Aftereffects of Delay Adaptation in Visual and Tactile Duration Reproduction

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Author note

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Abstract

Producing brief actions often involves multiple temporal cues that might not always synchronize with each other. In a basic action-effect relationship, the effect is often delayed. How our brain incorporates this delay across different modalities in a sensorimotor close-loop action is less known. To investigate this, we conducted two experiments centered on duration reproduction with delayed sensory feedback. Participants were asked to reproduce a duration, either in visual modality (Experiment 1) or in tactile modality (Experiment 2). During the adaptation phase, an action's resulting effect, either visual or tactile stimulation, was delayed for 150 ms but stopped simultaneously with the action in one session, while in the other control session it was synchronized. In the subsequent test phase, various action-effect delays, ranging from 0 to 150 ms, were introduced. Our findings revealed that the reproduced durations during the test phase were influenced by both delay adaptation and the varying action-effect delays. Adaptation to the delayed sensory feedback generally shortened the reproduction, which was more pronounced with tactile than visual feedback. Additionally, compared to visual sensory feedback, reproduction using tactile feedback placed more trust on the tactile cue, resulting in a steeper rise in motor reproduction duration as the feedback delay increased. Furthermore, introducing these delays during the test phase also progressively lengthened the prior representation of the standard duration. Our findings thus suggest that the temporal delay adaptation is shaped by the sensorimotor integration. This integration operates based on the sensorimotor reliability, and the weights vary across modalities, with a higher weight on the tactile modality than the visual modality.

Keywords: Time perception, delay adaptation, multisensory and motor integration

Introduction

Perceiving time is integral to our everyday activities, not just for lengthy experiences like watching a movie but also for fleeting moments spanning mere seconds, especially tied to actions (Buhusi & Meck, 2005; Merchant & Yarrow, 2016). Yet, our subjective time does not always align with objective time. Several factors, ranging from stimulus intensity, motion, to one's emotional states and voluntary actions, influence how we perceive time (Eagleman, 2008; Johnston et al., 2006; Meck, 1983; Park et al., 2003; Shi et al., 2012; Yarrow et al., 2001). Moreover, the perception of time varies across different sensory modalities (Issa et al., 2020; Johnston et al., 2006; Ogden et al., 2010; Paton & Buonomano, 2018; Wearden et al., 2006). Research has pinpointed multiple brain regions involving timing tasks, suggesting that time processing is more distributed rather than governed by an amodal 'inner clock' (Bueti, 2011; Bueti et al., 2008; Lewis & Miall, 2009). For example, a given duration may seem shorter when experienced visually or tactilely as opposed to auditorily (Jones et al., 2009; Walker & Scott, 1981; Wearden et al., 1998). Additionally, it has been suggested that the timing related to actions and motor movements may differ from the timing of perceived sensations (Bueti & Walsh, 2010).

When we navigate through real environments, multiple timing cues are often generated simultaneously. The ability to integrate diverse sensory and motor temporal cues into a coherent percept is fundamental. When we push a light button, we not just feel the 'push' from the hand, but also see the light on immediately. Other complex actions, like playing piano, demand adeptly coordinating multiple temporal aspects. Players visually interpret sheet music while coordinating finger movements, audibly discerning the produced tunes, sensing the piano keys' tactile feedback as they press with varied force and duration, and simultaneously coordinate the actions of both hands and pedal work. These multimodal actions and multisensory cues supply crucial temporal information for a captivating musical performance. Despite the factor that timing may vary across sensory modalities and between sensory and motor processes, how do we often experience a coherent time perception when bombarded with various multisensory inputs and sensorimotor actions? A prevailing theory posits that the brain combines all available information

to form coherent perception based on their reliabilities, as suggested by Bayesian inference models (Ernst & Banks, 2002; Jazayeri & Shadlen, 2010; Shi et al., 2013), the idea can be dated back to Helmholtz's "perception as inference" (Helmholtz, 1867).

Yet, there isn't always a perfect sync between sensory inputs and actions. For instance, during a virtual meeting with a shaky internet connection, a person might detect a disconnect between the video and audio, or a lag between their speech and the corresponding video and audio feedback. Such temporal misalignments can provoke a sensation of 'cognitive dissonance' (Festinger, 1962). To counter this unsettling feeling of 'cognitive dissonance', our brain strives to weave the diverse information into a coherent perception. Strikingly, adapting to environments with temporal delay, such as during long-distance video conferences, can significantly diminish or even nullify our initial perception of that delay. In research conducted by Cunningham and colleagues (2001), participants engaged in a simulated shooting video game where there was a 235 ms delay in the visual feedback. Initially they performed badly and eventually reached comparable performance as the control group at the end of the delay adaptation. However, when the delay was removed, their performance drastically declined (down to about 52% accuracy), exhibiting a "negative aftereffect". Similarly, Stetson et al. (2006) found a negative aftereffect when participants adapted to an action-feedback delay task (pressing a button produced a delayed flash), they recalibrated their perception of sensorimotor synchronicity. After this delay was removed in a subsequent test, nearly 40% of the time, participants felt as the resultant flash from their action occurred before the action. This illusory inversion of action and effect underscores the adaptability of our sense of timing to various environments.

In examining the integration of sensory and motor timings amidst temporal discrepancy, it is essential to consider the sensory precisions among sensory modalities. For instance, in tasks requiring synchronized movements, auditory metronomes have shown superior synchronization accuracy compared to visual ones, while comparable tactile performance (relative to auditory performance) was found when the tactile information is sufficiently emphasized (Ammirante, Patel, & Russo, 2016; Chen, Repp, & Patel, 2002). This multifaceted interplay between

multisensory timings is deeply intertwined with actions, influencing how we perceive and coordinate these actions. Action itself can also influence action-related timing. For instance, voluntary key pressing and saccadic eye movements can affect the perception of visual timing, such as Chronostasis illusion (Haggard et al., 2002; Yarrow et al., 2001). Both actual and unrelated movements have been found to impact perceived tactile duration and temporal judgments (Juravle, Binsted, & Spence, 2017; Jia et al, 2015).

While ample studies have highlighted our capability to adapt to temporal discrepancies, few have explored the aftereffects of such delay adaptations on duration reproduction across different modalities. However, addressing this gap is critical to ascertain whether temporal sensorimotor adaptation is indeed according to the sensory reliability. If our brain places more trust in sensory feedback than in previously formed prior during the adaptation, post-delayed adaptation should result in a greater reliance on sensory feedback during duration reproduction rather than the delay. Based on this premise, we compared the role of visual and tactile delayed sensory feedback in duration reproduction. Given that the superior temporal sensitivity of the tactile modality compared to the visual one, we hypothesized that a greater degree of temporal delay would be disregarded in tactile than visual modality, as the reproduction process anticipates the feedback rather the motor action (i.e., disregards the preceding delay). To validate this, we conducted two experiments, separated for visual and tactile feedback. In both experiments, participants reproduced a standard duration and received sensory (visual or tactile) feedback during the reproduction. One session introduced a temporal delay of 150 ms during adaptation, while the other session maintained synchronized sensory feedback as a control. During the test phase, we adjusted the delayed feedback from a synchronized 0 ms to delay of 150 ms to determine the extent of delay integrated into the reproduction. A steeper increase in the reproduced durations as the delay increased would indicate a greater dismissal of the action-feedback delay.

Method

Participants

Experiment 1 recruited 20 volunteers. Among them, 19 participants completed the testing (19-31 years old, average of 24.1, 8 females and 11 male). Experiment 2 also recruited 20 participants and 19 participants completed the testing (21-33 years old, average of 25.7, 12 females and 7 male). All participants had self-reported normal or corrected-to-normal vision and were naive to the purpose of the experiments. The sample size was determined based on previous studies (Ganzenmüller et al., 2012), which showed a significant effect of sensory feedback delay with 13 to 14 participants. We increased to 20 participants, aiming for robust results. All participants signed the informed consent form prior to the experiment and received 9 Euro per hour for their participation. The experiment was approved by the Ethics Committee of the LMU Munich Faculty of Psychology and Pedagogics.

Apparatus

The experiments took place in a sound-isolated dark cabin. We developed the experimental program using the “Psychopy” package (Peirce et al., 2019) in PyCharm. Participants viewed visual stimuli on a ViewPixx LCD monitor (VPixx Technologies Inc., Saint-Bruno, Canada) with a refresh rate of 120 Hz, with a consistent viewing distance of 60 cm, maintained by a chin rest, and they provided their behavioral responses using a standard keyboard. Tactile stimuli were presented with an AEC TACTAID VBW32 vibrator attached on the response finger, connected to the computer via an audio amplifier. To prevent irrelevant vibration and sound interference, participants wore foam earplugs and put their arms on a pillow.

Stimuli and Procedure

Stimuli. Experiment 1 utilized a gabor patch as the visual stimulus on the gray background to reduce afterimage effects. In contrast, Experiment 2 solely presented tactile stimuli without any visual components. Both visual and tactile stimulus (250 HZ) were presented for a standard duration of 800ms in each trial. Furthermore, these stimuli also served as sensory feedback when participants began to reproduce the duration.

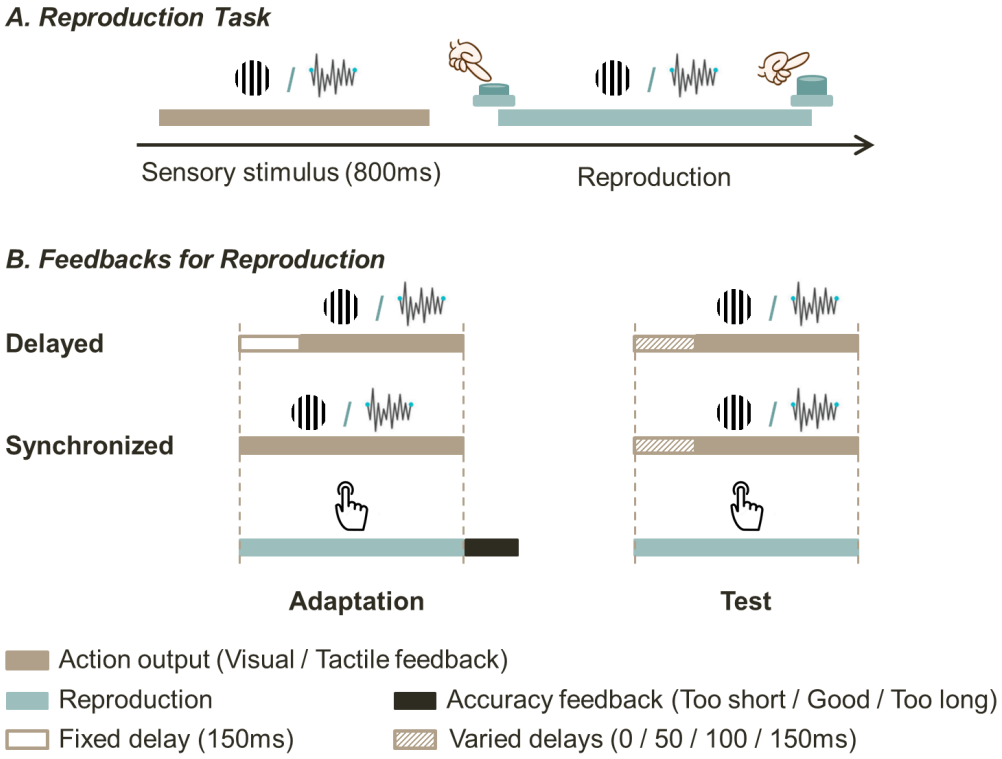

Figure 1. Schematic illustration of Experiments 1 and 2. The two experiments applied the same paradigm but differed in modalities of stimuli (Experiment 1: visual gabor patch; Experiment 2: tactile vibration). (**A**) A standard reproduction task, which comprised a 400 ms fixation, a 800ms standard duration of stimuli presentation, and a reproduction. (**B**) Illustrations of action output and accuracy feedback manipulations. During the adaptation phase (left panel), the action output (visual / tactile feedback) was presented either with a fixed delay of 150 ms (Delayed Feedback Condition) or synchronized with the reproduction action (Synchronized Feedback Condition). Immediately after the reproduction, participants received an accuracy feedback (indicated by the black bar). During the test phase, the delay between action and sensory feedback varied from 0 to 150 ms. No accuracy feedback was provided after the reproduction .

Procedure. Both Experiment 1 and 2 applied the same paradigm but employed different stimuli. Experiment 1 used a visual gabor patch (size: 1.7° of visual angle, spatial frequency: 0.08 cycles per degree), while Experiment 2 used tactile vibration for delivering the duration. Each experiment consisted of two sessions: synchronized and delayed feedback sessions. These sessions were conducted separately, with a minimum of 5 minutes break between them, and their order was counterbalanced among participants. Both sessions had two phases: an Adaptation phase and a Test phase. The task in both phrases was an identical duration reproduction task (Figure 1), but accuracy feedback was only given for the adaptation phase. Each trial started with a 400 ms fixation cross, and participants fixated on the cross until the first stimulus (gabor path/vibration) appeared for 800ms. After the stimulus disappeared, participants used their own pace to press and hold the "space" button to reproduce the duration as accurately as possible. During reproduction, a gabor patch / vibration appeared as sensory feedback (visual / tactile).

During the Adaptation phase, the onset of the visual / tactile sensory feedback occurred either simultaneously with the participant's response onset in the Synchronous session or 150 ms later in the delayed feedback session. However, the offset is always aligned with the response offset (Figure 1). In essence, the sensory feedback was 150 ms shorter than the motor reproduction in the delayed feedback session. After each reproduction, participants received accuracy feedback for 400ms in text whether their reproduction was "too short", "good", or "too long", based on their actual reproduced duration (< 720 ms, 720 to 880 ms, or > 880 ms, respectively). The Adaptation phase comprised 60 obligatory trials. Each participant practiced with the obligatory trials and got text feedback on the reproduction accuracy. The adaptation phase ended if 80% of the last ten trials fell within the "good" range. Otherwise, 10 more trials were added until they reached the 80% criterion. 68% of participants managed to reach the goal within 60 trials, and 79% reached the goal with one round of ten more trials. Three participants took more than two rounds to reach the goal. In Experiment 2, all participants managed to reach the goal within 60 obligatory adaptation trials.

The Test phase automatically followed the Adaptation phase. It consisted of 13 blocks. Each block started with five "top-up" Adaptation trials, with tasks identical to those in the corresponding Adaptation phase, including either synchronized or

delayed sensory feedback. The accuracy feedback was provided at the end of each "top-up" trial. The subsequent trials were test trials that introduced temporal delays of sensory feedback, varying between 0 and 150 ms in four levels (0, 50, 100, and 150 ms). Each level was randomly tested equally with each block (three repetition in Experiment 1 and 4 repetitions in Experiment 2). No accuracy feedback was provided for the reproductions for those test trials.

Data Analysis

Only the last 60 trials from the adaptation phase and those test trials were included for further data analysis. Then we calculated mean reproduced durations separately for each session, phase, sensory feedback delay, and individual participant. Statistical analyses were conducted in R (R Core Team, 2022). To determine the integration of visual and tactile sensory feedback with motor reproduction, we utilized linear regression.

Result

Reproduction during adaptation

Both Experiments 1 and 2 applied the Adaptation-Test paradigm to investigate the influence of the sensory feedback delay on duration reproduction after sensorimotor adaptation. The sensory feedback delay (visual feedback in Experiment 1 and tactile feedback in Experiment 2) was manipulated in the Adaptation phase between sessions, with either synchronized sensory feedback or delayed for 150 ms. The mean reproduction durations (± SEs) from Adaptation trials were calculated for each session of Experiments 1 and 2, which were 829 (± 17.7), 782 (± 12.1), 843 (± 6.3), and 788 (± 8.7) ms for the Visual/Delayed, Visual/Synchronized, Tactile/Delayed, and Tactile/Synchronized, respectively. A repeated-measure analysis of variance (ANOVA) was conducted on the 2-level within-subject factor of Delay (Delayed, Synchronized) and the 2-level between-subject factor of Modality (Visual, Tactile), which revealed a significant main effect of Delay ($F(1, 36) = 26.16$, $p < .001$, $\eta_g^2 = 0.20$) and non-significant effect for both the main factor of Modality ($F(1, 36) = 0.52$,

p = .475, η_g^2 = 0.01) and the interaction between the two main factors (F(1, 36) = 0.17, p = .678, η_g^2 = 0.00). These findings revealed significantly longer reproduction in the delayed feedback session compared to the synchronized ones, which was consistent in both visual and tactile modalities (between-session difference of 47 ms and 55 ms, respectively).

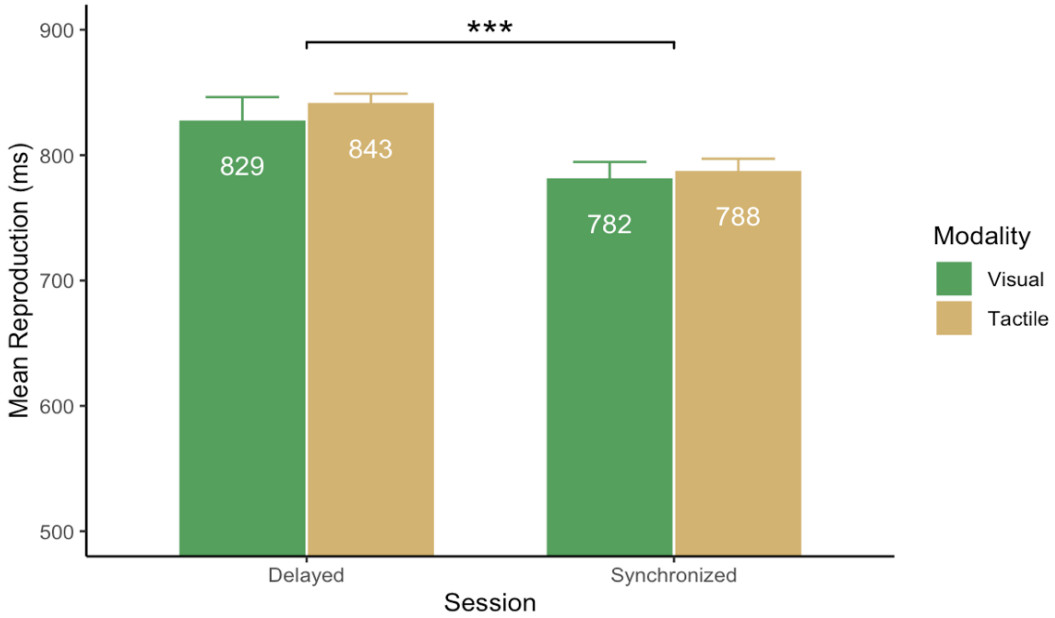

Figure 2. The mean reproduction duration from the Adaptation phases, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-session difference (p < 0.001: ***).

Mean reproduction after adaptation

Both experiments began with sensorimotor temporal adaptation (visual presentation in Experiment 1 and tactile presentation in Experiment 2, either synchronized or sensory feedback delayed), which was followed by a test session with varied sensorimotor delays. The mean reproduction durations (± SEs) from test trials were calculated for each session of Experiments 1 and 2, which were 885 (± 14.9), 957 (± 19.9), 844 (± 11.0), and 947 (± 13.5) ms for the Visual/Delayed, Visual/Synchronized, Tactile/Delayed, and Tactile/Synchronized, respectively. A repeated-measure ANOVA was conducted on the 2-level within-subject factor of Delay (Delayed, Synchronized) and the 2-level between-subject factor of Modality (Visual, Tactile), which revealed a

significant main effect of Delay ($F(1, 36) = 66.75$, $p < .001$, $\eta_g^2 = 0.32$). However, both the main effect of Modality ($F(1, 36) = 1.92$, $p = .175$, $\eta_g^2 = 0.04$) and the interaction effect between the two main factors ($F(1, 36) = 2.10$, $p = .156$, $\eta_g^2 = 0.01$) were not significant.

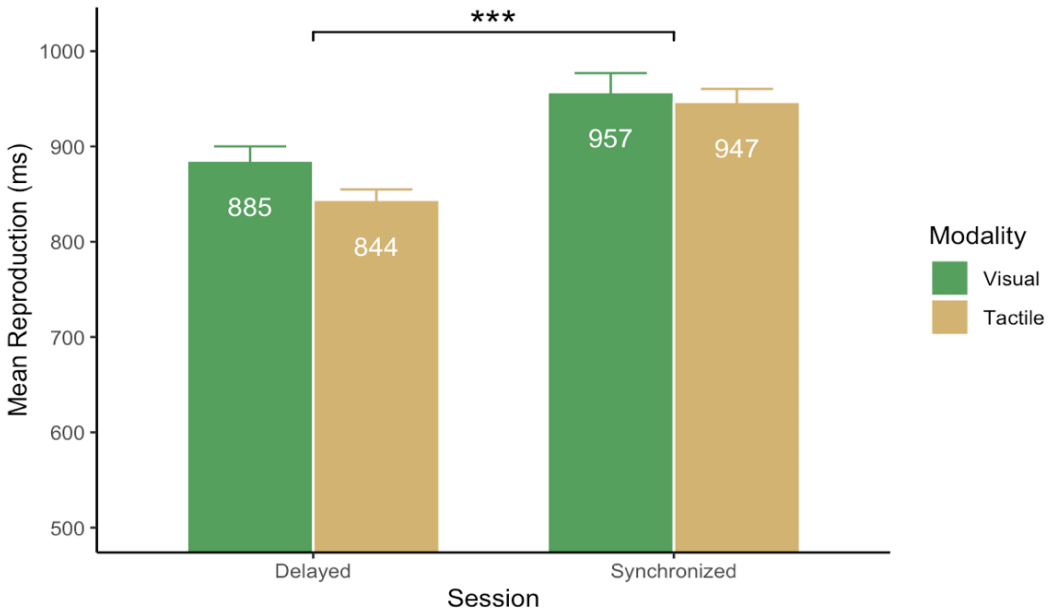

Figure 3. The mean reproduction duration from the test trials, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-session difference ($p < 0.001$: ***).

Adapting a briefer sensory feedback led to a significantly shorter reproduced duration, suggesting successful manipulation of the duration representation. In other words, sensory feedback influences the duration prior representation, ultimately affecting duration reproduction in the test phase. Interestingly, both tactile and visual shortened sensory feedback resulted in comparable shortened reproduced durations after adaptation, implying that it is the delay in sensory feedback rather than the specific sensory modality that impacts the average reproduction duration in the test phase.

Reproduction differences between sessions

The reproduced duration was notably different between sessions in both Adaptation and Test phases in both experiments. The mean reproduction difference (± SEs) was

calculated between the Synchronized and Delayed sessions (Synchronized - Delayed) for each phase of Experiment 1 and 2, which were -46 (± 17.4), 72 (± 18.3), -54 (± 9.1), and 103 (± 11.1) ms for the Visual/Adaptation, Visual/Test, Tactile/Adaptation, and Tactile/Test, respectively. A 2 Phase (Adaptation, Test) × 2 Modality (Visual, Tactile) ANOVA was conducted, revealing a significant main effect of Phase ($F(1, 36) = 81.91$, $p < .001$, $\eta_g^2 = 0.56$), and non-significant effect of Modality ($F(1, 36) = 0.68$, $p = .415$, $\eta_g^2 = 0.01$) as well as the interaction ($F(1, 36) = 1.66$, $p = .206$, $\eta_g^2 = 0.02$). These results indicated the duration of sensory feedback was incorporated into the sensorimotor reproduction especially when lacking the guiding accuracy feedback.

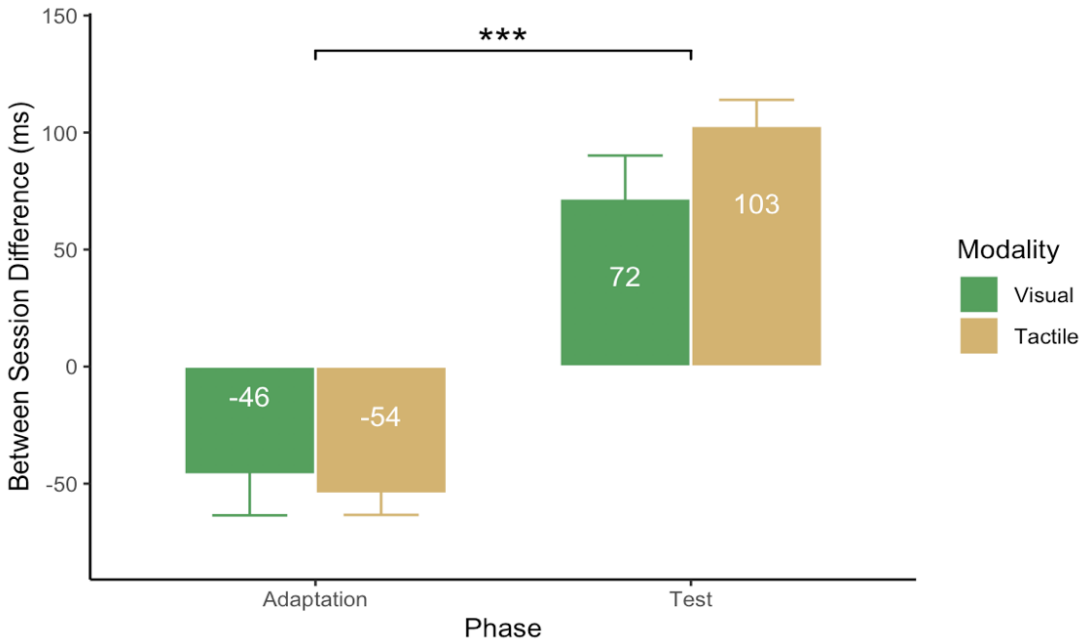

Figure 4. The mean reproduction duration differences between sessions (Synchronized - Delayed), separated for each phase (Adaptation / Test) and modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-phase difference ($p < 0.001$: ***).

Constant Overestimation in the absence of accuracy feedback

In a recent study on sensory visual feedback (Chen & Shi, 2023), a constant overestimation was observed in visual duration reproduction tasks without accuracy feedback. Based on this, we compared results from Experiments 1 and 2,

juxtaposing the Adaptation phase with corresponding Test trials. The average reproduction duration in the Adaptation phase was compared to the average reproduction of the test trials with the same sensory delays (i.e., synchronized feedback trials in the synchronized feedback session, and 150 ms delay trials in the Delay session).

In the synchronized feedback session (Figure 5A), the mean reproduction durations (± SE) were 782 (± 12.1), 788 (± 8.7), 927 (± 16.7), and 870 (± 15.3) ms for Adaptation/Visual, Adaptation/Tactile, Test/Visual, and Test/Tactile, respectively. A 2 Phase (Adaptation, Test) × 2 Modality (Visual, Tactile) ANOVA revealed a non-significant main effect of Modality ($F(1, 36) = 2.53$, $p = .120$, $\eta_g^2 = 0.05$), but a significant main effect of Phase ($F(1, 36) = 108.95$, $p < .001$, $\eta_g^2 = 0.49$) and an interaction effect between two main factors ($F(1, 36) = 8.22$, $p = .007$, $\eta_g^2 = 0.07$). The interaction was largely due to the significant difference between visual and tactile Test phases ($t(18) = 2.52$, $p = .021$).

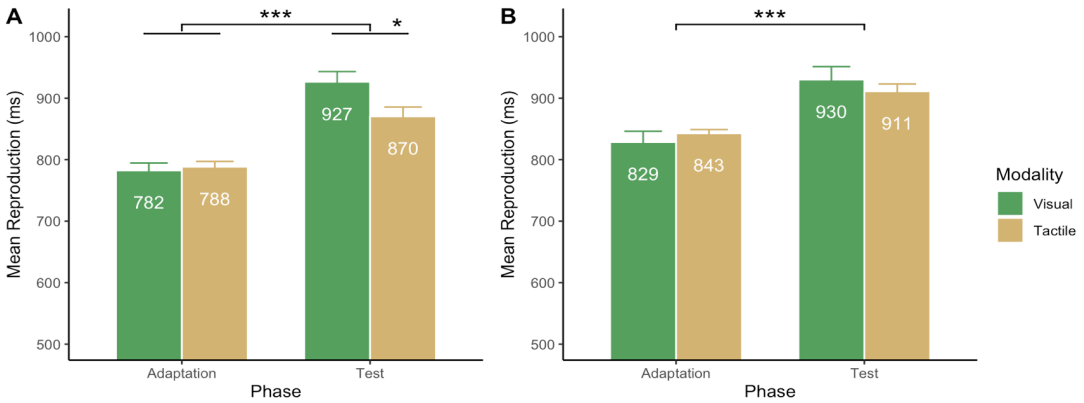

Figure 5. Constant overestimation from between-phases comparisons in both Experiment 1 (Visual) and Experiment 2 (Tactile). In synchronized feedback session (**A**), the general mean reproduction duration was compared between Adaptation trials and Test trials with 0 ms delay. In the delayed feedback session (**B**), the comparison was between Adaptation trials and Test trials with 150 ms delay. The asterisks mark the significant between-session difference (p < 0.05: *; p < 0.01: **; p < 0.001: ***).

In the delayed feedback session (Figure 5B), the mean reproduction durations (± SE) were 829 (± 17.7), 843 (± 6.3), 930 (± 21.1), and 911 (± 12.1) ms for Adaptation/Visual, Adaptation/Tactile, Test/Visual, and Test/Tactile, respectively. A

similar ANOVA analysis highlighted only a significant main effect of Phase ($F(1, 36) = 59.17$, $p < .001$, $\eta_g^2 = 0.30$). The main effect of Modality ($F(1, 36) = 0.02$, $p = .896$, $\eta_g^2 = 0.00$) and interaction effect ($F(1, 36) = 2.25$, $p = .143$, $\eta_g^2 = 0.02$) were non-significant.

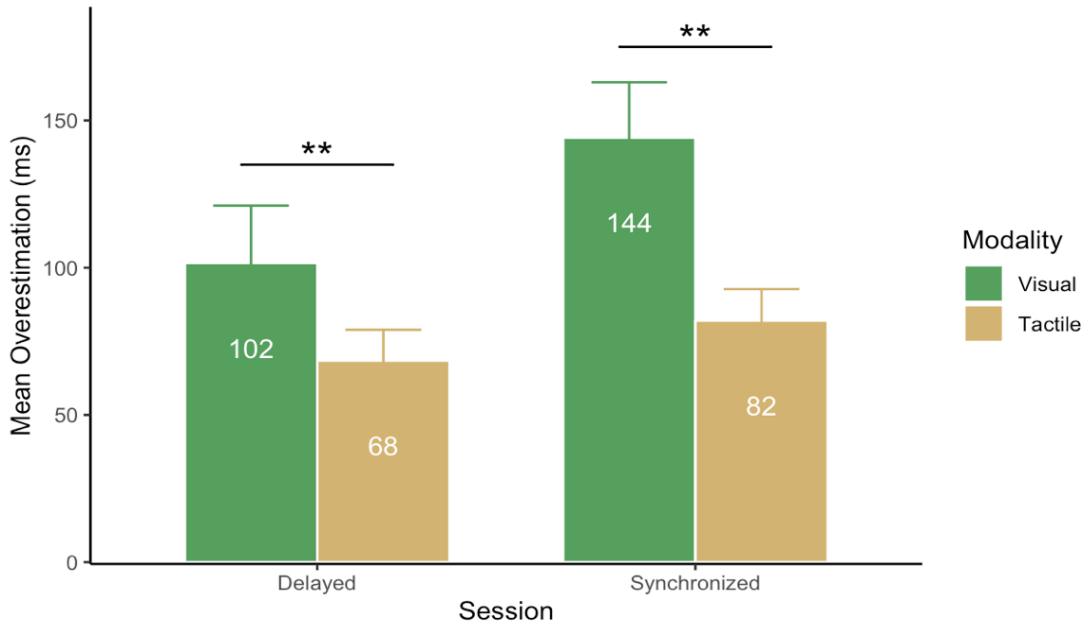

Figure 6. The mean overestimation in the Test phase relative to Adaptation phase, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-modality difference ($p < 0.01$: **).

The overestimation between phase was calculated for each Session in both Experiment 1 and 2. The mean overestimated durations (± SE) were 102 (± 19.5), 68 (± 10.5), 144 (± 18.8), and 82 (± 10.7) ms for Delayed/Visual, Delayed/Tactile, Synchronized/Visual, and Synchronized/Tactile, respectively. A 2 (Session: Delayed, Synchronized) × 2 Modality (Visual, Tactile) ANOVA analysis revealed a significant between modality main effect, $F(1, 36) = 9.94$, $p = .003$, $\eta_g^2 = 0.12$. Neither between session main effect ($F(1, 36) = 3.14$, $p = .085$, $\eta_g^2 = 0.04$) nor the interaction effect ($F(1, 36) = 0.84$, $p = .366$, $\eta_g^2 = 0.01$) were significant.

These results replicated previous study's finding of the constant overestimation in the absence of accuracy feedback across both visual and tactile modalities, regardless of any temporal delay between reproduction action and action output.

Additionally, the amount of overestimation might be different in visual and tactile modalities.

Sensorimotor Integration

The temporal delay was varied from 0 ms to 150 ms in the Test phases both in the synchronized (0ms) and delayed feedback (150ms) sessions. A further analysis was conducted comparing the Test phases in both sessions, focusing on this variation.

Visual Modality. A 2 (Delay: delayed, synchronized) × 4 (delayed Level: 0, 50, 100, 150 ms) ANOVA assessed the impact of varied visual temporal discrepancies in the Test phase. The main effects were significant for both Delay ($F(1, 18) = 15.46$, $p < .001$, $\eta_g^2 = 0.17$) and Delay Level ($F(1, 54) = 25.36$, $p < .001$, $\eta_g^2 = 0.11$). The interaction effect, however, was not significant ($F(1, 54) = 0.11$, $p = .954$, $\eta_g^2 = 0.00$). To further investigate the main effect of Delay Level, post-hoc comparisons were performed using pairwise t-test (adjusted for multiple comparisons with Benjamini-Hochberg correction). The comparisons were significant with $p = .047$ and .008 between 0 and 50ms and between 50 and 100ms, respectively. All other comparisons from 0 ms to 150ms were significant with *ps* < .001.

Tactile Modality. Similar to Experiment 1, another 2 (Delay: delayed, synchronized) × 4 (Delay Level: 0, 50, 100, 150ms) ANOVA assessed tactile temporal discrepancies in the Test phase. The main effects were significant for both Delay ($F(1, 18) = 85.94$, $p < .001$, $\eta_g^2 = 0.46$) and Delay Level ($F(1, 54) = 223.19$, $p < .001$, $\eta_g^2 = 0.48$). The interaction effect was not significant ($F(1, 54) = 1.01$, $p = .397$, $\eta_g^2 = 0.00$). The post-hoc analysis showed all comparisons from 0 ms to 150ms were significant with *ps* < .001.

These results revealed a consistent pattern of sensorimotor integration in both visual and tactile reproduction. In the Test phase, the reproduction duration increased linearly as the given duration increased, separated from the impact of delayed adaptation, which was also prominent in both experiments. Based on these, we conducted linear analysis, as we reported below.

Cross Modality Comparison. Further analysis was conducted comparing the

results of Experiments 1 and 2 to further investigate the difference between visual and tactile sensory timing in sensorimotor integration. A mixed model analysis comprising 2 (Delay: delayed, synchronized) × 4 (Delay Level: 0, 50, 100, 150ms) within-subject factors and a 2-level (Modality: Visual, Tactile) between-subjects factor was conducted for reproduction in Test phase. Consistent with above results, the two within-subject main effects were both significant, Delay, $F(1, 36) = 66.75$, $p < .001$, $\eta_g^2 = 0.30$, Delay Level, $F(1, 36) = 272.64$, $p < .001$, $\eta_g^2 = 0.26$. The main effect of the between-subject factor Modality, however, was non-significant, $F(1, 36) = 1.92$, $p = .175$, $\eta_g^2 = 0.04$. It is worth noting that the analysis revealed only one significant interaction, Modality × Delay Level interaction, $F(1, 36) = 30.75$, $p < .001$, $\eta_g^2 = 0.04$, indicates that the effect of Delay Level on the reproduction is influenced by the modality type. All the rest interactions were not significant, Fs$(1, 36) < 2.10$, ps $> .15$, η_g^2s < 0.01.

Based on above analyses, the relationship between the delayed duration (Delay Level) and adaptation type (Session: delayed, synchronized) and reproduction duration in the Test phase was further investigated with a linear mixed-effects model:

$$\text{Reproduction Duration} = \beta_0 + \beta_D \times \text{Delay} + \beta_s \times \text{Adaptation}$$

The linear model was fitted for both Experiment 1 and 2 (visual and tactile) with varied Delay durations and the binary categorical predictor of Adaptation with values 0 and 1 corresponding to delayed and synchronized sessions. The model equations are as follow:

$$\text{Visual Modality: } RD_V = 850 + 0.47 \times \text{Delay} + 72 \times \text{Adaptation}$$

$$\text{Tactile Modality: } RD_T = 772 + 0.95 \times \text{Delay} + 103 \times \text{Adaptation}$$

An ANOVA was conducted using a linear mixed-effects model with Satterthwaite's method to assess the effects of the Delay Level factor (0, 50, 100, 150ms) and Adaptation factor (delayed, synchronized), which revealed significant effects in both visual modality (Delay Level, $F(1, 131) = 36.43$, $p < .001$; Adaptation, $F(1, 131) = 66.89$, $p < .001$) and tactile modality (Delay Level, $F(1, 131) = 385.24$, $p < .001$;

Adaptation, $F(1, 131) = 357.98$, $p < .001$). These results indicated that both delay duration and adaptation type had significant impact on the reproduction duration in both visual and tactile modalities.

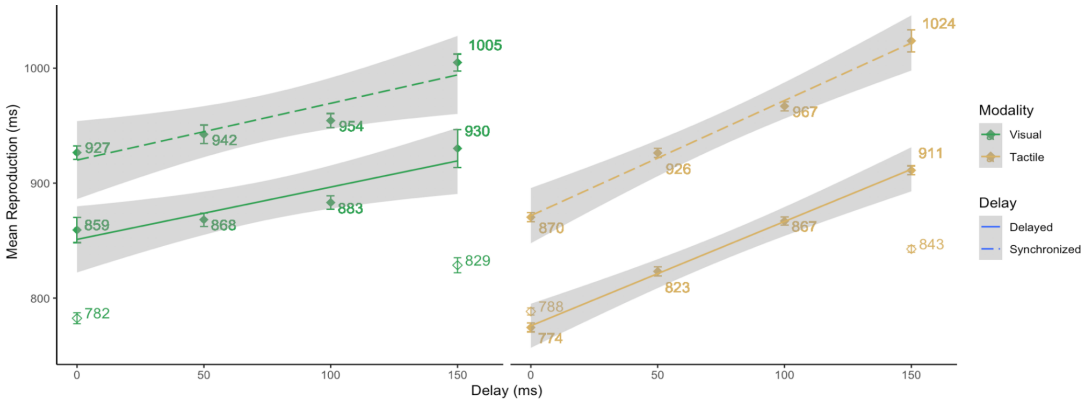

Figure 7. The mean reproduction duration for each delay level in both sessions (delayed, synchronized) and both experiments (Visual: left panel, Tactile: right panel). Each adaptation phase had one single mean reproduction duration for a fixed delay of either 0ms (synchronized) or 150ms (delayed). The mean reproduction duration of varied delayed levels in the test phase was fitted with the linear regression model. Across both experiments, the delayed feedback session exhibited a consistently lower intercept, while the slope remained comparable within each modality, but steeper in the tactile modality.

To sum up, these findings suggest that adaptation to the delayed feedback was different (from intercepts) between modalities and the amount of delayed feedback integration in the test phase also differed for the visual and tactile modality.

Discussion

The present study aimed to explore the differential aftereffects of delay adaptation in visual and tactile duration reproduction. In one session during the adaptation phase, we introduced a sensory feedback delay and shortened of 150 ms, while in the other session, the feedback remained synchronized. During the test phase, the sensory feedback spanned from being fully synchronized to a delay of 150 ms. The visual and tactile sensory feedback were tested in two separated experiments. The results revealed a consistent delay adaptation effect across both modalities, but they differed in terms of the extent of adaptation and sensorimotor integration.

Influences of accuracy feedback

During the adaptation, participants received accuracy feedback at the end of each trial. This was designed to encourage them to rely on their motor reproduction rather than the sensory feedback. The accuracy feedback proved effective. Despite a 150 ms reduction in sensory feedback during reproduction, the reproduced duration was approximately 800 ms (829 ms for visual feedback and 843 ms for tactile feedback, comparable across modalities, $t(19) = -0.79$, $p = .442$). Nevertheless, participants were unable to fully discount the delay. The reproduced duration was notably longer (with a session difference of 47 ms and 55 ms for the visual and tactile feedback, respectively) in the delayed feedback sessions compared to the synchronized ones. This suggests that the sensory feedback duration was still factored into the sensorimotor reproduction, consistent with early research (Ganzenmüller et al. 2012; Shi et al. 2013).

A significant distinction between the adaptation and test phase was the lack of the accuracy feedback during the test trials. Consequently, participants had to rely on their own pre-existing prior (developed during the adaptation) and balance the integration weights of the motor duration and sensory feedback duration. Without the guiding accuracy feedback, as evidenced by the linear mixed models, the session difference (between synchronized and delayed) expanded to 72 ms for the visual and 103 ms for the tactile modality. This suggests a greater incorporation of the delay in the reproduction. In other words, without accuracy feedback, participants began to place more trust in the sensory feedback (e.g., in the extreme case, if the duration reproduced in the delayed session extended by 150 ms relative to the synchronized session, it would signify participants rely entirely on the duration of the sensory feedback's duration over the motor duration). This shift towards sensory reliance was more pronounced in the tactile than the visual modality.

Modality-specific sensorimotor integration

When comparing visual and tactile sensory feedback, our results showed that tactile feedback led to a greater incorporation of delay in reproduction than visual feedback. This is evident from the linear trends, or slopes, derived from the linear mixed model, with tactile feedback showing a slope of 0.95 compared to the visual

feedback's slope of 0.47. The slope can be interpreted as an indicative weight of sensory feedback in the sensorimotor integration (Shi et al. 2013), integrating durations from two sources, motor timing and sensory feedback. A slope of 0 represents a flat trend, suggesting that delayed sensory feedback does not impact on reproduction and is solely motor-driven. Conversely, a slope of 1 implies that the delay is entirely reflected in the reproduction, leaning entirely on sensory feedback. By adjusting the extent of temporal delay between the reproduction action and sensory feedback, it permitted us to quantify the respective slopes. Our findings suggest that reproduction that incorporated direct tactile feedback on the action finger heavily relied (with a slope of 0.95) on the tactile sensory feedback for duration reproduction, as opposed to the motor action itself. On the other hand, When using visual feedback, reproduction appears to balance the weight between the motor and sensory feedback, with a weight of 0.47 for the visual feedback.

Shifts of the prior with varied delayed feedback

In both experiments we included a control session with synchronized sensory feedback during the adaptation phase. This session enabled us to examine influences of accuracy feedback (present during the adaptation but absent during the test) and varied delayed feedback on prior formation.

With the accuracy feedback, both visual and tactile duration reproduction were relatively close to the target duration of 800 ms (visual at 782 ms, tactile at 788 ms). However, in the absence of the accuracy feedback, reproduction with synchronized sensory feedback in the test phase was lengthened to 927 ms for visual feedback and 870 ms for tactile feedback. Two potential contributing factors may account for this lengthening effect. First, the consistent overestimation may arise from divided attention during reproduction. As we have demonstrated in a previous study (Chen & Shi, 2023) that compared the presence and absence of the accuracy feedback, the lack of accuracy feedback lengthened reproduction about 13.5% in both subsecond and sup-second reproductions. The second contributing factor is the perturbation of various delays. Since the delays we equally administered ranged from 0 to 150 ms, the averaged delay was about 75 ms in the test phase. This means, the sensory feedback was shortened by an average of 75 ms compared to the adaptation phase. Given that the prior developed in the adaptation (the synchronized session) was

based on full synchronized feedback, introducing such delays in the test phase lengthened the reproduced duration to equate the perceived duration. As a result, the mean reproduction in the test phase expanded nearly 150 ms for both modalities, resulting in 957 ms for visual and 947 ms for tactile reproductions. It is noteworthy that both modalities had nearly identical mean reproductions, suggesting that observers might perceive and encode durations similarly across visual and tactile modalities. Nevertheless, the impact of the sensory feedback and delay might vary, evidenced by the differing integration weights we observed. Dissecting these two components to understand their individual influences, however, requires future research.

It is important to note that the lengthening trends in the synchronized sessions mirrored those in the delayed feedback sessions, given that we didn't observe any interactive effects. The overestimation in terms of ratio was larger in the synchronized feedback session (Visual: 18.5%, Tactile: 10.4%) and smaller in the delayed feedback session (Visual: 12.2%, Tactile: 8.1%). This implies that the acquisition of the prior (with or without delay) during the adaptation phase acts additively to the overestimation brought about by the absence of the accuracy feedback and introduced delays. In other words, adaptation of delay sensory feedback influenced the prior (that is, how the standard duration is perceived), while the trial-to-trial variation in delay primarily impacted the sensorimotor integration. Without the accuracy feedback, those trial-to-trial sensorimotor integrations (with the delay) progressively update the internal prior, resulting in an overestimation that we observed.

In conclusion, this study explored influences of delayed sensory feedback in visual and tactile duration reproduction. We observed consistent adaptation effects for both visual and tactile modalities, but different afftereffects. Compared to reproduction in visual modality, reproduction in tactile modality placed more trust (weight) to the sensory feedback and disregarding the delay between the action and sensory feedback, resulting in steeper lengthening in reproduction. Additionally, we observed overestimation in the absence of accuracy feedback and with the presence of delay. Overall, the present findings suggested that the temporal delay adaptation was influenced by the sensorimotor integration. The integration was governed by sensory reliability, weighted differently across modalities, with a higher

weight on the tactile modality than the visual modality.

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