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The aftereffects of ventriloquism: Are they sound-frequency specific?

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Abstract

Exposing different sense modalities (like sight, hearing or touch) to repeated simultaneous but spatially discordant stimulations generally causes *recalibration* of localization processes in one or both of the involved modalities, which is manifested through *aftereffects*. These provide opportunities for determining the *extent* of the changes induced by the exposure. Taking the so-called *ventriloquism* situation, in which synchronized sounds and light flashes are delivered in different locations, we examine if auditory recalibration produced by exposing tones of one frequency to attraction by discordant light flashes generalizes to different frequencies. Contrary to an earlier report, generalization was obtained across two octaves. This result did not depend on which modality attention was forced on through catch trials during exposure. Implications concerning the functional site of recalibration are briefly discussed.

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Keywords: Sensory perception; Intersensory processes; Perceptual adaptation; Sound localization

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1. Introduction

The visual and the auditory system maintain coordinated representations of external space. The coordination is presumably achieved and maintained by systematically cross-checking between the two modalities. Research on audio-visual spatial coordination, like that on other cases of intermodal coordination, has been mostly based on conflict situations, in which discordant informations regarding the location of potentially the same event is fed simultaneously in the two modalities. Exposure to such spatial discordance produces both online immediate biases and offline aftereffects.

Presenting an observer with synchronous but spatially discrepant auditory and visual information creates a percept in which sound is located nearer to the location of the visual input (Bermant & Welch, 1976; Bertelson & Radeau, 1981; Klemm, 1909; Radeau & Bertelson, 1987). This visual bias of auditory location is generally known as *the ventriloquist effect* (Bertelson, 1999). The effect involves a genuinely perceptual component and cannot be reduced to post-perceptual corrections (Bertelson & Aschersleben, 1998; Bertelson & Radeau, 1981). Although demonstrations have often been based on quasi-realistic situations (e.g., steam kettles and whistling noises as in Jackson (1953), or speech and the moving face of the talker as in Witkin, Wapner, & Leventhal, 1952), these are by no means necessary, as biases are easily obtained with stripped-down stimuli such as sound bursts and light flashes (Bertelson & Radeau, 1981; Bertelson, Vroomen, de Gelder, & Driver, 2000; Choe, Welch, Gilford, & Juola, 1975; Radeau & Bertelson, 1987; Vroomen, Bertelson, & de Gelder, 2001).

Exposure to the ventriloquism situation also leads to compensatory *aftereffects*, consisting in post-exposure shifts in auditory localization (Canon, 1970; Radeau, 1973; Radeau & Bertelson, 1974, 1976–1978; Recanzone, 1998), and sometimes also in visual localization (e.g., Radeau, 1973; Radeau & Bertelson, 1974, 1976 Experiment 1). It is generally agreed that aftereffects reflect a recalibration process that results in a reduction of the perceived discrepancy, and would play an important role in achieving and maintaining a coherent intersensory representation of space (Held, 1965; Welch, 1978).

At the root of our present research program is the notion that aftereffects may provide information, not available in immediate effects, regarding the *extent* of the changes induced by exposure to conflict situations. Probing for the occurrence of aftereffects at several stimulus values can tell us whether these changes are specific to the values used in the conflict situation or instead generalize to a range of neighboring stimuli. This research strategy was inaugurated by Bedford (1989) who examined the extension of visuo-proprioceptive spatial recalibration in a task consisting of learning new mappings between visual location and placing of a finger. She found that adaptation achieved in one particular location transferred entirely to all other locations along the azimuth. Other work on visuo-proprioceptive or visuo-motor re-mapping has however produced a different pattern of spatial transfer, with aftereffects largest at the adaptation location and going down with increasing distance from that location (Field, Shipley, & Cunningham, 1999; Ghahramani, Wolpert, & Jordan, 1996). A similarly decreasing pattern of spatial generalization has also been reported by Vroomen, Bertelson, Frissen, and de Gelder (2001) for the aftereffects of ventriloquism.

In the present study, we considered another extension-related question, namely whether the visual recalibration of perceived sound location is specific to the spectral characteristics of the sounds used during adaptation. One reason for being interested in that question was its possible relation to the distinction between two basic sound localization mechanisms based on respectively interaural level differences (ILD) and interaural time differences (ITD). ILD is known to be the main cue for localizing sound frequencies above 1.5 kHz and ITD for lower frequencies (Blauert, 1997; Cohen & Knudsen, 1999). Finding that adaptation does not generalize from one of these two frequency ranges to the other one would suggest that it affects specifically these somewhat peripheral mechanisms, rather than one located at a more central site.

Results briefly mentioned by Recanzone (1998) seemed to support the latter suggestion, although the relation to ILD and ITD was not considered in the paper. Three participants were exposed to either 750 or 3000 Hz tone bursts synchronized with a light flash 8° to the right. Strong auditory aftereffects (7.08° overall) occurred when the test stimuli's frequency was the same as that of the adapters, but none at all with test stimuli at the other frequency. Given the importance of their possible implications, these results, based on a single direction of adaptation and only three participants, clearly needed some verification. Here, the generalization across the same two sound frequencies of the visually induced recalibration of apparent sound location was examined, for both leftward and rightward adaptation, with pure tones and light flashes as material, and a more substantial number of participants. Three patterns of results were in principle possible: First, no transfer whatsoever across sound frequencies, as reported by Recanzone (1998); second, complete transfer, as Bedford (1989) found for visuo-proprioceptive re-mapping; third, partial transfer, meaning an aftereffect that is maximal around the adapting frequency and goes down with increasing distance from that frequency, as in Field et al. (1999) and Ghahramani et al. (1996), also for the visuo-proprioceptive case.

2. Experiment 1

Following the classical pre-tests–adaptation–post-tests paradigm, participants in this experiment localized tones at two frequencies, 750 and 3000 Hz, before and after repeated exposure to one of these tones synchronized with a spatially discordant light flash, 9° to its left or its right. This design provided, for each adaptation frequency, separate measures of aftereffects at the adaptation frequency and at the other one.

2.1. Method

2.1.1. Participants

Eighteen students from Tilburg University (age 18–30, twelve female), all naïve as to the purpose of the Experiment, and with normal hearing and normal or corrected to normal vision, participated in two sessions each, at separations of at least 1 h.

2.1.2. Apparatus and material

The testing was carried out in a completely dark soundproof booth. The setup consisted of three display units which were occluded by means of a black, acoustically transparent cloth and an array of push buttons. Display units, each of which consisted of a loudspeaker with an LED over its centre, were arranged along a semi-circular array at 85 cm from the participant's head, at eye level and at −9°, 0°, and +9° distance from centre in the horizontal plane. Pushbuttons, 108 in total, were arranged along another semi-circular array 20 cm in front of the display units, and 30 cm below them. The auditory stimuli were 200 ms pure tones (with 5 ms linear rise/fall envelopes) at either 750 or 3000 Hz, presented at 70 dB(A).

2.1.3. Procedure

Each session consisted of 120 auditory pre-tests, followed by 60 bimodal exposure trials, and then by 120 post-tests. On pre- and post-tests, the sound was presented 20 times on each of the three loudspeakers at each of the two frequencies (750 and 3000 Hz). All combinations of speaker location and sound frequency were presented in random order, with 3 s intertrial intervals. The participant was instructed to always push the button corresponding to the apparent horizontal location of the presented sound. Bimodal exposure trials all consisted of the presentation of the 200 ms sound in the central loudspeaker in synchrony with the 200 ms lighting up of the LED of the adjacent display unit, to the left or to the right, depending on the session. To impose attention to the visual distracter, two catch trials, on which the sound was presented without accompanying light flash, were interspersed at random among the exposure trials, and participants were instructed to report their occurrence verbally. Half the participants ($n = 9$) had all their bimodal exposure trials with the 750 Hz tone, and the other half with the 3000 Hz tone. Each participant was adapted to the left on one session and to the right on the other session, in balanced order.

2.2. Results

Performance on catch trials was flawless.

Separately for each speaker location and test frequency, responses that were more than 2.5 standard deviations from the mean were excluded from the analysis. They represented 1.6% of the data. Aftereffects were calculated by subtracting mean reported locations on pre-tests from those on post-tests. Aftereffects were counted as positive when they went toward the visual distracter.

Aftereffects for each combination of adaptation frequency and test frequency (Fig. 1) were all substantial, with small differences between those measured with same frequency tests and with different frequency tests. They were submitted to an Adaptation Frequency (750 vs. 3000 Hz) × Test Frequency (same as in adaptation vs. different) × Direction of Adaptation repeated measures ANOVA. The overall aftereffect, across all conditions, was highly significant ($F(1, 16) = 78.50$, $p < 0.001$). None of the main effects, Adaptation Frequency ($F < 1$), Test Frequency ($F(1, 16) = 1.73$, $p = 0.21$) nor Direction ($F(1, 16) = 3.48$, $p = 0.067$) was significant, neither was any of the interactions. Among these, the one between Adaptation

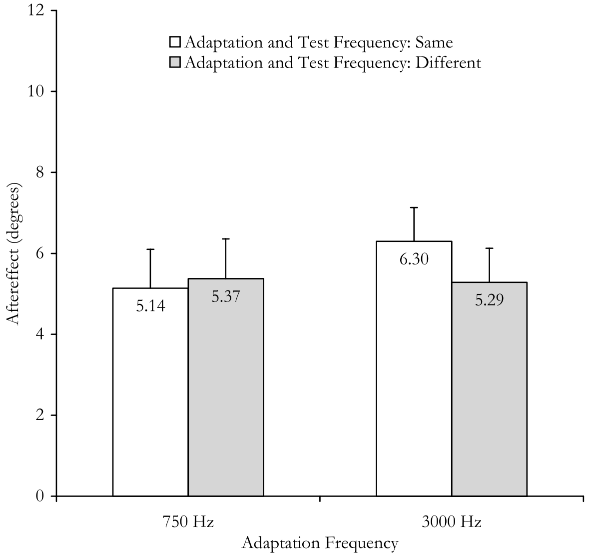

Fig. 1. Experiment 1: Mean aftereffects per combination of adaptation frequency and test frequency (with standard errors). Separate groups of nine participants were adapted at each frequency.

Frequency and Test Frequency was however close to significance ($F(1, 16) = 4.43$, $p = 0.052$). This presumably reflects the existence across the two Adaptation Frequencies of Test Frequency effects which, although small, go in opposite directions. By t-tests, none of these two effects reached significance (3000 Hz: $t(8) = 2.01$, $p = 0.079$; 750 Hz: $t < 1$).

Individual results (Fig. 2) show considerable variations in mean aftereffect, but the differences between "same" and "different" were all small and displayed no

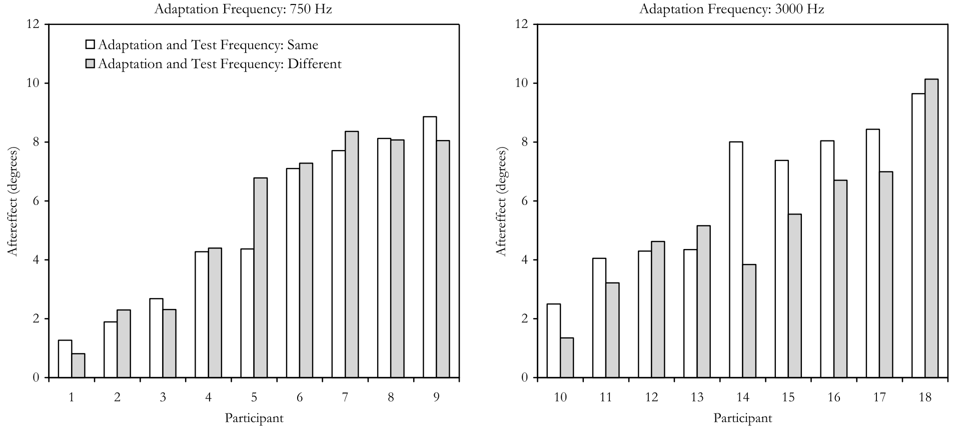

Fig. 2. Experiment 1: Individual results. In each group, participants were ordered according to *overall* effect size.

systematic tendency: 10 of 18 participants had a larger aftereffect in the "same" condition. This deviation from equi-frequency is of course non-significant ($p = 0.41$).

2.3. Discussion

Measuring recalibration with a tone whose frequency is different from the one used during exposure had no significant effect on the size of the aftereffects. Judging from this result, visual recalibration of auditory location is not specific to sound frequency. This conclusion, of course, contrasts sharply with that of Recanzone (1998). There are however several differences between the procedures of the two studies that might have contributed to the discordant outcomes. The main one is that Recanzone used a larger number of exposure trials (2500, against 60 here), and one may wonder whether prolonged exposure does not bring about a "fine tuning" process, by which recalibration would become more specific of the particular sound frequency at which it was produced. Other differences concern the locations at which exposure was conducted, a single central location like here or a range of locations (nine in Recanzone's case), and the allocation of conditions to the participants. Recanzone's participants were adapted in a single direction, but at each of the two sound frequencies, while each of ours was adapted, on separate sessions, in the two directions, but at a single frequency. A new experiment was run in which these various differences were minimized.

3. Experiment 2

This new experiment was run with the same setup and the same design as Experiment 1, but with a procedure modified in such a way as to bring it closer to that of Recanzone (1998). The modifications concerned the number of adaptation trials (2400 instead of 60 in Experiment 1), the number of locations at which adaptation was conducted (five instead of a single one) and the conditions under which each participant worked (now a single direction of adaptation, but both frequencies, on separate sessions).

3.1. Method

3.1.1. Participants

Fourteen new participants from the same student population (age: 19–32, 11 female) participated in two sessions each.

3.1.2. Apparatus and material

The setup and stimuli were the same as in Experiment 1, except that the number of display units was increased to seven, located at −27°, −18°, −9°, 0°, 9°, 18° and 27° from the centre.

3.1.3. Procedure

Each of the two sessions consisted of 200 auditory pre-tests, followed by 2400 exposure trials, and then 200 post-tests. Pre- and post-tests were now initiated by the participant by pressing a button 20 cm in front of her/him with the pointing hand, a procedure ensuring that all pointing movements started from a constant position. The sound was presented 20 times on each of the five central loudspeakers (at −18°, −9°, 0°, +9°, and +18°), and at each of the two frequencies, all in randomized order.

On bimodal exposure trials, the sound was presented in randomized order across the five speaker locations, and the light flash always on the left adjacent unit for half the participants, and to the right for the other half. An average of 25 catch trials, on which the light flash was omitted and which the participants had to count, were interspersed at random locations among exposure trials. As in Experiment 1, their role was to force attention to the visual distracters. The participant reported his final count at the end of the adaptation phase, immediately before the post-tests. Each participant was adapted with one frequency on one session and with the other frequency on the other session, in balanced order.

3.2. Results

Catch trial detection, estimated from participants' reported counts, ranged from 82% to 100%. Application of the same principles as in Experiment 1 resulted in the exclusion of 1.4% of outlying responses.

As seen in Fig. 3, substantial aftereffects were obtained in each of the four conditions. Differences between conditions with same frequency tests and with different

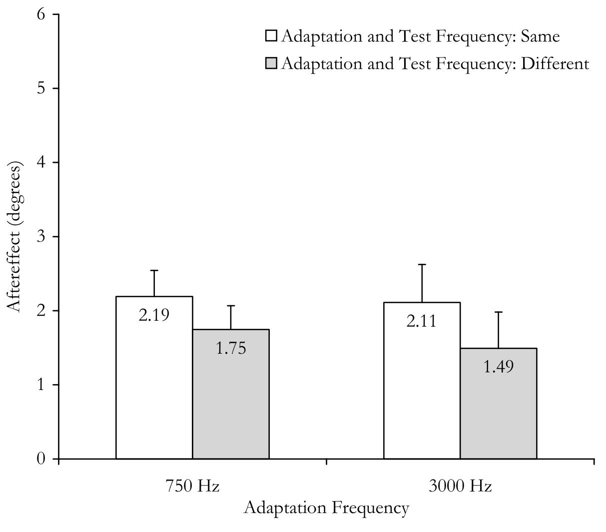

Fig. 3. Experiment 2: Mean aftereffects per combination of adaptation frequency and test frequency (with standard errors). Separate groups of seven participants were adapted in each direction.

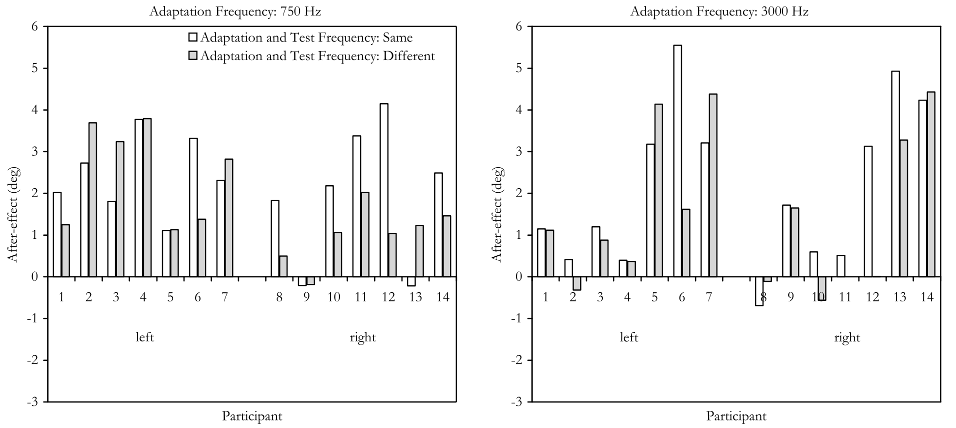

Fig. 4. Experiment 2: Individual results. In each panel, participants from each group were ordered according to their *overall* effect size across adaptation frequencies.

frequency tests, although still small, now went for both adaptation frequencies in the direction of stronger aftereffects in the "same" condition. In the Adaptation Frequency (750 vs. 3000 Hz) × Test Frequency (Test Frequency same as Adaptation Frequency vs. different) × Direction repeated measures ANOVA, the overall aftereffect was highly significant ($F(1,12) = 31.26$, $p < 0.001$), but neither Test Frequency ($F < 1$), Adaptation Frequency ($F < 1$), Direction ($F(1,12) = 1.94$, $p = 0.19$) nor any of their interactions was significant. This was in particular the case for the Adaptation Frequency × Test Frequency interaction that was nearly significant in Experiment 1, but now fell clearly short of significance ($F(1,12) = 2.84$, $p = 0.118$).

At the level of individual participants, Fig. 4 shows that the differences between aftereffects measured at the adaptation frequency and at the other frequency showed again large variations. Seven out of the 14 participants had larger aftereffects in the same condition for adaptation frequency 750 Hz, and 10 out of 14 for adaptation frequency 3000 Hz, both deviations from equi-probability non-significant by sign-test.

3.3. Discussion

Just as in Experiment 1, aftereffects measured at either of the two adaptation frequencies were only slightly and non-significantly larger than those measured at the other frequency. The changes we introduced in our procedure to make it more similar to Recanzone's, at the levels of number of adaptation trials, number of exposure locations and different conditions each participant worked with, failed to eliminate the contrast between the respective results. However, one difference whose possible influence has not been considered so far concerns the modality to which attention was directed by catch trials during exposure. In the two preceding experiments, it was the visual modality, whereas Recanzone had his participants monitor the auditory signals for occasional amplitude reductions. Could it be the case that increased attention to the auditory stimulus during adaptation makes recalibration more specific of the spectral characteristic of that stimulus? To check on this possibility, the task of Experiment 2 was in the next experiment administered with Recanzone's auditory catch trials substituted for our visual ones.

4. Experiment 3

Experiment 3 was in all details identical to Experiment 2, except that during exposure participants performed an auditory monitoring task instead of a visual one.

4.1. Method

Fourteen new participants from the same student population (age: 18–24, 11 female) took part in two sessions each. Apparatus, material and procedure were as in Experiment 2, except that catch trials (again an average of 25 interspersed among exposure trials) now consisted of the attenuation of the tone by 10 dB. Participants were again instructed to count the number of catch trials.

4.2. Results

Individual performance on catch trials ranged from 76% to 100%. One percent of outlying responses were discarded.

Fig. 5 shows that substantial aftereffects were obtained in each of the four conditions. They are now stronger at both adaptation frequencies in the condition with

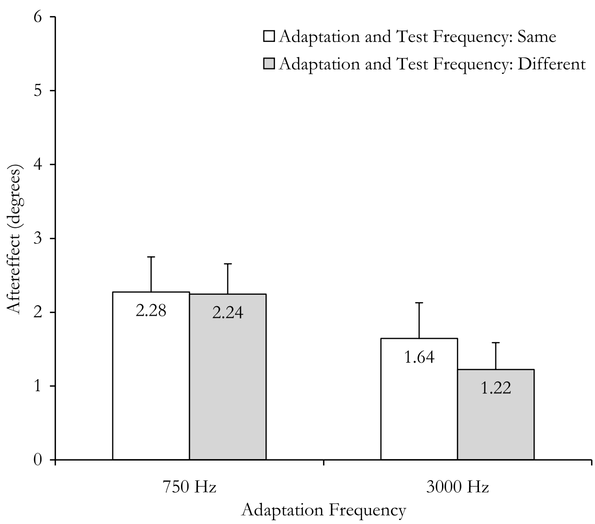

Fig. 5. Experiment 3: Mean aftereffects per combination of adaptation frequency and test frequency (with standard errors). Separate groups of seven participants were adapted in each direction.

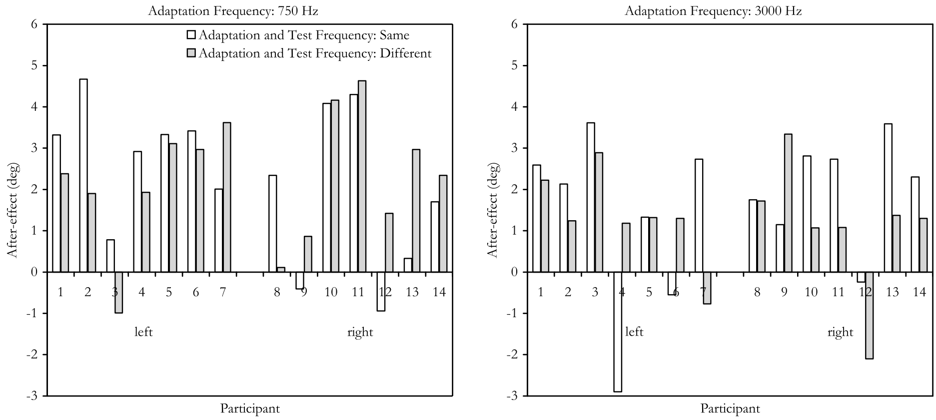

Fig. 6. Experiment 3: Individual results. In each panel, participants from each group were ordered according to their *overall* effect size across adaptation frequencies.

"same" test frequency, but none of the two differences was significant by *t*-test, both $ts < 1$. In the Adaptation Frequency (750 vs. 3000 Hz) × Test Frequency (Test Frequency same as Adaptation Frequency vs. different) × Direction of Adaptation (left vs. right) repeated measures ANOVA, the overall aftereffect, across all conditions, was highly significant ($F(1,12) = 49.82$, $p < 0.001$), but neither Adaptation Frequency ($F(1,12) = 2.46$, $p = 0.143$), Test Frequency ($F < 1$, supporting the above mentioned *t*-test results), Direction ($F < 1$), nor any of their interactions (the three-way interaction $F(1,12) = 2.72$, $p = 0.125$, all two-way $F\text{s} < 1$) were significant.

This pattern of results is thus nearly identical to the one obtained in Experiment 2. To check on the absence of difference between the two results, a 2 (Experiment 2 or 3) × 2 (Adaptation Frequency) × 2 (Test Frequency same or different) ANOVA was carried out. Except for the overall effect ($F(1,26) = 116.61$, $p < 0.001$), none of the main effects nor of their interactions was significant (all $F\text{s} < 1$).

At the level of individual participants (Fig. 6) there were again large variations. Seven out of 14 participants had larger aftereffects at adaptation frequency for adaptation frequency 750 Hz, and 9 out of 14 for adaptation frequency 3000 Hz, both deviations from equi-probability non-significant by sign-test.

4.3. Discussion

Replacing the visual catch trials of Experiment 2 by auditory ones had no detectable effect on the pattern of extension, which for the two adaptation frequencies remained strong generalization to the other frequency, with only a small and non-significant reduction. The use of an auditory monitoring task could thus not be the reason behind Recanzone's no-generalization result.

5. General discussion

In each of the preceding three experiments, exposure to spatially discrepant tones and light flashes resulted in strong and highly significant recalibrations of apparent sound location, and measuring these recalibrations at tone frequencies distant by two octaves from the one used during adaptation, rather than at the same frequency, produced only small and non-significant reductions of recalibration size. These practically identical results were obtained across wide variations in experimental parameters such as number of adaptation trials, adaptation at a single or several locations, attention orientation to one or the other of the involved two sensory modalities, and range of conditions each participant was exposed to.

Our findings are thus clearly inconsistent with the notion of spatial recalibration as specific to the sound frequency used during exposure. To that extent, they are in sharp contrast to those of Recanzone (1998) who obtained no generalization whatsoever between exactly the same two tone frequencies. The changes introduced in our procedure across the successive experiments were meant essentially at identifying the sources of the contrasting findings. In Experiment 3, these changes culminated in having all the main parameters practically identical to those in Recanzone's experiment. The only remaining explanation of the contradiction must reside in the small scope (three participants) of Recanzone's investigation. Some of the present participants also displayed small or inexistent degrees of transfer, like participants 8 and 12 in Experiment 2 and participant 8 in Experiment 3 (this one for adaptation at 750 Hz only).

As explained in Section 1, the main theoretical motivation for the present study was the information it might provide regarding the possible roles of the basic ILD and ITD sound localization mechanisms in recalibration. Of the two frequencies we used, one, 3000 Hz, belongs to the range in which ILD dominates, and the other one, 750 Hz, belongs to the ITD range. Confirming Recanzone's (1998) finding of strong specificity would have suggested that recalibration takes place at the level of these peripheral mechanisms. Our observation of important generalization between the two frequencies implies that, to the contrary, recalibration probably takes place at a later processing stage, after outputs from the two peripheral systems have been combined.

The present result, strong generalization with only small and non-significant reduction across frequency change, is, as already mentioned, inconsistent with one of the three patterns considered in Section 1, strict specificity. Given that observed reductions were significant in none of the experiments, it is for the time being compatible with total generalization, but a larger range of frequency shifts must still be examined before the alternative possibility of a diminishing gradient can be completely ruled out.

Our search for an explanation of the contradiction between our results and those of Recanzone has led us to consider the possible effect of selectively attending to either modality. The comparison of the results from respectively Experiments 2 and 3 revealed no effect whatsoever on the generalization pattern. On the other hand, there was also no effect on the overall size of the aftereffects. Although it has no relation to the main objectives of our study, this result could at first sight be taken as contradicting earlier results in the literature showing a dependence of that size on which modality attention was focused on during exposure. Both Canon (1970) and Radeau (1974) measured auditory and visual aftereffects after a period of exposure to audio-visual discrepancy, during which participants pointed selectively either to the sounds or to the flashes. Auditory aftereffects were larger in the visual pointing conditions than in the auditory pointing ones, and vice versa for visual aftereffects. (There were actually no visual aftereffects after visual pointing in Canon's experiment.) Focusing selective attention in one modality through pointing instructions apparently increased its relative weight in the recalibration process. Similar results were obtained by Kelso, Cook, Olson, and Epstein (1975) for a case of visuo-proprioceptive conflict.

There are important differences between the methods by which attention to modality was controlled in these three studies (through selective pointing) and in our own one (through stimulus or stimulus change detection), which may have played a role in bringing about the divergent outcomes. First, pointing involves other processes than just orientation of attention, most notably motor processes. On the other hand, the attention it requires is specifically attention to target location, which may not necessarily be required by the detection tasks. The whole question of the role of attention in cross-modal interaction should clearly be revisited with better consideration for the various possible ways of manipulating it.

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