Realignment of temporal simultaneity between vision and touch

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Adaptation to temporal asynchrony between senses (audiovisual and audiotactile) affects the subsequent simultaneity or temporal order judgment. Here, we investigated the effects of adaptation to temporal asynchrony between vision and touch. Participants experienced deformation of virtual objects with a fixed temporal lag between vision and touch. In subsequent trials, the visual and haptic stimuli were deformed with variable temporal lags, and the participants judged whether the stimuli became deformed simultaneously. The point of subjective simultaneity was shifted toward the adapted lag. No intermanual transfer of the adaptation effect was, however, found. These results indicate that the perceptual simultaneity between vision and touch is adaptive, and is determined separately for each hand. *NeuroReport* 19:319–322 © 2008 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

Multimodal integration enables robust and precise perception [1]. Simultaneous input of event signals into multiple sensory modalities is essential for efficient interaction between senses [2,3]. Although simultaneity is a clear objective concept, its perceptual process is complicated. For example, both top-down and bottom-up factors affect the subjective simultaneity between senses, such as attention [4], direction of motion [5], and distance to an event [6,7]. Interestingly, recent studies have shown that the subjective simultaneity can be changed by experience. After repeatedly experiencing a constant audiovisual temporal lag, the point of subjective simultaneity (PSS) shifts toward the adapted lag in the subsequent simultaneity [8] or temporal order [9,10] judgment tasks. The shift of audiovisual PSS toward the adapted lag occurs for various stimulus types such as instantaneous stimuli (e.g. visual flash and auditory click [8,9]) or complex, dynamic stimuli (e.g. speech [10]). In contrast, only change in temporal resolution (i.e. just noticeable difference, JND), but no shift of PSS, was reported in audiotactile adaptation [11]. The adaptability of simultaneity between vision and touch, however, remains unknown.

The effects of adaptation to temporal asynchrony are not consistent among pairs of senses. In particular, although the change of JND is commonly observed between various pairs of senses [11,12], the shift of PSS toward an adapted lag, which indicates the realignment of simultaneity, is only reported between vision and audition [8–10]. The realignment of simultaneity might be specific to audiovisual temporal processing, and no realigning mechanism might exist between the other senses. To clarify whether the realignment of simultaneity is a special case of audiovisual adaptation, however, it is necessary to investigate the effects of adaptation on the simultaneity judgment (SJ) between vision and touch.

In this study, we investigated the effects of adaptation to temporal asynchrony, particularly, the realignment of simultaneity between vision and touch, using a method similar to audiovisual adaptation [8–10]. Temporal order judgment (TOJ) and SJ are frequently used to examine the perceptual processes of temporal relationships between two events. The TOJ, in which observers judge the order of two events, is better for measuring JND; whereas, the SJ, which is used by observers to judge whether two events occur simultaneously, is better for measuring PSS [13]. As we focused on the realignment of simultaneity, we chose the SJ task. In experiments 1 and 2, we investigated whether adaptation to asynchrony induces the shift of PSS between vision and touch. In experiment 3, we also investigated whether the adaptation effect would get transferred intermanually.

Methods

Eight individuals participated in experiment 1, eight in experiment 2, and five in experiment 3. All participants had normal or corrected-to-normal vision and normal stereopsis. The experimental setup is shown schematically in Fig. 1a. The participants stood in a dark room, with their heads fixed on a chin rest. The visual stimulus was drawn on a 21-inch cathode-ray tube monitor (100 Hz), and was reflected on an opaque mirror that was placed horizontally in front of the participants. They wore CrystalEyes3 (Stereographics; San Rafael, California, USA) shutter glasses for binocular stereo display. The haptic stimulus was presented to the participant's index finger by a PHANToM force-feedback device (SensAble Technologies; Massachusetts, USA) placed under the opaque mirror. The participants could move their index finger only along the depth axis (Z axis in Fig. 1). Their hands could not be seen, and there was no visual pointer indicating their finger position. The visual and haptic stimuli were aligned spatially. The temporal delay of the visual stimulation from the haptic stimulation owing to the presentation devices was approximately 5 ms (standard deviation <1 ms).

The virtual object is depicted in Fig. 1b, which the participants experienced as a rectangular solid object (15 mm wide along the X axis and 40 mm deep along the Z axis), located at a height of 800 mm above the ground. The object underwent a compressive deformation along the depth axis (i.e. Z axis in Fig. 1b). The participants looked at the top surface and passively touched the far surface of the object. The profile of deformation was defined as $D(t)=7.5\{1+\sin[\pi(2t/500-0.5)]\}$, where $D(t)$ (mm) represents the amount of deformation at t ms after the onset of deformation (Fig. 1c). The profiles of visual and haptic deformation were identical. The onset asynchrony between visual and haptic deformation was defined as the temporal lag between vision and touch.

The visual object was covered by 75 blue texture patches (diameter: 1.2 mm and luminance: 25.0 cm/m^2) that were randomly aligned on the top surface of the object against a black background (17.0 cd/m^2) (Fig. 1d). In a visual-display routine (50 Hz per eye), the texture patches moved in line with the profile of visual deformation. In a haptic-display routine (1000 Hz), the force was presented when the participants touched the virtual object. The presented force was $0.03\Delta z^2$ (N), where Δz (mm) represents the distance from the far surface of the object to the index finger along the Z axis. The stimulus of the preceding sensory modality began deformation 250 ms after the onset of a trial.

In experiment 1, each session (10–12 min) consisted of 120 adaptation trials, followed by 44 repetitions of the combination of four top-up exposures and one test trial. A short beep sound was presented before each test trial. In experiments 2 and 3, each session consisted of 250 adaptation trials (8 min), followed by 176 test trials (8–10 min), which were conducted in a separate block. In the adaptation trials, the participants performed an oddball-detection task. The task was to press a button when they detected either a visual or a haptic deformation (5 mm) that was smaller than the other frequent deformations (15 mm), which occurred in 5% of the trials. The trial began immediately after the previous one. This oddball task allowed the participants to attend to both vision and touch. The temporal lag of visual deformation from haptic deformation was kept constant in each session: -250 ms (visual deformation preceded haptic deformation by 250 ms), $+250$ ms (haptic deformation preceded visual deformation by 250 ms), or 0 ms (visual and haptic deformations were simultaneous). In the top-up trials, the participants did not perform any task, but were instructed to attend to both visual and haptic stimuli. The temporal lag was identical to that of the preceding adaptation trials. In the test trials, the task was to judge whether the deformation of vision and touch occurred simultaneously. The temporal lags were ± 240, 120, 90, 60, 30, or 0 ms. Each lag was presented in a random order. After the deformation, the participants reported their judgment by pressing a button. On obtaining a response, the next trial was initiated immediately.

The stimulated hands in the adaptation and test trials were same in experiments 1 and 2 (right hand), and different in experiment 3 (LR: left adaptation and right test and RL: right adaptation and left test). The location of the stimulus object was the same in all conditions regardless of the stimulated hand. After practicing the tasks, the participants conducted six sessions in experiment 1 (three repetitions of two adaptation lags), three sessions (three adaptation lags) in experiment 2, and four sessions in experiment 3 (two adaptation lags $\times$ tested hands: LR or RL). The order of the sessions was counterbalanced. The participants briefly rested outside the dark room between the sessions. The experiments lasted for approximately 60–90 min.

In the data analysis, the rate of simultaneity responses as a function of temporal lag was fitted by a truncated Gaussian function for each test phase (i.e. each adaptation lag) and for each participant [8]. The fitting function was $y=\min\{1,\alpha \times \exp[-(x-\mu)^2/2\sigma^2]\}$, where μ is the mean of the Gaussian function corresponding to the PSS; σ, the standard deviation; and α, the amplitude. The variables σ and α are related to the temporal window and robustness of SJ.

Results

The mean detection rates in the adaptation phases were 0.98 in experiment 1, 0.93 in experiment 2, and 0.97 in

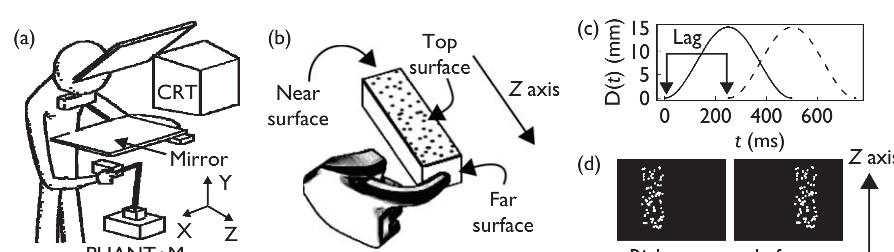

Fig. 1 Apparatus and stimulus. (a) Schematic illustration of the experimental setup. (b) Schematic representation of the virtual object. (c) An example profile of deformation (temporal lag$=-250$ ms). Solid and dashed lines indicate visual and haptic deformations, respectively. The horizontal axis indicates the time from the onset of visual deformation, and the vertical axis indicates the extent of deformation. The duration (500 ms) and maximum extent (15 mm) of deformation were identical for both visual and haptic deformation. (d) Stereogram representative of visual stimulus (cross-fusing). Participants looked at the top surface of the virtual object.

experiment 3, which confirm that the participants attended to both vision and touch. The mean r^2 values of fit for SJs in the test phases were 0.97 in experiment 1, 0.97 in experiment 2, and 0.98 in experiment 3.

In experiment 1, the PSS in the test phases clearly showed the bias toward the adapted lag (i.e. the realignment of simultaneity; Fig. 2, top left). A one-way repeated-measures analysis of variance (ANOVA) revealed significant main effects of adaptation lag only for PSS [$F(1,7)=8.50$, $P<0.05$]. The mean PSS was −37.6 ms for the −250-ms lag and −20.2 ms for the +250-ms lag, resulting in an adaptation amplitude of 17.4 ms (3.5% of the adaptation lag). Unlike PSS, the main effect of the adaptation lag was significant neither for σ [$F(1,7)=0.10$, $P=0.76$] nor for α [$F(1,7)=2.68$, $P=0.15$].

In experiment 2, the PSS shift toward the adapted lag occurred without the top-up exposures during test trials (Fig. 2, top-middle). A one-way repeated-measures ANOVA revealed the significant main effect of the adaptation lag [$F(2,14)=22.4$, $P<0.001$], and post-hoc multiple comparison (Ryan's method, $\alpha=0.05$) revealed that the PSS increased with the adaptation lags. The mean PSS was −34.1 ms for the −250-ms lag, −20.3 ms for the 0-ms lag, and −5.2 ms for the +250-ms lag. The adaptation amplitude was thus approximately 30 ms (5.8% of the adaptation lag), which was larger than that in experiment 1. As in experiment 1, the main effect of the adaptation lag was not significant for σ [$F(2,14)=1.52$, $P=0.25$] and α [$F(2,14)=2.16$, $P=0.16$].

In experiment 3, in which the adapted and tested hands were reversed, we found no change in PSS (Fig. 2, top-right). A two-way repeated-measures ANOVA revealed that neither main effect nor interaction was significant (PSS: $F<1$, $P>0.54$; σ: $F<1.1$, $P>0.36$; and α: $F<2.0$, $P>0.24$). The mean PSS was −24.5 ms (for LR, −250 ms), −20.8 ms (for LR, +250 ms), −26.3 ms (for RL, −250 ms), and −26.4 ms (for RL, +250 ms). The adaptation amplitude was thus, only 5 ms at the most. To confirm the difference in PSS shift between the same and reversed hand conditions, we performed a two-way repeated-measures ANOVA (adaptation lag × experiment) for the five participants who took part in both experiments 2 and 3. The results showed that the main effect of adaptation lag [$F(1,4)=10.4$, $P<0.05$] and interaction [$F(1,4)=9.45$, $P<0.05$] was significant. Post-hoc analysis revealed that the effect of adaptation lag was significant only in experiment 2, in which the adapted and tested hands were identical [$F(1,4)=13.4$, $P<0.05$ for experiment 2 and $F(1,4)=0.14$, $P=0.73$ for experiment 3]. These results indicated that the PSS shift caused by the adaptation was specific for the adapted hand.

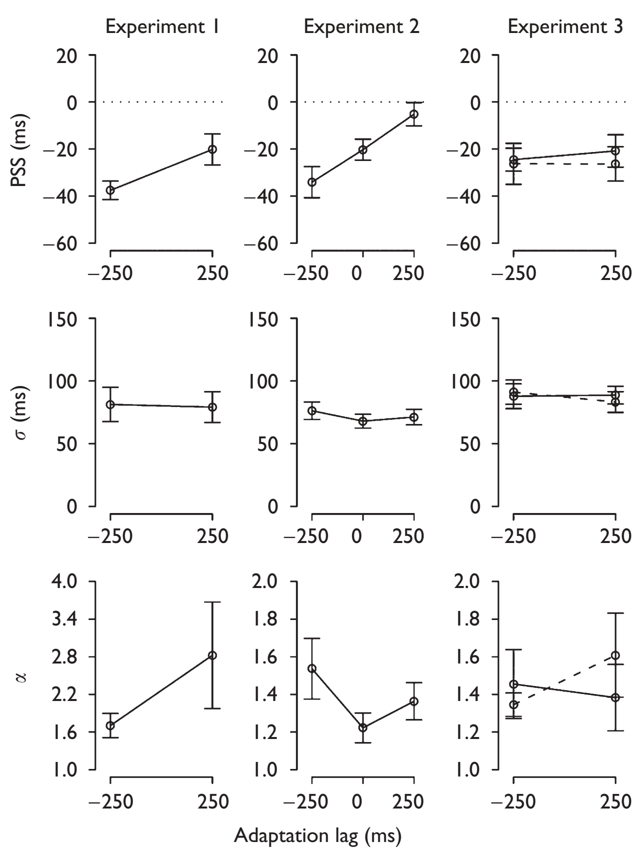

Fig. 2 The averaged point of subjective simultaneity (PSS) and coefficients of regression as a function of adaptation lags. In experiment 3 (right column), the solid and dashed lines indicate left adaptation and right test (LR) and right adaptation and left test (RL) conditions, respectively. The horizontal dotted lines in the top row represent the physical simultaneity (PSS=0 ms). Negative PSS and adaptation lags indicate that the visual deformation precedes the haptic deformation. Error bars denote the standard errors of the mean.

Discussion

In this study, we investigated the effects of adaptation to temporal asynchrony between vision and touch. In experiment 1, we found a clear indication of the realignment of temporal simultaneity between vision and touch after experiencing the fixed temporal lag. Experiment 2 replicated the realignment of simultaneity using the adaptation method without top-up exposures. Interestingly, no intermanual transfer of adaptation was observed in experiment 3.

The direction and amount of PSS shift in the vision–touch adaptation (3.5–5.8% of the adaptation lag) were similar to those in the audiovisual adaptation (5–12% [8], 6.7% [9], and 4.3% [10] of adaptation lags). Until now, realignment of simultaneity (i.e. shift of PSS) between senses has only been reported in audiovisual adaptation, and our results are the first to demonstrate that temporal realignment occurs between vision and touch. Although the realignment of temporal simultaneity does not take place between audition and touch [11], a recent study reported that the temporal limit of synchrony–asynchrony discrimination between audition and touch is higher than that between vision and the other senses (Fujisaki, W and Nishida, S. Audio-tactile, visuo-tactile, and audiovisual temporal synchrony perception. Presented at the 8th annual IMRF meeting, 2007. See Refs [14,15] for contradictory results in TOJ tasks). Therefore, one possible interpretation is that the less accurate modality (i.e. vision) becomes the adapting modality and is aligned with the more accurate modality (i.e. audition or touch).

Although the realignment direction and magnitude were similar in audiovisual and tactile–visual adaptation, we found no intermanual transfer between vision and touch. This is in striking contrast to the interear transfer in the audiovisual aftereffects [8]. Currently, we have two speculative explanations for the lack of intermanual transfer. One possible reason is that the left and right hands possess different, independent clocks of touch sensation, and that the temporal interaction between vision and touch occurs locally (i.e. between the visual clock and the adapted body part). Supporting this possibility, Miyazaki *et al.* [16] showed that simultaneity can be recalibrated between the left and right hands. Another reason is based on the relative accuracy in temporal domains. Perhaps, vision might be more accurate than touch in the stimuli and the task used in our experiments, and therefore the perceived timing of touch was aligned with vision. As the adaptation stimulus was delivered to one hand (i.e. hand-specific), no intermanual transfer was observed. If this is the case, when we induce temporal uncertainty in vision, it becomes the adapting modality; the intermanual transfer can then be expected. Whether these results reflect the constraints of sensory interaction (stimulus-independent) or of relative temporal accuracy (stimulus-dependent) warrants further investigation on how relative temporal accuracy influences adaptation amplitude and transfer.

Although most of the previous studies used top-up readaptation exposures during SJ trials, we did not use top-up exposures in experiments 2 and 3 to investigate the intermanual transfer. We, nevertheless, found a clear lag–adaptation effect in the adapted hands. Indeed, the extent of PSS shift was slightly greater in experiment 2 than in experiment 1. We cannot pinpoint the reason, but the difference in the number of adaptation trials, the strategy, or the response bias would be the possible candidates. These results indicated that the effect of adaptation to temporal asynchrony on subjective simultaneity might last longer than one might expect, as in the long-lasting aftereffects in the McCollough effect [17] and prism adaptation [18]. With long-lasting aftereffects, measuring their decay function would provide further insights into the adaptation mechanisms [18].

The audiovisual recalibration of simultaneity occurs for both instantaneous [8,9] and continuous stimuli [10,11]. In this study, we focused on the sense of touch, which includes many kinds of senses (e.g. tactile and proprioception), and used the naturalistic display (the dynamic deformation of a virtual object) instead of a simple display (e.g. instantaneous visual flash and tactile vibration or electropulse stimuli [3,19]). To clarify the mechanisms of the simultaneity recalibration, the question of whether the recalibration also occurs for instantaneous stimuli between vision and touch should be examined.

Conclusion

Realignment of simultaneity occurs between vision and touch; whereas, the adaptation effect does not transfer to the opposite hand. These results indicate that the perceptual simultaneity between vision and touch is adaptive, and is determined separately for each hand.

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