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Recalibration of Audio-motor Subjective Simultaneity

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Abstract: Temporal consistency between body movement and corresponding auditory feedback is crucial to perceive external auditory events. The present study examined whether delay detection of self-generated sound was modulated by short-term exposure of delayed auditory feedback. The durations of auditory feedback delay were ranged from from 19-253 ms to 286-519 ms. The delay detection threshold (DDT), that is, the point at which the delay detection rate was 50%, was significantly different across conditions. This indicates that the DDT was modulated by the range of the delay used in the experiment; the DDT became longer as the delay lengthened. We propose that the perceptual delay in auditory feedback of self-body movement is automatically calibrated to the frequently exposed duration between self-body movement and the auditory feedback.

Keywords: delay detection threshold, delayed auditory feedback, perceptual recalibration, simultaneity judgment

1. Introduction

Temporal consistency between self-body movement and the associated sensory feedback is crucial to perceive external auditory events. However, the judgment of synchrony between a body movement and the associated sensory feedback is not a straightforward process. For instance, when playing a musical instrument, there is an intrinsic delay between the self-body movement and the generation of the sound. Furthermore, visual, tactile, and auditory information all have unique latencies in the time required to reach the brain, and these differences must be integrated to judge synchrony among different modalities.

In this study, we used several different delay ranges to investigate the extent to which the delay between self-body movement and corresponding auditory feedback affects perceived simultaneity [1]. We systematically introduced various delay ranges in the timing of auditory feedback and measured delay detection threshold (DDT). Precisely, DDT is defined as the delay length at which the probability that self-body movement and the associated auditory feedback are perceived as synchronous is 50%. In our experiment, the delay range varied from 19-253 ms to 286-519 ms. Recalibration of subjective simultaneity in response to delayed auditory feedback would be indicated by variations in the DDTs according to the delay range used.

2. Methods

2.1 Participants

Sixty-six healthy students took part in the experiment. Each participant was assigned to one of five experimental conditions. All participants were right-handed and had normal hearing.

2.2 Apparatus and procedures

We generated auditory feedback regarding the finger movements of the participants using a synthesizer (Micron SE; Alesis). The synthesizer was placed on a table and was connected to an audio delay-inserting hardware device (SPX2000; Yamaha). The delayed auditory feedback was presented to the participants via headphones (HDA 200; Sennheiser).

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The participants wore an eye-mask to prevent any visual input during the experiment. They were asked to press the key on the apparatus and judge whether the auditory feedback (full-range pulsed sound, 2 ms in length) was delayed compared with their finger movements. The participants were asked to respond verbally in a forced choice manner (‘delayed’ or ‘not delayed’) at the end of the trial. A 10-sec rest period followed each trial, and the presentation order of the delay lengths was pseudo-randomized.

The intrinsic delay in auditory feedback with this setup was about 19 ms. There were eight auditory feedback delay lengths for each condition in the simultaneity judgment task. Each delay length was presented eight times, for a total of 64 trials. The range of delay lengths (including the intrinsic delay) varied across conditions as follows: from 19 to 253 ms under condition 1, from 119 to 353 ms under condition 2, from 186 to 419 ms under condition 3, from 19 to 119 ms under condition 4, and from 286 to 519 ms under condition 5. Under conditions 1–3 and 5, the delay lengths were in 33.3 ms intervals, and under condition 4, the delay lengths were in 14.3 ms intervals.

2.3 Data analysis

We used the asynchrony judgement information to calculate the delay detection probability for each delay length. To examine the differences in the shape of the judgment curve between conditions, logistic curves were fitted to the participant responses. Furthermore, we calculated the delay length at which synchrony and asynchrony judgment probabilities are equal (50%) from the fitted curves. In addition, the just noticeable difference (JND) is calculated as half the difference between the lower (25%) and upper (75%) bounds of the threshold, which reflects the subjective sensitivity to the delay near DDT.

3. Results

The fitted curves for conditions 1–4 are shown in **Fig. 1**. The average DDT across all participants was 136.3±31.6, 208.9±31.5, 309.1±45.6, and 89.1±13.4 ms under conditions 1, 2, 3, and 4, respectively (**Fig.2**). Under condition 5, all participants reported that the auditory feedback was delayed in all trials. We found a significant effect of condition (One-way ANOVA, $F_{3,56} = 107.2$, $P<.01$). Subsequent analyses revealed that the DDTs were significantly different between every pair of conditions (Tukey–Kramer’s HSD, $P<.01$).The average JND across all participants was 18.7±11.8, 28.7±14.4, 30.8±7.8, and 18.2±4.5 ms under conditions 1, 2, 3, and 4, respectively (**Fig.3**). Although there was a significant effect of the delay in JND ($F_{3,56}$ = 3.2, P<.05), the difference between conditions was not significant for each pair of conditions (Tukey–Kramer's HSD).

These results indicate that the delay range used under each condition modulated the DDT, but not the JND. To assess the time-series change in DDT during the experiment, we calculated the DDT for each block of eight trials within the total 64 trials (**Fig.4**). The DDT appears to have been recalibrated according to the delay range through the first two to three blocks, as the DDT increases in the later blocks. This effect was most prominent under the condition 2.

4. Discussion

Our findings indicate that the DDT between a self-body movement and the associated auditory feedback is automatically recalibrated toward the mean of the auditory-feedback delay range employed in the experiment.

We suggest that the observed shift in DDT is the result of recalibration of subjective simultaneity via exposure to delayed auditory feedback. Previous studies have demonstrated that exposure to a fixed delay between auditory and visual stimuli for a period of several minutes induces a shift in the audio-visual subjective simultaneity in the direction of the fixed delay [2–3]. This phenomenon is known as 'temporal recalibration (TR)'. Similarly, TR has been demonstrated between voluntary self-body movement and the associated visual or auditory stimulus [4–5]. Our findings indicate that TR occurred even without an adaptation phase (exposure to a fixed delay of some modality for several minutes), which was employed in many previous studies. The experimental delay ranges served as adaptation stimuli; thus, the DDT might have been shifted toward the mean delay of the delay range employed.

Temporal recalibration of subjective simultaneity might be explained as a relearning of the forward model. It is postulated that when an individual moves their body, a motor command is sent from the motor cortex to the muscle and a copy signal of the motor command (the 'efference copy') is simultaneously sent to the parietal lobe. The efference copy makes it possible to internally predict the sensory feedback caused by the self-generated movement (the 'forward model') [6–7]. The present results suggest that the forward model can relearn the temporal contingency between self-body movement and the associated auditory feedback when the prediction about auditory feedback vary slightly from actual feedback timing (less than 300 ms). Exposure to a delay in auditory feedback induces the forward model to learn the new temporal relationship between self-generated movement and the associated auditory feedback.

The DDT obtained in condition 3 was ~300 ms, which is far larger than that reported in previous studies [5,8]. Nevertheless, a 200–300-ms delay in sensory feedback is the key to the mechanism of multisensory integration. For example, our previous studies revealed that a delay in visual feedback of less than 200–300 ms was perceived as 'not delayed' with associated tactile or proprioceptive feedback [9]. Blakemore et al. [10] showed that a delay in tactile feedback of the self-movement delivered by a robotic hand could increase the tickliness of the tactile sensation up to 300 ms. Our result that the limit of DDT shift was about 300 ms (the shift was

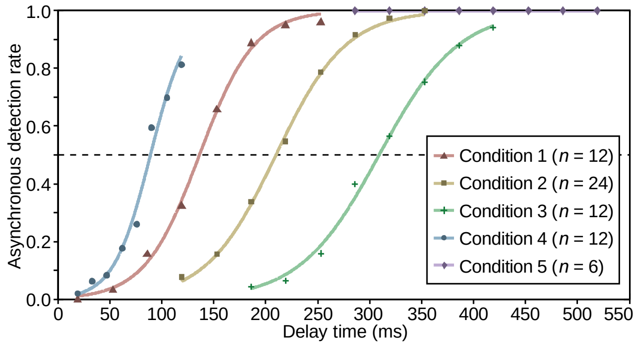
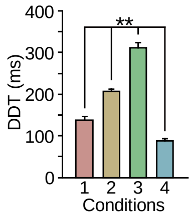
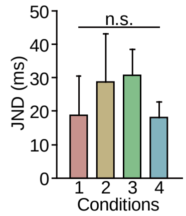


Figure 1 Delay detection curve





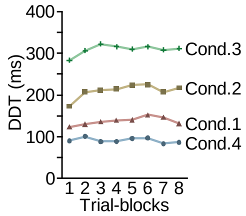


Figure 2 DDT Figure 3 JND Figure 4 Shift of DDT

not observed under condition 5) also supports the notion that the brain can only adapt to the inter-sensory delay within 200–300 ms.

Another reason for the relatively late DDT, in addition to TR, may be that the participant noticed the existence of an electric external apparatus in the experimental setting. A previous study reported that the audio–visual DDT was lengthened when a sound was associated with an object located far away from the participant [11]. This is interpreted as evidence that the brain takes the distance of the sound-making object into account and compensates for the time required for the sound to arrive at the individual. We suggest that a similar effect occurs when individuals engage with an external system like a tool or musical instrument. Usually the feedback delay of an external system is not clear beforehand, and hence flexibility is understandably advantageous in recalibrating the internal model to match the external system.

5. Conclusion

The present study found that DDT was modulated by the chosen delay range such that DDT became longer as the delay increased. This recalibration was no longer observed during exposure to a delay range with minimum delay greater than 250 ms. We suggest that the perceptual delay in auditory feedback of a self-body movement is, to some extent, automatically recalibrated to the delay between self-body movement and repeatedly presented auditory feedback. Additional studies are necessary to further elucidate the internal mechanisms underlying these processes.

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