RELEARNING SOUND LOCALIZATION WITH DIGITAL EARPLUGS

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1. INTRODUCTION

The auditory system infers the location of sound sources from the processing of different acoustic cues. As the size of the head and the shape of the ears change over development, the association between acoustic cues and our expectation of external spatial position can not be fixed at birth, but has to be plastic. Recent studies on humans have shown that the auditory system is still capable of such plasticity during adulthood (Javer and Schwartz, 1995; Hofman et al., 1998; Van Wanrooij and Van Opstal, 2005). We aim to explore the principles that govern an adaptation to shifted Interaural Time Differences (ITDs), one of the two binaural cues for azimuthal perception with the Interaural Level Differences (ILDs).

We equipped six participants with binaural digital earplugs that allow us to delay the input to one ear, and thus disrupt the ITDs. Participants were asked to wear the plugs during all waking hours for 10 days and their ability to localize sounds on the horizontal plane was tested everyday in free field conditions.

2. METHODS

Participants. Two female and four male students aged 26-32 years, with no history of hearing disorder or neurological disease, participated as paid volunteers, after having given informed consent. The experimental procedures were approved by the local ethics committee.

Plugs. Each plug contains a programmable signal processor, microphone and transducer and was fitted to the ears of each participant to create an acoustic seal (attenuation around 25 dB). The gain of the plugs was adjusted to achieve normal loudness levels. The plugs could be programmed to delay the incoming sound by a desired duration.

Design and stimuli. Sound localization tests were controlled by a custom-designed Matlab script (r.2009a; MathWorks) and stimuli were generated using TDT System 3 (Tucker-Davis-Technology). The listener was seated in a hemi-anechoïc room, in front of an array of 25 speakers (Orb Audio) mounted on a 180° arc placed at 90 cm of the listener's head on the horizontal plane, giving an azimuthal resolution of 7,5°. In a first sound localization task, the stimulus consisted of 250 ms pulsed-train (5 bursts of 25 ms) of low-pass filtered pink noise (cf = 2 kHz). This type of stimulus ensures that the ITDs contribute largely to the azimuthal perception (Middlebrooks and Green, 1991). In a second sound localization task, the stimulus was identical to the first one, except that its spectrum was randomized from trial to trial by roving the intensity in 1/6 octave bands by up to 40 dB. The spectral uncertainty of this stimulus was used to reduce the effectiveness of spectral cues (Wightman and Kistler, 1997 ; Kumpik et al., 2010). The overall level of both stimuli was 60 dB(A) at the position of the listener's head.

To allow a listener to indicate the perceived location a of stimulus, a laser pointer and a head-tracker (Polhemus Fastrak) were attached on his head, both pointing toward a 0° in azimuth and elevation direction for a centred head position.

Procedure. During a sound localization run, each location was pseudorandomly presented five times, for a total of 125 trials per run. No feedback was given. At the beginning of a run, the listener was asked to seat and lean his neck on a neck rest, so that his head was centred and that the laser pointed the central speaker (0° in azimuth and elevation). This initial head position was recorded and the listener had to place his head back in this position (at less than 2 cm and 2°) before starting each trial. To start a new trial, the listener had to press the button of a stylus. If his head was correctly placed when the button was pressed, a stimulus was played from one of the 25 speakers. If the head was misplaced no sound was played and the listener was asked to place his head back to the initial position. After a stimulus was played, the listener had to direct his head (and the laser pointer) toward the speaker from which he perceived the sound originating and to press the stylus button to validate his answer. The azimuth of the pointed speaker was computed from the data given by the head-tracker.

Both sound localization measurements (fixed spectrum and random spectrum tasks) were first taken without plugs. Secondly, they were repeated with the plugs inserted and no delay added. Participants were then asked to continue wearing the plugs while engaging in daily activities, during all waking hours. The sound localization measurements were repeated the next day and repeated with a delay of 625 µs added in the left plug. At this point of the experiment, no further modification were made to the plug's sound processing. These measurements were then repeated each day during a 10 to 12 days period. At the end of the experiment, measurements were taken with the plugs still inserted, and repeated immediately after removal of the plugs.

Analysis. The metric used to measure the localization accuracy of each listener was the mean signed error (MSE), a measure of the average discrepancy between listener's responses and targets locations. Permutation tests were used to compare the MSEs between different tests of a given listener.

3. RESULTS

Insertion of the earplugs without delay affected the localization accuracy of three participants (results significantly different from those without plugs), even after 24 hours of wearing the plugs. Additionally, the delay added in the left earplug introduced a much smaller shift in the auditory space representation of these participants than the others. For these reasons, only the results of the remaining three participants (P2, P3 and P5) are presented here. For those participants, no significant difference has been found between the results obtained during the task using a fixed spectrum stimulus and the task using a random spectrum stimulus. Therefore, only the results of the fixed spectrum stimulus task are detailed.

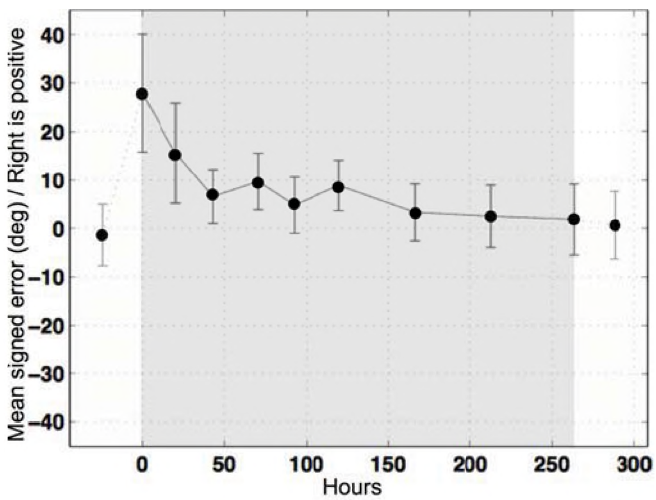

Figure 1. Evolution of P3's MSE. Hour zero corresponds to the measurement immediately after insertion of the plugs. First measurement was taken without plugs, last one, immediately after removal of the plugs.

The delay added in the left earplug shifted importantly the responses of P2, P3 and P5 in the right direction: MSE differences between the measurement without plugs and the first measurement with plugs and delay = 24.2° (P2), 29.3° (P3) and 21.4° (P5). After 48 hours, MSE differences between without and with plugs decreased to: -0.95° (P2), 7.8° (P3) and 5.4° (P5). At the end of the experiment (10 to 12 days of wearing the plugs), the MSEs of P2, P3 and P5 were not significantly different to those measured before the experiment, without plugs. When measured immediately after removal of the plugs, the MSEs of those participants were still not significantly different to those measured before the experiment, therefore no aftereffect has been observed. Figure 1 shows the MSE evolution of P3 during the experiment. Figure 2 shows the raw data of the sound localization tests of P3 before, during and after wearing of the plugs.

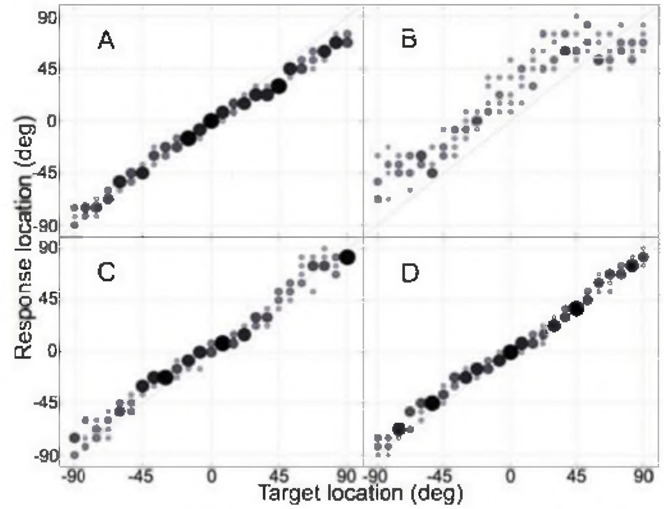

Figure 2. Raw results of P3: without plugs (A), immediately after addition of a 625 µs delay in the left plug (B), on the last day of wearing the plugs (C) and immediately after removal of the plugs (D). Grey value and radius of the dots increase with the number of similar responses for a specific target.

4. DISCUSSION AND CONCLUSIONS

The results show that the human auditory system is capable of a fast adaptation to shifted ITDs. The finding that the three participants showed no aftereffect in the opposite direction indicates that the adaptation could be attributed to a reweighting in the processing of the different spatial cues, more than to a recalibration of the ITDs. When wearing the plugs, the shifted ITDs are in contradiction with the other spatial cues and with visual feedback. A potential strategy of the auditory system could be to progressively put this biased information aside and to start relying exclusively on the other cues. As comparable results have been measured when testing with fixed or random spectrum stimuli, the spectral cues do not seem to play a key role in the adaptation to altered ITDs. Thus, a reweighting in favour of ILDs may have been the optimal strategy for sound localization with shifted ITDs. Future experiments will aim to deepen our understanding of this adaptive process and to determine the cortical sites that are involved.

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