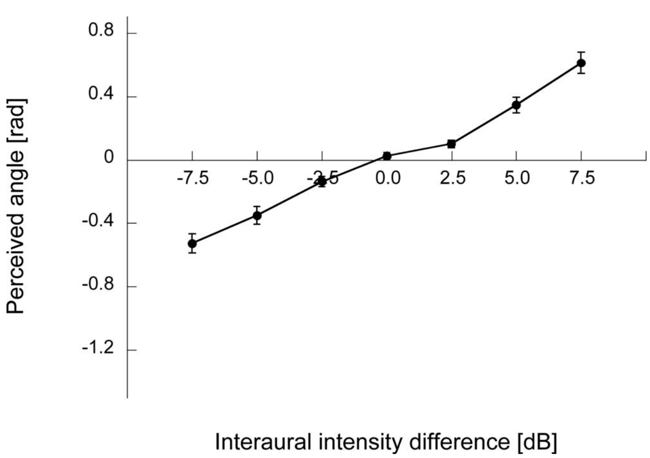


FIG. 3. Relation between the preset IID and the perceived location during the (IID) control trials of the localization phase of experiment 1b (error bars denote the standard errors of the means).

## C. Discussion

The effect of the ITD on the perceived sound source location in the critical trials is similar to that of experiment 1a ($\eta^2=0.85$ in experiment 1a, $\eta^2=0.76$ in experiment 1b). The same is true for the effect size of the linear component revealed by the polynomial contrast analyses ($\eta^2=0.71$ and $\eta^2=0.69$, respectively). Hence, the fact that there were only control trials with ITDs in the localization phase of experiment 1a seems to be irrelevant for the localization judgments during the critical trials.

Differentially adapting processors for ITDs and IIDs might pose a further alternative explanation of the shift-back effect found in experiments 1a and 1b. Phillips and Hall (2005) asked participants to give laterality judgments for tone pulses of two different frequencies which differed either in ITD or in IID. The tone pulses were preceded by adaptor tones of the same two frequencies that were highly lateralized on opposite sides based on the same interaural cue as the test tones. An adaptation effect was found, that is, for each of the two test tones the perceptual weight given to the interaural cue that was present with the adaptor tone was reduced and hence the point of perceived centrality was displaced toward the side of the adaptor tone with the same frequency. In the compensation phases of the current experiments the value of the ITD was constant during each trial while the IID was regulated by the participant and hence subject to permanent change. This presentation of a fixed ITD could have led to a similar adaptation effect as described by Phillips and Hall (2005) and thus to a decrease in the perceptual weight of the ITD.

Experiment 1c was conducted in order to test this adaptation hypothesis against the attentional modulation hypothesis. In the localization phase of experiment 1a, each trial started with the continuous playback of one of the five meaningless words with constant values for the ITDs and IIDs; in

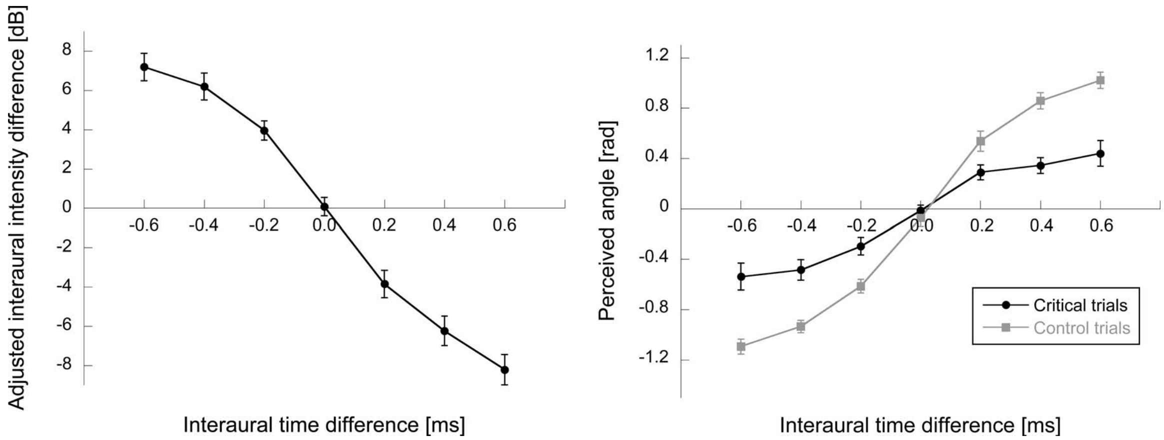


FIG. 4. Left panel: IIDs chosen to compensate for given ITDs during the compensation phase of experiment 1c (error bars denote the standard errors of the means). Right panel: Relation between the preset ITD and the perceived location during the critical trials and the control trials of the localization phase of experiment 1c (error bars denote the standard errors of the means).

the critical trials the ITDs were preset and the IIDs corresponded to the final value selected by the participant such that the sound appeared to originate from a central location in the compensation phase. In the localization phase of experiment 1c, in contrast, the critical trials in the localization phase were simply playbacks of the compensation trials. Thus, participants listened to exactly the same sequence of ITDs and IIDs as during the compensation phase, which means that during one trial, the ITD was constant at the preset value and the IID corresponded to the various values selected by the participant during the compensation phase.

Thus, the possible effect of adapting to a fixed ITD during one trial on the one hand and the effect of allocating attention to the to-be-adjusted IID on the other hand were distinguishable. If the shift-back effect found in experiments 1a and 1b were due to an adaptation to ITDs, then this adaptation must be present during both the compensation phase and the localization phase of experiment 1c because participants listen to exactly the same stimuli in the relevant trials in both phases. Hence, the sounds that were localized at a central position in the compensation phase should also be localized at a central position in the localization phase. Thus, if the adaptation hypothesis were correct, then the results of experiment 1c should deviate from those of experiments 1a and 1b in that there should be no shift-back effect in the localization phase. In contrast, if the shift-back effect found in experiments 1a and 1b were caused by shifting listeners' attention toward the IIDs by the process of regulating this cue during the compensation phase, then an off-center localization during the localization phase in which attention is more evenly distributed should still be observed. In other words, if the attentional modulation hypothesis were correct, then there should be a shift-back effect in experiment 1c that is similar to the shift-back effects observed in experiments 1a and 1b.

## IV. EXPERIMENT 1c

### A. Method

#### 1. Participants

Participants were 12 female and 8 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 19 to 50 years ($M=26$, SD $=8.5$). All participants reported normal hearing. They were paid for participating or received course credit.

#### 2. Apparatus and stimuli

Apparatus and stimuli were identical to those of experiment 1a except for the following. For every trial during the compensation phase, the entire sequence of slider movements (and, hence, the entire sequence of the participant's IID manipulations) was recorded in terms of both the movement velocity and duration (with a resolution of 1 ms) and the new position of the slider. For the critical trials of the localization phase the movements of the slider were simulated by changing the IID as recorded during the compensation phase. The IIDs of the control trials were changed according to a sine-shaped function with random amplitude (between 5 and 10 dB) and random cycle duration (between 2000 and 5000 ms). Before and after the sine-shaped change in the IID of the control trials the IID was constant at 0 dB for a random interval (between 1000 and 2000 ms before and between 2000 and 3000 ms after the changing process).

#### 3. Procedure

The procedure was identical to that of experiment 1a except for the localization phase. Participants were told that they would hear sounds that would change in perceived direction. They were instructed to wait until the playing of the sound stopped and to indicate the final location of the sound. They saw the same sketch of the head and red dot as during the localization phase of experiment 1a and did not see the slider.

#### 4. Design

The design was identical to that of experiment 1a.

### B. Results

Figure 4 (left panel) illustrates the relation between the preset ITD and the IID chosen to compensate for the effects of the ITD during the compensation phase. A MANOVA showed that the effect of the preset ITD on the chosen IID was statistically significant [$F(6,14)=21.41$, $p<0.001$, $\eta^2=0.90$]. An analysis of the polynomial contrasts showed statistically significant trends of orders 1 and 3 [$F(1,19)=127.50$, $p<0.001$, $\eta^2=0.87$; $F(1,19)=18.61$, $p<0.001$, $\eta^2=0.50$].

Figure 4 (right panel) shows the relation between the ITD and the perceived location during the localization phase. A MANOVA for the control trials showed a significant effect of the ITD on the perceived sound source location [$F(6,14)=94.55$, $p<0.001$, $\eta^2=0.98$]. A MANOVA for the critical trials showed a statistically significant effect of the ITD [$F(6,14)=8.36$, $p=0.001$, $\eta^2=0.78$]. An analysis of the polynomial contrasts revealed that the linear and the cubic component were statistically significant [$F(1,19)=51.84$, $p<0.001$, $\eta^2=0.73$; $F(1,19)=5.05$, $p=0.037$, $\eta^2=0.21$].

### C. Discussion

The effect of ITD on the perceived sound source location in the critical trials is similar to that of experiment 1a ($\eta^2=0.85$ in experiment 1a, $\eta^2=0.78$ in experiment 1c). The linear component revealed by the polynomial contrast analyses is also similar ($\eta^2=0.71$ in experiment 1a and $\eta^2=0.73$ in experiment 1c).

The fact that the localization of the critical trials during the localization phase was off center, even though participants during the localization phase listened to the same fixed ITD and identical changes of the IID as during the compensation phase, is incompatible with the hypothesis that the shift-back effect obtained in experiments 1a and 1b was due to selective adaptation to ITDs during the compensation phase. If adaptation caused the shift-back effect in those experiments, then the effect should have disappeared in the localization phase of experiment 1c. This is so because participants listened to the same sequences of constant ITDs and changing IIDs during the compensation and the localization phase, as a consequence of which adaptation should have occurred in both phases of the experiment. In contrast, the present results are clearly compatible with the assumption that the *task of adjusting* the IID shifted listeners' attention toward the IIDs, thus giving more perceptual weight to this cue during the compensation phase than during the localization phase.

An analogous shift-back effect as in experiments 1a–1c should be observed when the roles of ITDs and IIDs are reversed. Experiment 2 was conducted to test this prediction. However, as mentioned in the Introduction, there is some evidence that ITDs play a dominant role in localization when low-frequency components are contained in the sounds (Wightman and Kistler, 1992, Shinn Cunningham *et al.*, 2000). If this were correct, then during the compensation phase we would try to shift participants' attention toward the interaural cue that already is the dominant cue. This could lead to a decrease in the shift-back effect. To anticipate, this is what we found.

## V. EXPERIMENT 2

### A. Method

#### 1. Participants

Participants were 29 female and 10 male persons, most of whom were students at the Heinrich-Heine-Universität Düsseldorf. Their age ranged from 18 to 47 years ($M=24$, SD=5.8). All participants reported normal hearing. They were paid for participating or received course credit.

#### 2. Apparatus and stimuli

Apparatus and stimuli were identical to those of experiment 1a, with the following exceptions. The sounds were presented with preset IIDs instead of ITDs. As a reference point for choosing a reasonable range of IIDs, the mean value of the IIDs chosen by the participants to compensate for the maximum ITD ($\pm 600$ $\mu$s) of experiment 1a was computed. The mean IID for this judgment situation was 7.42 dB. We therefore selected ITDs of −7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB for experiment 2. The slider in the compensation phase of the experiment allowed participants to adjust the ITD in a range of $\pm 600$ $\mu$s.

During a pilot study, Lang had the subjective impression that in some trials even an ITD of $\pm 600$ $\mu$s would not seem to compensate for the given IID. For this reason a checkbox labeled "not enough" was displayed next to the slider. 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 in the midline. These trials were excluded from all further analyses.

#### 3. Procedure

The procedure was the same as in experiment 1a except that the to-be-adjusted variable during the compensation phase was the ITD.

#### 4. Design

The independent variable was the IID, which was manipulated within subject in seven steps (−7.5, −5.0, −2.5, 0, 2.5, 5.0, and 7.5 dB). The dependent variables were (a) the chosen ITD during the compensation phase and (b) the perceived location during the localization phase of the experiment. As mentioned above, we expected a smaller effect size than in experiment 1a because during the compensation phase we tried to shift participants' attention toward the interaural cue that already is the dominant cue. We presumed an effect size of $\eta^2=0.45$. A statistical power analysis using G*Power3 (Faul *et al.*, 2007) showed that in order to detect effects of $\eta^2=0.45$ of the independent variable given $\alpha=\beta=0.05$, $N=12$ participants were needed.

### B. Results

Two participants had to be excluded because for one or more given IIDs they chose the not enough checkbox during all trials. For the remaining participants this was the case for 2.0% of the trials. The left panel of Figure 5 illustrates the relation between the preset IID and the ITD chosen to compensate for the effects of the IID during the compensation

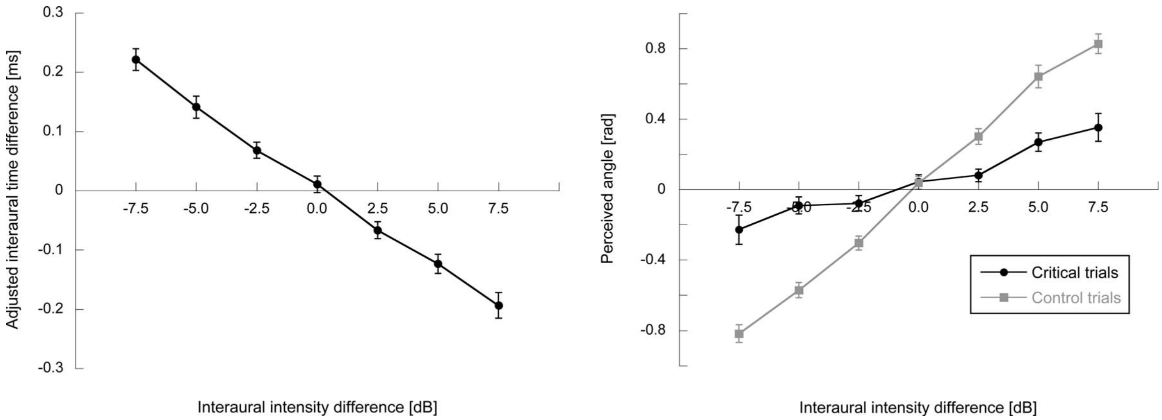


FIG. 5. Left panel: ITDs adjusted by the participants in order to compensate for preset IIDs during the compensation phase of experiment 2 (error bars denote the standard errors of the means). Right panel: Relation between the preset IID and the perceived location during the critical trials and the control trials of the localization phase of experiment 2 (error bars denote the standard errors of the means).

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 [$F(6,31)=30.87$, $p<0.001$, $\eta^2=0.86$]. An analysis of the polynomial contrasts showed that only the linear component was statistically significant [$F(1,36)=159.66$, $p<0.001$, $\eta^2=0.82$].

Figure 5 (right panel) shows the relation between the IID and the perceived location during the localization phase. A MANOVA for the control trials showed a significant effect of the IID on the perceived sound source location [$F(6,31)=48.45$, $p<0.001$, $\eta^2=0.90$].

For the critical trials participants had compensated the IIDs by appropriate ITDs during the compensation phase. Thus, one should expect a perceived location at the midline (i.e., a perceived angle of zero) if the processes operating during the compensation and localization phases were identical. As in experiment 1a, this does not appear to be the case, albeit the shift of the perceived location of the critical trials toward the location predicted by the preset interaural cue (IID) was smaller than in experiment 1a. A MANOVA for the critical trials showed that the effect of the IID was nevertheless statistically significant [$F(6,31)=4.75$, $p=0.002$, $\eta^2=0.48$]. An analysis of the polynomial contrasts showed that only the linear component was statistically significant [$F(1,36)=24.30$, $p<0.001$, $\eta^2=0.40$].

### C. Discussion

The analysis of the compensation phase data showed that participants had understood the task of canceling out the preset IIDs by appropriate ITDs. However, the data from the localization phase showed that the processes operating while manipulating ITDs to compensate for IIDs cannot be considered equivalent to the processes operating during sound localization in a normal listening situation. The shift-back effect observed in experiments 1a–1c also occurred in experiment 2. However, the effect was smaller in this experiment; this is consistent with the assumption that low-frequency ITDs play a dominant role in sound localization and, hence, attention was directed to the interaural cue that already is the dominant cue.

## VI. GENERAL DISCUSSION

The trading ratios found in our experiments are comparable to those reported by Young and Levine (1977) for 500 Hz tones: In experiment 1a we found a trading ratio of 80.1 $\mu$s/dB for a preset ITD of 600 $\mu$s (79.4 $\mu$s/dB for a preset ITD of 500 $\mu$s in Young and Levine, 1977); in experiment 2 we found a trading ratio of 27.7 $\mu$s/dB for a preset IID of 7.5 dB (40.4 $\mu$s/dB for a preset IID of 8 dB in Young and Levine, 1977).

The results of the current experiments show that trading ratios more strongly favored IID when adjusting IID, and more strongly favored ITD when adjusting ITD, relative to a neutral listening context. This implies that during the compensation phases a greater perceptual weight was applied to the to-be-adjusted cue in relation to the fixed cue. This finding suggests that the task of canceling out the effect of one binaural cue by a compensatory value of the other cue implies a shift of attention toward the to-be-adjusted cue which in turn gives more perceptual weight to this cue. This change in the perceptual weights to ITDs and IIDs due to a shift of attention toward one of the cues holds an explanation for both the fact that trading ratios differ depending on which of the cues is regulated as reported by Young and Levine (1977) and for the shift-back effect found in the current experiments. The question arises if our attention approach can be regarded as an extension of the regression interpretation by Trahiotis and Kappauf (1978). What would this mean? It seems possible that attention to one interaural cue (e.g., IID) is accompanied not only by an increased weight of this cue in relation to the other cue but also by the evocation of an internal reference tone with the sound source position of interest (e.g., a central position). This reference tone might be a “remainder” of the practice trials in our experiments or be the result of all-day listening experience. It is plausible to assume that the IID of a reference tone in a central position would be 0 dB. When adjusting the IID of a tone a comparison process between the IID of this tone and the IID of the reference tone (0 dB) could start and lead to a regression to 0 dB.

In contrast to Young and Levine (1977) in our experiments no reference tone was presented. So the plausibility of

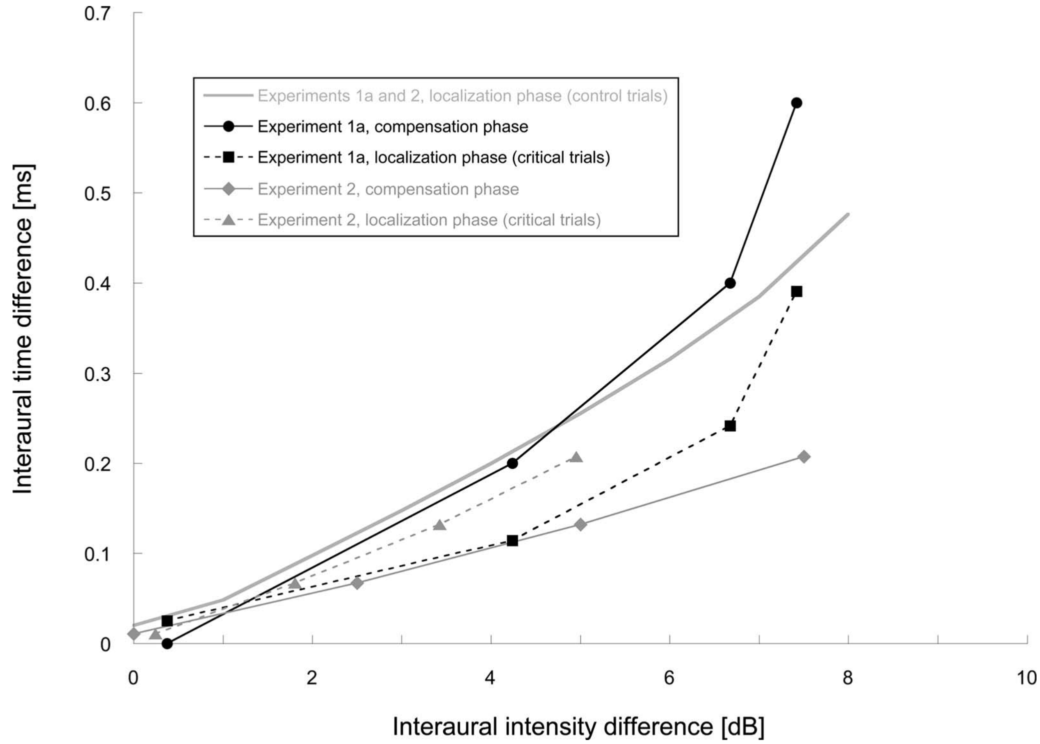


FIG. 6. Equivalence relations during the two phases of experiments 1a and 2 and in the nonconflict situation of the control trials.

the arguments mentioned above depends on the question if participants have internal representations of reference tones that could serve as anchors for regression. In order to test whether an internal representation of a reference tone plays a role in trading experiments in which no (explicit) reference is presented, an experimental design would be needed that prevents the buildup and/or the use of such an internal representation effectively.

Experiments 1b and 1c showed that the shift-back effect can be explained neither in terms of an over-representation of the preset interaural cue (experiment 1b) nor in terms of selective adaptation to the preset and thus constant cue (experiment 1c).

One possible problem has been unmentioned until now. In the localization phases participants had a pointing device which they used to indicate the location of the virtual sound source. This pointing device could have served as a visual reference for the central position. In contrast, during the compensation phases there was no visual reference for centrality. The question arises if this led to a systematic deviation in the position that the participants considered to be the central position in both phases of the experiments. The critical trials with a preset ITD of 0 $\mu$s and a preset IID of 0 dB, respectively, can help to determine if such a deviation occurred. In each trial of the compensation phases the starting position of the control slider was set randomly such that the listener had to adjust a compensation value even for the critical trials in which the preset cue was set to zero. The fact that the mean compensation values for a preset cue of 0 $\mu$s or 0 dB were very close to zero indicates that there was no systematic error as to the central position during the compensation phases (see Figs. 1, 2, 4, and 5—left panels).

The attentional manipulation should be considered short lived because during the localization phase the sounds were perceived as originating from an off-midline location consistent in its trend with the preset interaural cue. The short-term nature of the attention allocation poses a possible explanation as to why Jeffress and McFadden (1971) found no effect of their manipulation by selective feedback solely on the basis of ITDs or solely on the basis of IIDs. They compared the trials *following* the trials with selective feedback, rather than the trials in which the feedback was given.

In more general terms, the present results clearly show 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. 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).

In order to illustrate the difference, approximations to the current equivalence relations were computed for the two phases and trial types of experiments 1a and 2. In the compensation phases of both experiments and in the critical trials of the localization phases ITDs and IIDs were set into opposition, while in the control trials of the localization phases only one cue was present. Separate equivalence relations were computed for

(a) the control trials of the localization phases of both experiments (no opposition),
(b) the compensation phases of both experiments (the cues were in opposition and attention was directed on one of the cues by the compensation task), and

(c) the critical trials of the localization phases of both experiments (the cues were in opposition but attention was not manipulated).

The equivalence relation of the control trials was obtained as follows. In experiment 1a the data points of the control trials represent the relation between the preset ITD and the perceived location. In experiment 2 the data points of the control trials represent the relation between the preset IID and the perceived location. In order to obtain a function that relates the ITDs to the IIDs, the data points of the control trials of both experiments were approximated by polynomial functions. These functions were set to be equal and resolved for the ITD variable. For both experiments polynomials of orders 1–3 were evaluated in order to determine the best approximation. The best fit to the data points of the control trials of experiment 1a was observed with a third order polynomial $[F(3,3)=6311.4,\ p<0.001,\ R^2=1.000]$. The best fit to the data points of the control trials of experiment 2 was observed with a linear equation $[F(1,5)=1516.5,\ p<0.001,\ R^2=0.997]$. ITDs corresponding to IIDs between −8 and 8 dB in steps of 1 dB were computed. The equivalence relations of the compensation phases of both experiments were obtained by plotting the to-be-adjusted dimension against the preset dimension. The equivalence relations of the critical trials of the localization phases of both experiments were computed as follows. For each preset ITD or IID the perceived location of the *critical trials* was inserted into the regression equation (see above) of the *control trials* of the same experiment. This equation was solved for the corresponding ITD or IID. In this way the ITD or IID was obtained that leads to the same perceived location when presented without a binaural cue of inverse sign. This may be regarded as the residual ITD or IID that had not been compensated for in the compensation phase and thus accounted for the shift-back effect. Hence, the difference between the *preset* ITD or IID and this residual represents the portion of the preset interaural cue that had been compensated for by the adjustment of the other cue.

Figure 6 shows the resulting relations. Comparing the two phases of experiment 1a clearly shows a shift of the equivalence relation toward IIDs in the compensation phase in comparison with the localization phase. A converse shift toward ITDs can be seen in the compensation phase of experiment 2.

It is worth mentioning that most data points are below the curve computed from the control trials. Consistent with the dominant role of ITDs in sounds with low-frequency content, when ITDs and IIDs are set into opposition a shift toward ITDs takes place so that ITDs receive more weight than in a nonconflict situation.

Returning to the central focus of this series of experiments, we want to mention that we currently consider two mechanisms that may operate as a result of the attention shift induced by the task of compensating one interaural localization cue by adjusting the other cue. First, the perceptual weight of the to-be-adjusted cue *per se* may vary along a continuum. Second, the probability of listening to a time image or a time/intensity image may vary.

Whether one of these mechanisms, or perhaps a combination thereof, operates as a result of the attention shifts described here is currently an open question, which may be answered by future research.

[1]The term "trading ratio" suggests a linear relationship between ITDs and IIDs. 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 $\mu$s/dB at an ITD of 600 $\mu$s"). 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 louder, respectively, on the left channel whereas positive values indicate that it was earlier or louder, respectively, on the right channel.


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