Accuracy Feedback and Delay Adaptation Effects in Visual and Tactile Duration Reproduction

Abstract

Brief actions involve multiple temporal cues that may not always synchronize, and in basic action-effect relationships, the effect is often delayed. How the brain incorporates delays across modalities in a sensorimotor duration reproduction remains unclear. To investigate this, we conducted two experiments on duration reproduction with delayed sensory feedback. Participants reproduced durations in either visual (Experiment 1) or tactile (Experiment 2) modalities. In the adaptation phase, an action-induced effect, either visual or tactile stimulation, was delayed by 150 ms in one session and synchronized in the control session, with accuracy feedback provided after each trial. In the testing phase, random action-effect delays (0-150 ms) was introduced, and accuracy feedback was removed. The findings revealed that accuracy feedback effectively recalibrated motor time but did not eliminate the delay. Without accuracy feedback, tactile reproduction relied more on the tactile feedback than on motor time, resulting in greater lengthening of motor reproduction compared to the visual feedback. These findings suggest that temporal delay adaptation is influenced by accuracy feedback and sensorimotor integration, with sensorimotor reliability assigning a higher weight to the tactile than the visual modality.

Keywords: Time perception, accuracy feedback, 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 lasting only seconds, especially tied to actions (Buhusi & Meck, 2005; Merchant & Yarrow, 2016). Yet, our subjective time does not always match objective time. Several factors, such as stimulus intensity, motion, 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, time perception 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 involved in timing tasks, suggesting that time processing is 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 of actions and motor movements may differ from the timing of perceived sensations (Bueti & Walsh, 2010).

When navigating real environments, multiple timing cues are often generated simultaneously. Integrating multiple 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 coordinating the actions of both hands and pedal work. These multimodal actions and multisensory cues supply crucial temporal information for a captivating musical performance. Even though 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, Church, et al., 2013), the idea can be dated back to Helmholtz's "perception as inference" (Helmholtz, 1867).

Yet, sensory inputs and actions are not always perfectly synchronized. For instance, during a virtual meeting with a shaky internet connection, a person might notice 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 resolve the conflicting information into a coherent perception. Remarkably, 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. Research by Cunningham and colleagues (2001) illustrates this adaptation. Participants engaged in a simulated shooting video game with a 235 ms delay in the visual feedback. Initially they performed badly and eventually recalibrated sensorimotor delay and reached comparable performance as the control group at the end of the delay adaptation. However, when the delay was removed, their performance drastically declined to about 52% accuracy, exhibiting a "negative aftereffect". Similarly, Stetson et al. (2006) found a negative aftereffect in an action-feedback delay task. Participants recalibrated their perception of sensorimotor synchronicity when pressing a button produced a delayed flash. In a subsequent test, after this delay was removed, participants felt that the resultant flash from their action occurred before the action nearly 40% of the time. This illusory inversion of action and effect underscores the adaptability of our sense of timing to various environments.

In their study on duration perception under delayed feedback, Ganzenmüller et al. (2012) demonstrated that an onset delay during a duration reproduction task lengthens the reproduced duration, while offset delay shortens it, although to a lesser extent. Interestingly, participants nearly lengthened the reproduced duration by the amount of the onset delay within the same modality. This lengthening effect persisted as long as the delay was present, showing immediate adaptation. In other words, individuals may focus on comparing the duration of the probe event and the action-induced event (i.e., within-modality sensory comparison), disregarding delay and lengthening their motor action, even though instructions emphasized the importance of accurately reproducing motor time. One potential reason for such an effect is that Ganzenmüller et al. (2012) did not provide feedback on the accuracy of each motor time reproduction. Comparing durations within the same modality might be easier than comparing sensory and motor time, leading participants to shift to within-modality sensory comparison rather than sensorimotor comparison. This raises several important yet unanswered questions: Would accuracy feedback recalibrate the motor prior

for delayed-output reproduction? After delay recalibration, how does the brain treat the delay in the absence of accuracy feedback? Would the recalibrated motor prior shift back to its original state without the delay? Does sensory modality play a role in the integration of delayed feedback?

Based on previous temporal recalibration studies (Cunningham et al., 2001; Stetson et al., 2006), we anticipated that accuracy feedback would calibrate motor time for a given duration, but were uncertain about the extent of this recalibration. We hypothesized that recalibration adjusts the motor action based on the difference between the probe duration (P) and action-induced feedback (F) to meet accuracy requirements, with this difference being a function of the delay (D):

$$P - F = \Delta + wD, \tag{1}$$

where Δ is a general reproduction bias and w is the weight of the delay. A weight of 0 indicates complete trust in motor timing, ignoring any delay in the feedback, while a weight of 1 indicates full trust in action-induced feedback, lengthening motor time (as shown by Ganzenmüller et al., 2012). Assuming the general bias is similar for both delayed or synchronized manipulations, we could infer the weight of the delay in recalibration by comparing the two conditions.

In the absence of accuracy feedback, we expected the recalibrated motor time to gradually shift back to its original state. In addition, according to Bayesian sensorimotor integration (Ganzenmüller et al., 2012; Körding & Wolpert, 2004; Shi, Church, et al., 2013), the reproduced duration (R) is an integration of motor time (M) and the delayed action-induced event time (F):

$$R = vM + (1 - v)F \tag{2}$$

Given that the motor time and delayed event time have a fixed relationship $M = F + D$, Equation (2) can be rewritten as:

$$R = F + vD \tag{3}$$

The weight of the action-induced event time might also depend on the reliability of the sensory modality (Ernst & Banks, 2002; Körding & Wolpert, 2004; Shi, Ganzenmüller, et al., 2013) and modality appropriateness (Welch & Warren, 1980). For example, studies have shown touch had a stronger influence on vision than vision on touch on sequent of visual and tactile events (Bresciani et al., 2006). By varying the delay, we could obtain the weight of motor time for different

modalities.

To validate these hypotheses, we conducted two experiments, separated for visual and tactile feedback. In both experiments, participants reproduced a standard duration and received action-induced feedback (visual or tactile) during the reproduction. During the adaptation, we provided accuracy feedback and compared delayed and synchronized action feedback. In the testing phase, we removed the accuracy feedback and varied the onset delay.

Method

Participants

To avoid potential cross-modal transfer effects, we recruited different groups of participants for the visual (Experiment 1) and tactile (Experiment 2) duration reproduction tasks. Each group initially included 20 participants, but one in each group failed to complete the testing. Thus, each group ended up with 19 participants (Experiment 1: ages 19-31, mean 24.1, eight females and 11 males; Experiment 2: ages 21-33, mean 25.7, 12 females and seven males). All participants had self-reported normal or corrected-to-normal vision and were naive to the purpose of the experiments. They provided informed consent before the experiment and received 9 Euros per hour for their participation. The experiment was approved by the Ethics Committee of the LMU Munich Faculty of Psychology and Pedagogics.

The sample size was determined based on previous studies. A previous study (Ganzenmüller et al., 2012) found a large effect size for visual delay versus synchronous reproduction feedback ($\eta^2 = .769, f = 1.82$). Another study (Tomassini et al., 2011) also found a large effect size for modality differences between visual and tactile durations ($\eta^2 = .67, f = 1.42$). With a significant level $\alpha = .05$ and a statistical power of 95%, our calculations for between-subject comparison showed that at least 15 participants were needed to achieve the desired power. To ensure robust results, we increased to 20 participants per group.

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 to the response finger, connected to the computer via an audio amplifier. We placed the tactile stimulation close to the response to enhance the spatial proximity of sensorimotor integration. Participants wore foam earplugs to prevent irrelevant vibration and sound interference and put their arms on a pillow.

Stimuli and Procedure

Stimuli. Both Experiments 1 and 2 applied the same paradigm but employed different modality stimuli. Experiment 1 used a visual Gabor patch (size: 1.7° of visual angle, spatial frequency: 0.08 cycles per degree) on the gray background to reduce afterimage effects. Experiment 2 used tactile vibration (250 Hz) as the main stimulation for target duration and sensory feedback, while the visual fixation serves as the trial start signal. In both experiments, the stimuli appeared for 800 ms in each trial. Furthermore, the same type of stimulus (either visual or tactile) also served as an action-induced event when participants began to reproduce the duration.

Procedure. Each experiment consisted of two sessions: synchronized and delayed. These sessions were separated by a minimum 5-minutes break, and their order was counterbalanced among participants. Each session included an adaptation phase and a testing phase, both involving the same duration reproduction task (Fig. 1).

Each trial started with a 400 ms fixation cross, and participants fixated on the cross until the first stimulus (a Gabor patch or vibration) appeared for 800 ms. After the stimulus disappeared, participants pressed and held the “space” button at their own pace to reproduce the duration as accurately as possible. Upon button press, depending on the session and the phase, the same Gabor patch or vibration appeared immediately or with a delay. The stimulus disappeared as soon as the button was released. During the adaptation phase, the action-induced visual or tactile feedback appeared immediately in the synchronized session but was delayed 150 ms in the delayed session. In other words, the action-induced event was 150 ms shorter than the actual action duration (Fig. 1). During the testing phase, however, for both sessions, the action-induced events were delayed by a random interval of 0, 50, 100, and 150 ms.

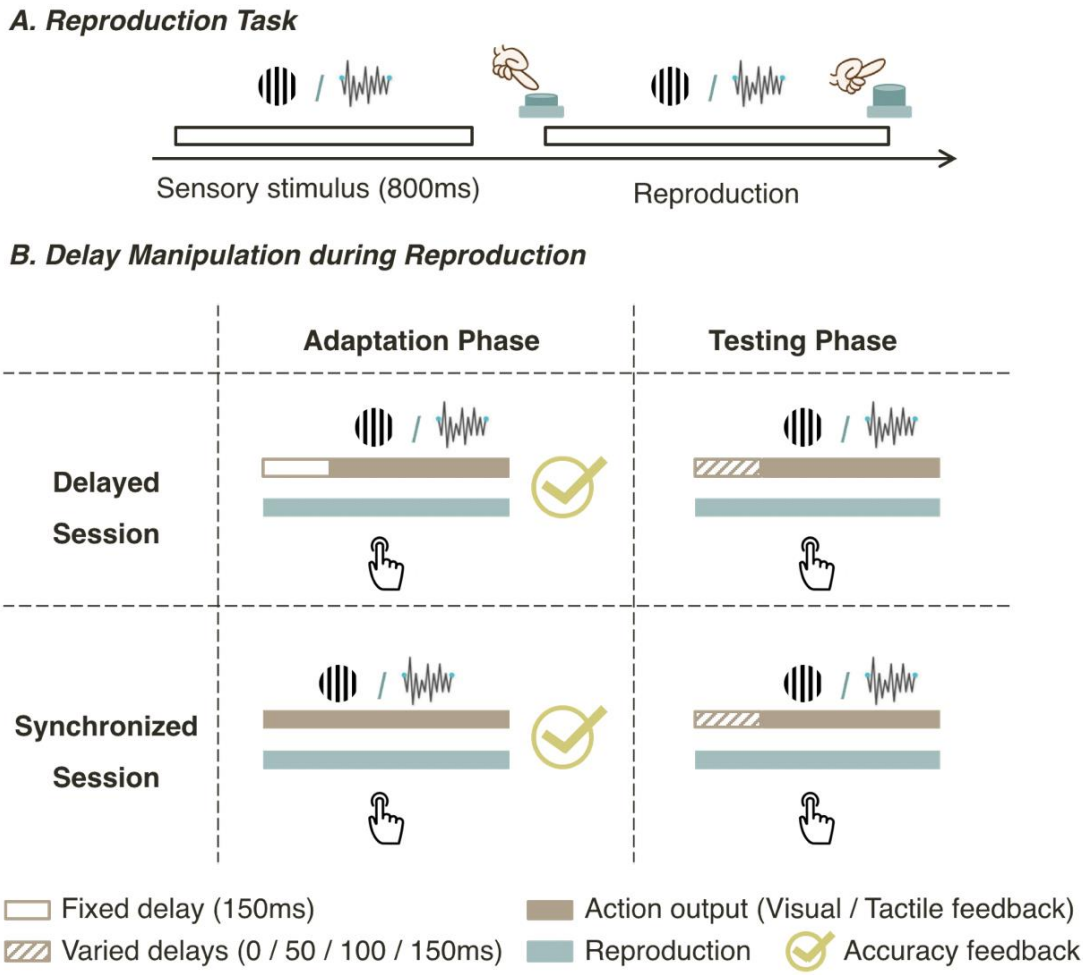

Figure 1. Schematic illustration of the study's design. The two experiments shared the same paradigm but differed in modalities through which stimuli were presented (Experiment 1: visual; Experiment 2: tactile). (**A**) In a reproduction task, participants first fixated on a central cross for 400 milliseconds (not shown). Next, a stimulus was presented for 800 milliseconds, and participants were then asked to reproduce the perceived duration. (**B**) Each experiment consisted of an adaptation phase (left panel), followed by a testing phase (right panel). In the adaptation phase, the action-induced (visual / tactile) feedback was presented either with a fixed delay of 150 ms (Delayed session) or synchronized with the onset of the action (Synchronized session). Participants received an accuracy feedback ("Too short", "Good" or "Too long") immediately after the reproduction (denoted by the "tick" symbol). In the testing phase, the delay between action and action-induced feedback varied from 0 to 150 ms, but no accuracy feedback was provided after the reproduction.

Accuracy feedback was provided *only* during the Adaptation phase or 'top-up' adaptation trials in the testing phase. To encourage participants to rely on motor timing rather than the duration of the action-induced event, they received accuracy feedback in text for 400 ms after each reproduction during the adaptation phase. The feedback indicated whether their reproduction was "too short,"

"good," or "too long" based on their relative error. The “good” window was defined as ±10% Weber fraction around 800 ms, following the convention of previous studies (e.g., Ganzenmüller et al., 2012). Specifically, reproduced motor durations between 720 to 800 ms were considered as “good”. Reproduced duration outside this window were marked as either “too short” or “too long”.

The adaptation phase included 60 obligatory trials. Participants reproduced these trials and received text feedback on their reproduction accuracy. The adaptation phase ended if 80% of the last ten trials fell within the “good” window. Otherwise, 10 additional trials were added until they reached the 80% criterion. 68% of participants reached the goal within 60 trials, and 79% reached the goal within one round of 10 trials. Three participants took more than two rounds to reach the goal. In Experiment 2, all participants reached the goal within the initial 60 trials.

The testing phase began automatically after the adaptation phase. It consisted of 13 blocks. Each block started with five “top-up” adaptation trials, identical to those in the adaptation phase, with accuracy feedback. For the subsequent testing trials, a random delay interval of 0, 50, 100, or 150 ms was introduced. Each delayed interval was tested equally within each block (three repetitions in Experiment 1 and four repetitions in Experiment 2). No accuracy feedback was provided for the reproductions for these testing trials.

Data Analysis

To equalize trial numbers across participants, we only took the last 60 trials from the adaptation phase and those testing trials for further data analysis. We then calculated mean reproduced durations separately for each session (delayed / synchronized), phase (adaptation / testing), 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

Adaptation Phase: Duration Reproduction with Accuracy Feedback

First, we examined if accuracy feedback during the adaptation phase could train participants to ignore the 150-ms delay. We compared the mean reproduction durations between the synchronized and delayed sessions and the tactile and visual modalities. The mean reproduction

durations (±SEs) during the adaptation phase were 829±17.7 ms for Visual/Delayed, 843±6.3 ms for Tactile/Delayed, 782±12.1 ms for Visual/Synchronized, and 788±8.7 ms for Tactile/Synchronized conditions (Fig. 2A). A mixed analysis of variance with the within-subject factor Delay (Delayed, Synchronized) and the between-subject factor of Modality (Visual, Tactile) revealed a significant main effect of Delay ($F(1, 36) = 26.16$, $p < .001$, $\eta_g^2 = 0.20$). Neither the main effect of Modality ($F(1, 36) = 0.52$, $p = .475$, $\eta_g^2 = 0.01$) nor the interaction between Delay and Modality ($F(1, 36) = 0.17$, $p = .678$, $\eta_g^2 < 0.01$) were significant. These findings suggest that, despite accuracy feedback for each trial, the delay still lengthened the reproduction action by 46±17.4 ms for the visual modality and 54±9.1 ms for the tactile modality. Assuming the general bias was the same for the delayed and synchronized session, based on Equation (1), about one-third of the 150 ms delay was integrated in motor time (Visual: 0.307±0.12; Tactile:0.362±0.06). On the other hand, accuracy feedback during the delayed adaptation informed action to shorten the action-induced event by two-thirds of the delayed time. Interestingly, there was no significant difference between the visual and tactile modality ($t(18) = -0.48$, $p = .638$, *Cohen's d* = -0.14, $BF = 0.338$), suggesting that accuracy feedback might dominate sensorimotor recalibration during the adaptation phase, making the influence of modality precision negligible.

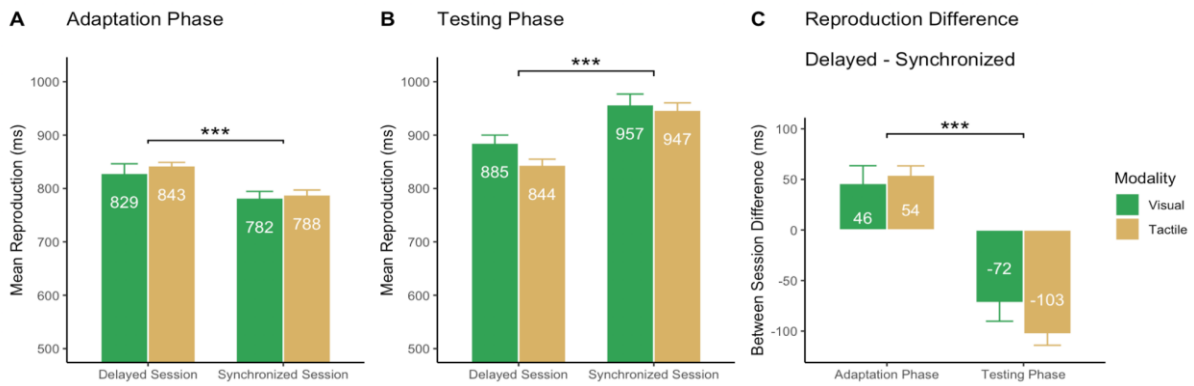

Figure 2. Mean reproduction durations from the adaptation phases (A) and testing phase (B), separated by Session (Delayed / Synchronized) and Modality (Visual: green; Tactile: brown). Panel (C) shows the mean reproduction duration differences between sessions (with Synchronized - Delayed), separated for each phase (Adaptation/Testing) and modality. Asterisks mark the significant between-session difference (***: $p < 0.001$).

Testing Phase: Duration Reproduction without accuracy feedback

After the adaptation phase, the delay between reproduction and action-induced feedback varied

between 0 ms and 150 ms, critically, with no accuracy feedback. The mean reproduction durations (±SEs) were 885±14.9 ms for the Visual/Delayed, 844±11.0 ms for Tactile/Delayed, 957±19.9 ms for Visual/Synchronized, and 947±13.5 ms for Tactile/ Synchronized, respectively (Fig. 2B). A mixed ANOVA with the same factors as those used in the adaptation phase revealed a significant main effect of Delay ($F(1, 36) = 66.75$, $p < .001$, $\eta_g^2 = 0.32$). However, neither the main effect of Modality ($F(1, 36) = 1.92$, $p = .175$, $\eta_g^2 = 0.04$) nor the interaction effect between the Delay and Modality ($F(1, 36) = 2.10$, $p = .156$, $\eta_g^2 = 0.01$) were significant. Interestingly, in contrast to the adaptation phase, the synchronized session yielded longer reproduced duration than the delayed session. Next, we further analyzed across phase differences.

Adaptation versus Testing (or Accuracy Feedback versus No Feedback)

A three-way mixed ANOVA with between-participant factor Modality (Visual, Tactile) and within-participant factors Accuracy Feedback (With, Without) and Adaptation (Synchronized, Delayed) on the mean duration reproduction revealed significant main effects of Accuracy Feedback, $F(1,36) = 168.87$, $p < .001$, $\eta_g^2 = .41$, and Adaptation, $F(1,36) = 15.32$, $p <.001$, $\eta_g^2 =.067$, while there was no significant difference between modalities, $F(1,36) = 0.925$, $p = .343$, $\eta_g^2 =.015$. On average, the absence of accuracy feedback during the testing phase lengthened the mean reproduction by 99±8.27 ms compared to the adaptation phase with accuracy feedback. Additionally, the delayed adaptation phase increased the mean reproduction by 50±9.71 ms compared to the synchronized adaptation.

Notably, the interaction between Accuracy Feedback and Adaptation was significant, $F(1,36)=149.05$, $p < .001$, $\eta_g^2=.236$. This interaction reflects the opposite patterns shown in Figs. 2A and 2B. To better capture the interaction and opposite effect, we replotted the difference between the two sessions (Delayed - Synchronized, Fig. 3). Compared to the synchronized session, motor action was lengthened in the delayed adaptation session by about one-third of the 150-ms delayed time and the action-induced event time was shortened two-third of the delayed time. This likely created a shortened sensory feedback prior for the delayed session, resulting in a shortened reproduction for the delayed session in the testing phase when both synchronized and delayed sessions experienced the same delay variations.

There was also a significant three-way interaction, $F(1,36) = 7.7$, $p = .0087$, $\eta_g^2=.016$. This three-way

interaction was likely due to modality modulation in the testing phase but not in the adaptation phase. We will investigate this in detail in the next "sensorimotor integration" session.

Overestimation in the Absence of Accuracy Feedback

The cross-phase comparison revealed that the absence of accuracy feedback increased the mean reproduction. However, that average analysis did not consider the different delayed manipulations in the adaptation and testing phases. To have a better fair comparison, here we only selected a 150-ms delay condition for the delayed session and a synchronized condition (i.e., 0-ms delay) for the synchronized session from the testing phases. To better visualize the lengthening effect in the absence of accuracy feedback, we subtract the reproduction duration in the adaptation phase from the testing phase. Fig. 3 depicts the lengthening effect in the testing phase compared to the adaptation phase.

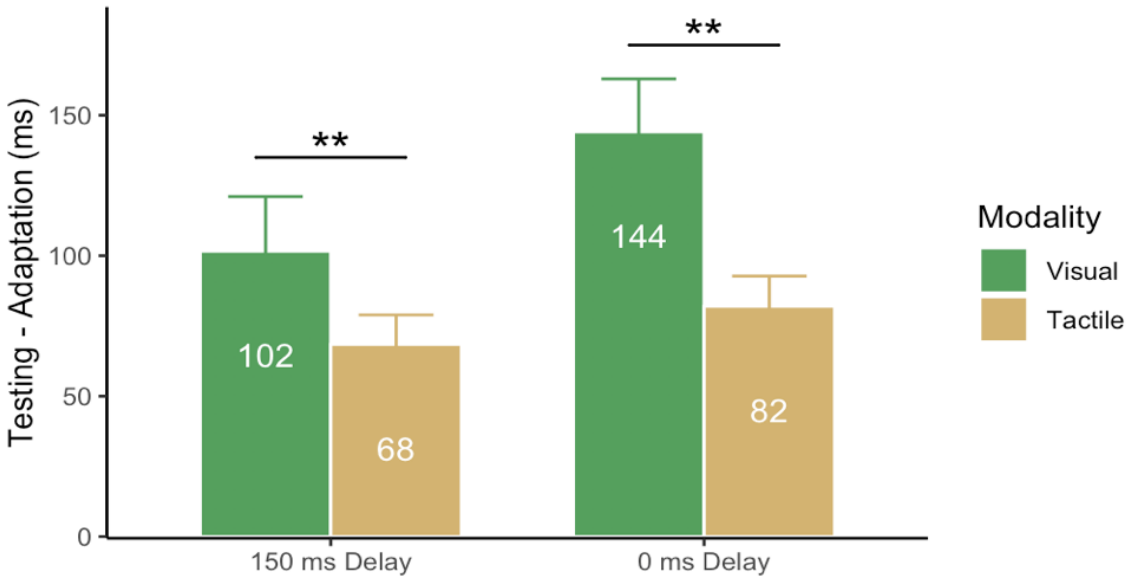

Figure 3. The mean lengthening effect (Testing - Adaptation) for the delayed (150-ms trials only) and synchronized (0-ms trials only) sessions, separated for the visual (green) and tactile (brown) modality. The asterisks mark the significant between-session difference (**: $p < 0.01$).

A two-way (Session: Delayed, Synchronized) × Modality (Visual, Tactile) ANOVA analysis revealed a significant main effect of Modality, $F(1, 36) = 9.94$, $p = .003$, $\eta_g^2 = 0.12$. However, 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. Importantly, the lengthening effects were all significantly

positive ($ts > 5$, $ps < .001$). These results suggest that without accuracy feedback to recalibrate the motor time in the testing phase, the motor reproduction shifted back to its original state, exhibiting a general overestimation consistent with previous findings (Chen & Shi, 2023; Shi, Ganzenmüller, et al., 2013). Interestingly, this reverting was less prominent for tactile than visual reproduction, indicating reproducing tactile durations were relatively more robust in the absence of accuracy feedback.

Sensorimotor Integration in the Absence of Accuracy Feedback

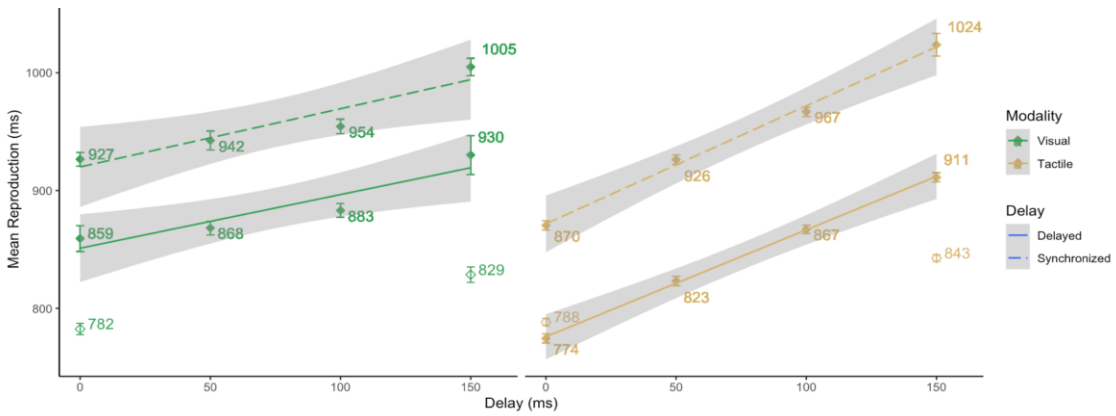

Figure 4. The mean reproduction durations (solid points) in the testing phase as a linear function of delay, separated for the delayed (solid lines) and synchronized (dashed lines) sessions, and Visual (left panel) and Tactile (right panel). The un-filled points indicate the mean reproduction duration in the adaptation phase. The mixed linear regression analysis revealed the slope was significantly steeper for the tactile (0.95) than visual (0.47) sensory feedback.

To quantitatively assess differential weights of action-induced visual versus tactile events in the absence of accuracy feedback, we further conducted linear mixed regression analyses. As stated in Introduction, the sensorimotor integration with delay manipulation can be expressed as Equation (3): $R = F + vD$, where F is the delayed sensory feedback, and D is the delay. Fig. 4 shows the linear trends with the delay manipulations in the testing phase, separated for the visual (green) and tactile (brown) sensory feedback, as well as the adaptation phase of delayed and synchronized session. The trends were consistent within each modality, but the trend with tactile stimuli was steeper than the visual stimuli.

Based on these observations, we conducted linear mixed regression, assuming the delay adaptation

only changed the motor prior, while the linear trend was determined by the weight of the sensory feedback in sensorimotor integration. That is, we conducted the following linear mixed-effects model within each modality:

$$\text{Reproduction Duration} = \beta_0 + \beta_D \times \text{Delay} + \beta_s \times \text{Adaptation}, \quad (4)$$

where Adaptation is a dummy variable (0 - delayed, 1 - synchronized) for the two sessions.

The estimated coefficients and linear models are as follow:

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

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

Both coefficients of Delay were significant, (Visual: $t(18) = 8.44$, $p < .001$, Tactile: $t(18) = 17.87$, $p < .001$). Compared across modalities, the slope was significantly higher with tactile than visual durations ($t(18) = 6.95$, $p < .001$, *Cohen's d* = 2.05, *BF* = 41084.52), indicating that duration reproduction relied more heavily on the action-induced event time with tactile than with visual stimulation in the absence of accuracy feedback.

Comparing the delayed vs. synchronized sessions, delayed adaptation significantly shortened the reproduction in the test session in both modalities (Visual: $t(18) = 3.93$, $p < .001$, Tactile: $t(18) = 9.27$, $p < .001$), consistent with the mean reproduction analysis. The overall shortening was not significantly different between the tactile and the visual modality ($t(18) = 1.550$, $p = 0.15$, *Cohen's d* = 0.47, *BF* = 0.713). These results indicated that both delay duration and adaptation type had significant impact on the reproduction duration. Delay adaptation shortened the action prior, which remained effective during the testing phase.

Taken together, these results revealed a consistent pattern of sensorimotor integration in both visual and tactile reproduction.The reproduction duration increased linearly as the given duration increased, separated from the impact of delayed adaptation, which was also prominent in both experiments.

Discussion

The present study aimed to investigate the impact of accuracy feedback on delay adaptation and the differential aftereffects of delay adaptation in visual and tactile duration reproduction. During

the adaptation phase, one session involved introducing a sensory feedback delay of 150 ms, while the other session had synchronized feedback. Critically, accuracy feedback was provided during the adaptation phase but not in the testing phase. In the testing phase, the delay of the action-induced sensory feedback varied from 0 to 150 ms, allowing us to use linear approximation to estimate the weights of sensorimotor integration in duration reproduction. Our findings indicated that accuracy feedback recalibrated the motor action, although one-third of the delay was still integrated into motor reproduction. In the testing session, recalibrated motor actions remained effective. Additionally, sensorimotor integration revealed that duration reproduction without accuracy feedback relied heavily on the action-induced tactile event than the visual event. The results demonstrate a consistent delay adaptation effect across both modalities, but the extent of adaptation and sensorimotor integration differed between visual and tactile feedback.

Influences of accuracy feedback

During the adaptation, participants received accuracy feedback at the end of each trial to encourage reliance on their motor reproduction rather than sensory feedback. Previous research showed that in the absence of accuracy feedback, motor reproduction was immediately lengthened to match the onset delay upon its initial injection (Ganzenmüller et al., 2012). Our study confirmed that accuracy feedback was critical factor for effectively recalibrating motor action, although participants could not completely 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 indicates that approximately one-third of the delay was integrated into motor reproduction, suggesting that sensory feedback was still factored into the sensorimotor reproduction, consistent with early research (Shi, Ganzenmüller, et al., 2013).

A significant distinction between the adaptation and testing phase was the lack of the accuracy feedback during the testing trials. Consequently, participants had to rely on their own pre-existing prior, recalibrate during the adaptation, and balance the integration weights of the motor duration and action-induced feedback duration. Without the guiding accuracy feedback, as evidenced by the linear mixed models, the session difference (synchronized - delayed) remained to be large: 72 ms for the visual and 103 ms for the tactile modality. This suggests the recalibrated motor prior (shortened action-induced feedback) remained ineffective in the testing phase.

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 motor 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, Ganzenmüller, 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 comparison (probe vs. 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 tactile feedback 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.

One might argue that this heavy reliance on tactile stimulation is due to close proximity setup, as the tactile feedback was closer to the response finger compared to the visual feedback. The spatial proximity has been shown to be a critical factor for multisensory integration (Chen et al., 2018; Koelewijn et al., 2010). However, we speculate that the contribution of spatial proximity, if any, might be relatively minor. On-body touch stimulation is often associated with general defensive action (Yeomans et al. 2002), so we expect that stimulation on other body parts would yield similar findings as stimulation on the response finger. Additionally, on-body touch stimulation often induces higher valence than the neutral visual stimulation, which might contribute to the higher weight of the tactile feedback compared to 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 testing) 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 testing 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 overestimation may arise from divided attention during reproduction. As demonstrated in a previous study (Chen & Shi, 2023) that compared the presence and absence of accuracy feedback, the lack of accuracy feedback lengthened reproduction by 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 testing 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 testing phase lengthened the reproduced duration to equate the perceived duration. As a result, the mean reproduction in the testing 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 varied, 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 examined the effects of delayed sensory feedback on visual and tactile duration reproduction. We observed consistent adaptation effects with accuracy feedback for both modalities, but different afftereffects without accuracy feedback. In the absence of accuracy feedback, tactile reproduction relied more on sensory feedback and ignored the delay between action and sensory feedback, resulting in greater lengthening of reproduction compared to the visual modality. Additionally, overestimation occurred in the absence of accuracy feedback and with the presence of delay. Overall, our findings suggest that temporal delay adaptation is influenced by accuracy feedback and sensorimotor integration. The integration was governed by sensory reliability and weighted differently across modalities, with a higher weight on the tactile feedback than visual feedback.

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