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Temporal recalibration to tactile–visual asynchronous stimuli

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Abstract

Here we demonstrate that the perceptual system adapts to tactile–visual temporal asynchronies (i.e., temporal recalibration). Participants were exposed to a train of tactile and visual stimuli with a constant time lag (either −100 ms, 0 ms, or 100 ms; with negative values indicating that the tactile stimulus came first). Following exposure, they were presented tactile–visual test stimulus pairs and judged whether the tactile or the visual stimulus was presented first (Temporal Order Judgement). Results show that subjective simultaneity (the PSS) was shifted in the direction of the exposure lag. The results fit reports on auditory–visual temporal recalibration and indicate that the brain adapts to temporal incongruencies between modalities in general.

Keywords: Intersensory perception; Tactile–visual; Temporal order judgment; Temporal recalibration

Studies on multisensory temporal perception have demonstrated that the brain corrects for small temporal asynchronies between different senses that may arise naturally due to differences in transmission and processing time [16,18,25,38,39]. Corrections may occur either immediately while the multisensory stimulus is being processed, as demonstrated in 'temporal ventriloquism' [18,25], or on a larger time scale reflecting adaptive changes in synchrony perception (i.e., temporal recalibration [9,13,40]). Both of these two phenomena have mainly been demonstrated between vision and audition. For example, Vroomen et al. [13,40] demonstrated auditory–visual temporal recalibration by exposing participants to a 3 min train of sound and light flashes with a constant time lag. Following exposure, participants performed an auditory–visual temporal order judgement task (TOJ task), or a simultaneity-judgement task about sound–light pairs with particular temporal offsets. The results showed that the point of perceived temporal alignment between the sound and the light (i.e., the point of subjective simultaneity, PSS) was shifted in the direction of the exposure lag such that the previously experienced temporal incongruency was reduced (see for similar results [13]). Fujisaki et al. [9] demonstrated similar findings, with the exception that in their study, lag adaptation widened the range in which simultaneity was perceived in the direction of the exposure lag, which consequently shifted the PSSs.

Temporal recalibration between other modalities than the auditory–visual one have so far been explored by Navarra et al. [19] and by Stetson et al. [36]. Navarra et al. [19] examined auditory–tactile temporal recalibration by exposing participants to auditory–tactile stimulus pairs with the auditory stimulus either synchronized to the tactile one, or the auditory stimulus leading by 75 ms. Unlike previous reports on auditory–visual temporal recalibration [9,40], the authors did not observe a shift in the PSS, but reported that the minimal interval needed to correctly judge the order of the auditory–tactile TOJ task (the just noticable difference, JND) was larger after exposure to desynchronized streams than after exposure to synchronous streams. These findings were attributed to a 'widening' of the temporal window in order to compensate for temporal misalignments later on. Alternatively though, it may also be the case that there was no recalibration proper, but that participants became confused by the asynchronous stimuli and therefore performed less accurately at the following TOJ task. More specifically, it might have been the case that participants noticed the auditory–tactile asynchrony, which in turn disrupted performance so that more errors were made in the TOJ task (i.e., interference at the 'decision' level rather than at the 'perceptual' level).

Visuo-motor temporal recalibration has been demonstrated by Stetson et al. [36]. They adapted participants to short delays between self-initiated key presses and subsequently delivered

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light flashes. There was also a visual–tactile control condition (Exp 2) in which the self-initiated motor component was removed. Here, participants were adapted to a key that automatically moved up to tap the participant's finger and that was followed by a flash with a 135-ms delay. Following exposure to the delayed flash, participants performed a TOJ task about the order of a tap and flash. The results demonstrated a small, although non-significant shift in the PSS (a 16 ms shift, $p = .06$) that was consistent with previous reports on auditory–visual recalibration [9,13,40].

In the present study, we further examined tactile–visual temporal recalibration. Multisensory interactions between vision and touch are interesting for a number of reasons. On the one hand, several studies have demonstrated analogies between auditory–visual and tactile–visual integration. Well known is a series of studies on crossmodal spatial attention where various links between the auditory, visual, and tactile dimensions have been demonstrated [7,28,30–35,43]. Similarities between modalities have also been found in spatial ventriloquism. In the typical spatial ventriloquist situation, the apparent location of a sound is shifted in the direction of a displaced distracter, which is most often a flash or another visually salient stimulus [1–3,23,24,41]. It has also been reported, though, that touch can attract the apparent location of a sound [6], and that vision can, in turn, attract touch (e.g. [10,21,22]). There is also a visual–tactile [4] and an auditory–tactile [5] analogue of the illusory double-flash effect [27]. In the original demonstration of this phenomenon, a single flash is perceived as multiple flashes when presented in combination with two clicks. In the auditory–tactile case, multiple clicks change the number of perceived taps, while in the visual–tactile case the perceived number of flashes is changed by multiple taps [4,5].

Most relevant for the present study is that temporal ventriloquism cannot only be induced by audio-visual stimuli (for auditory–visual studies see [11,12,18,25,39]), but also tactile–visual stimuli [14]. In this case, participants were presented two lights with a variable stimulus onset asynchrony (SOA) and judged which of the two lights appeared first. As in the audio-visual case, a tactile stimulus before the first and after the second light made participants more sensitive (i.e., lower just noticeable difference, or JND), presumably because the two taps attracted the temporal occurrence of the two lights, and thus effectively pulled the lights further apart in time.

Nevertheless, despite the various correspondences between vision, audition and touch, at this stage it is not entirely clear whether temporal recalibration will occur between vision and touch. One potentially relevant difference is that the natural temporal incongruencies that exists between vision and audition are likely to be larger than those between vision and touch because sound transduction time through air depends on the (variable) distance of the remote sound-emitting object, while tactile stimuli will always be on the body surface. At this stage, it is not clear whether this difference in intersensory temporal variability (or any other) has consequences for temporal recalibration. Here, we therefore examined whether tactile–visual temporal misalignment would, as in the audio-visual case, evoke a long-term temporal recalibration effect.

Participants were exposed to a 3 min train of tactile–visual stimulus pairs at −100 ms, 0 ms, or +100 ms temporal offset (negative values represent tactile first). Following exposure, participants performed a tactile–visual TOJ task in which they judged whether the tactile or the visual stimulus came first. If tactile–visual temporal recalibration is like auditory–visual recalibration, it should manifest itself by a shift in the point of perceived simultaneity in the direction of the exposure lag. Alternatively, JNDs might become larger (i.e., sensitivity gets worse) following exposure to asynchronous rather than synchronous stimulus pairs. The latter may either reflect a widening of the temporal window for intersensory integration [19] or confusion by the participant.

Participants: 10 students (all right-handed) from Tilburg University received course credits for their participation. They all reported normal touch and normal or corrected-to-normal seeing. Participants were tested individually and were unaware of the purpose of the experiment. They gave informed consent to participate in the study according to the Declaration of Helsinki and the ethics committee.

Stimuli: participants sat at a table in a dimly lit and soundproof booth. Head movements were precluded by a chin-rest. Visual stimuli were presented by a green light-emitting diode (LED), positioned at the table, at 50 cm from the participant's eyes (diameter of 0.5 cm, luminance of 40 cd/m^2). Tactile stimuli (250 Hz) were presented by a Sanko Electric mini-vibrator (type #1E120, Sanko Electric, Japan) with a diameter of 1.4 cm, that was embedded in a foam cube, placed directly against the visual stimuli (no spatial disparity). Visual and tactile stimuli had a duration of 10 ms. Half of the participants were instructed to place their left index finger in the foam cube, the other half used their right index finger. See Fig. 1b for a schematic view of the experimental set-up. Responses were made with the other hand by pressing one of two keys on a response box at the table. Participants either used their index finger for light-first responses and thumb for vibration-first responses, or vise versa (counterbalanced across participants). White noise was continuously presented through headphones at 65 dB(A) to mask the faint sound of the vibro–tactile stimulators.

Design: two within-subjects factors were used: Exposure lag during the exposure phase (−100 ms, 0 ms, and +100 ms), and SOA between the tactile and visual test stimulus (−240 ms, −120 ms, −90 ms, −60 ms, −30 ms, 0 ms, +30 ms, +60 ms, +90 ms, +120 ms, and +240 ms). These factors yielded 33 equiprobable conditions, each presented 12 times for a total of 396 trials. Trials were presented in nine blocks of 44 trials each. The exposure lag was constant within a block and counterbalanced across participants, while the SOA varied randomly.

Procedure: each block of experimental trials started with an exposure phase of 240 repetitions (∼3 min) of the tactile–visual stimulus pair (ISI = 750 ms) with a constant lag between the vibration and light. To ensure that participants were fixating the light during exposure, they had to detect the occasional occurrence (three per block) of a small red LED that was presented

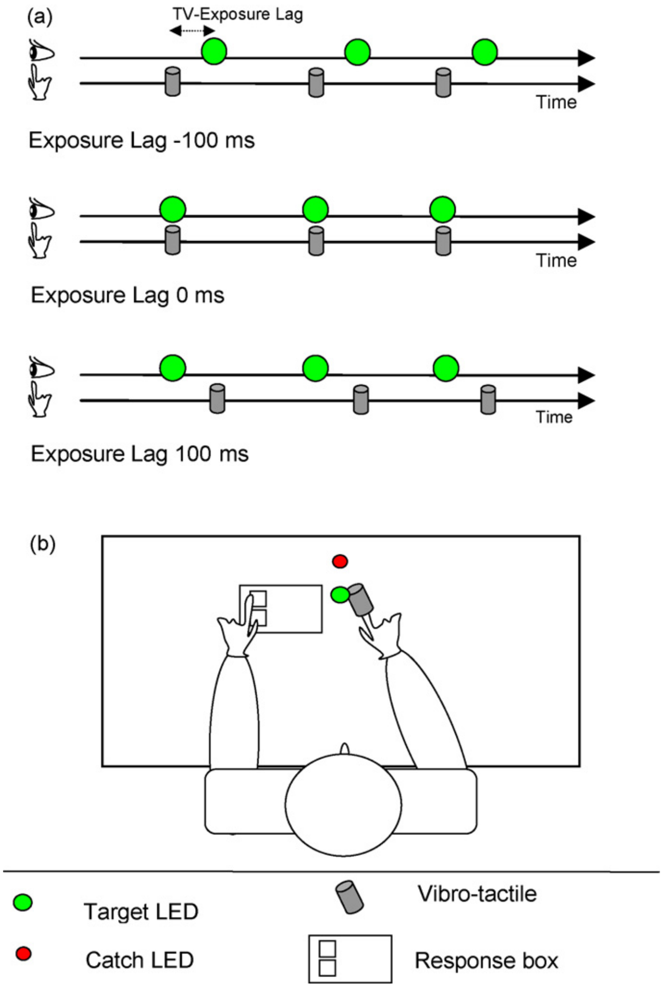

Fig. 1. Schematic illustration of the exposure conditions (a) and the experimental set-up (b). During exposure, participants were exposed to a train of tactile–visual stimulus pairs with a lag of −100, ms 0 ms, or +100 ms. In the test phase, tactile–visual pairs were presented with a particular SOA ranging from −240 ms to +240 ms.

Table 1
Mean points of subjective simultaneity (PSSs) in ms, mean just noticeable differences (JND) in ms, and standard errors of the mean in parentheses, for exposure lags of −100 ms, 0 ms, and 100 ms (negative values represent tactile-first exposure)

Exposure lag (ms)	PSS	Shift in PSS	JND
−100	−0.8 (7.6)	−9.4	36.5 (2.3)
0	8.6 (7.2)		32.3 (1.3)
+100	24.7 (7.5)	+16.1	32.6 (1.7)

The shift in the PSS reflects the difference with the synchronous condition.

simultaneously with, and 1 cm above the exposure light (i.e., a catch trial). Participants then pushed a special button.

After a 3000 ms delay, the first trial then started. Each trial consisted of two parts: a tactile–visual re-exposure phase followed by the presentation of a vibration and a light of which the temporal order had to be judged. The re-exposure phase consisted of a train of eight vibration–light pairs with the same time lag as used during the exposure phase of that block. After 1000 ms, the test stimulus was presented. The participant's task was to judge whether the vibration or the light was presented first. An unspeeded response was made by pressing one of two designated keys on a response box. The next trial started 500 ms after a response.

To acquaint participants with the TOJ task, experimental blocks were preceded by two practice blocks in which no exposure preceded the trials. The first practice block was to acquaint participants with the response assignments, and consisted of 16 trials in which only the largest SOAs were presented (±240 ms and ±120 ms). During this practice, participants received verbal feedback ("correct" or "wrong") about whether they gave the correct response or not. The second practice block consisted of 88 trials in which all SOAs were presented randomly, without feedback.

Trials of the practice session were excluded from analyses. The proportion of 'light-first' responses was calculated for each combination of exposure lag (−100 ms, 0 ms, +100 ms) and SOA (−240 ms to +240 ms) for each participant. Performance on catch trials was flawless, indicating that participants were indeed looking at the light during exposure. For each exposure lag, an individually determined psychometric function was calculated by fitting a cumulative normal distribution using maximum likelihood estimation. The mean of the resulting distribution (the interpolated 50% crossover point) is the point of subjective simultaneity (henceforth PSS), and the slope is a measure of the sharpness with which stimuli are distinguished from one another. The slope is inversely related to the just noticeable difference (JND) and represents the interval (absolute SOA) at which 25% and 75% visual-first responses were given. The average PSSs and the JNDs are shown in Table 1.

An ANOVA with within-subject factor exposure lag was performed on the JNDs and PSSs.[1] JNDs were unaffected by exposure lag, $F(2, 18) = 2.24$, $p = .14$, indicating that sensitivity did not become worse following asynchronous exposure. Paired *t*-test comparing the JNDs in the a-synchronous conditions (−100 ms, +100 ms) with the synchronous one (0 ms) also showed no widening of the temporal window (both p's > .15). The PSS data, though, showed a significant effect of exposure lag, $F(2, 18) = 6.31$, $p < .01$, indicating that exposure to tactile–visual asynchrony shifted the PSSs in the direction of the lag (see Fig. 2). Paired *t*-test showed that there was a significant difference in the PSS between tactile-first and visual-first exposure, $t(9) = 3.38$, $p < .01$ (a shift of 25.5 ms or 12.7% of the exposure lag in the expected direction). The size of this effect corresponds well with previous reports on auditory–visual recalibration (Fujisaki et al. 12.5%; Vroomen et al. 6.7%; Keetels and Vroomen, submitted 6.5%). Compared to the synchronous condition, there was a significant shift by visual-first adaptation, $t(9) = 1.96$, $p < .05$ (a 16.1 ms shift or 16.1%), and a marginally

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[1] *Note 1*: An ANOVA with within-subjects factor exposure lag, and between subject factor side of tactile stimulation was performed on the JNDs and PSSs. Both the JND and PSS data revealed no effect of side of tactile stimulation, both F's < 1, nor an interaction between the two factors, $F < 1$ and $F(2, 16) = 1.13$, $p = .35$, for the JNDs and PSSs, respectively. Data were therefore pooled over side of tactile stimulation.

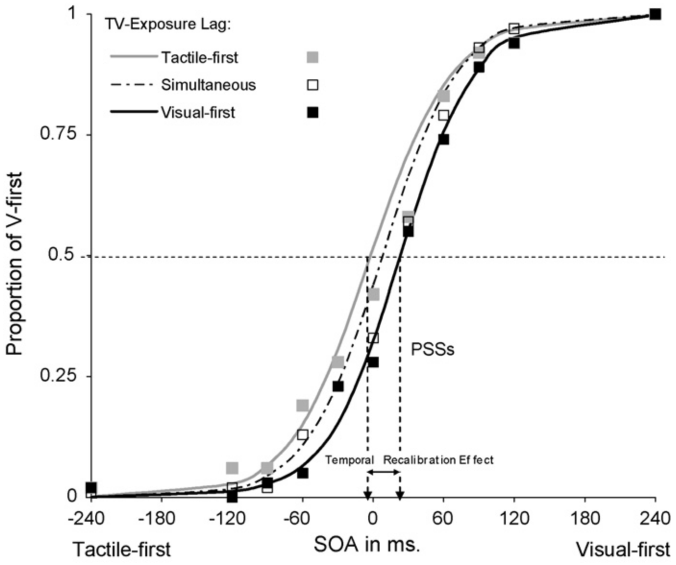

Fig. 2. The proportions of visual-first responses (V-first) for each tactile–visual exposure lag. The temporal recalibration effect reflects the shift in the PSSs.

significant shift by tactile-first adaptation, $t(9) = 1.65$, $p = .065$ (9.4 ms, or 9.4%).

Here, we demonstrate that subjective simultaneity adapts to temporally misaligned tactile–visual stimulus pairs (i.e., temporal recalibration). After being exposed to tactile-first stimulus pairs, more visual-first responses were given, while after exposure to visual-first stimulus pairs, more tactile-first responses were given. Remarkably, despite that the natural variability in tactile–visual asynchrony is, in comparision with the auditory–visual case, relatively small, the size of tactile–visual recalibration (an average shift of 12.7%) was close to previous reports on auditory–visual temporal recalibration [9,13,40]. This thus shows that the brain is quite flexible and adapts to auditory–visual or visual–tactile asynchronies in a similar way. Furthermore, no differences in sensitivity (i.e., the JND) between synchronous and asynchronous exposure were observed, and there was thus no sign of a widening of the temporal window [19,20].

The results also demonstrated a trend in the direction that the visual stimulus had to be presented slightly before the tactile one in order to be perceived as simultaneous (a PSS of +8.6 ms following synchronous exposure, although not significantly different from zero). This result is in accordance with auditory–visual studies where an asymmetry in PSS towards a visual lead has been found (e.g. [17,29,42,44]). This asymmetry in the PSS may reflect the longer neural transmission times needed for visual stimuli than for auditory or tactile stimuli [8,15], although it should be mentioned that the exact interval at which stimuli are perceived as simultanous also depends on stimulus properties like lightness, loudness and length of the stimuli.

A question that remains is why the temporal recalibration effect are relatively small (9.4 ms and 16.1 ms) if compared to the sizes of the exposure lags (100 ms asynchrony). In auditory–visual recalibration [9,13] and visuo-motor recalibration [36], recalibration shifts were also found to be smaller than the adapted magnitudes. Generally, two explanations have been put forward for this finding [9,36]. First, it may be that larger shifts are beyond the hardware limitation of the recalibration mechanism. Secondly, it may be that recalibration has to 'battle' the natural temporal asynchronies that have been established by years of experience. The latter entails that the shift in the PSS might become bigger with longer exposure periods. Further research is needed to address this issue in more detail.

One might also ask whether the visual task as used during the exposure phase (i.e., the detection of the onset of a visual catch stimulus) resulted in an attentional bias towards the visual modality. According to the 'law of prior entry' [37] attending to one sensory modality speeds up the processing of stimuli in that modality, resulting in a change in the PSS (although others have questioned the existence of prior entry [26]). Our visual task might thus have resulted in a shift of the PSS towards more 'visual-first' responses. However, given that the shift should be uniform for all conditions, and that temporal recalibration is expressed as a difference in the PSS between exposure lag conditions, the possible role of attention is subtracted out.

To conclude, the present study clearly demonstrates that the brain adapts to visual–tactile asynchronies (i.e., temporal recalibration). The function of temporal recalibration lies in the fact that temporal incongruencies that naturally arise from differences in neural transmission times or transduction times through air are reduced, and therefore do not hinder crossmodal integration on a larger time scale. Notably, this correction occurs despite the fact that tactile–visual incongruencies are smaller in natural situations than auditory–visual ones.

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