From Action to Time:
The Influence of Attention and Sensorimotor Integration on Time Perception

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Abstract

Embedded within a four-dimensional world, human perception is shaped by the amalgamation of sensory inputs from diverse modalities and motor signals. This synthesis aligns our perception with the fundamental nature of movement in the spatial and temporal dimensions. Attention and action are tightly coupled, exerting a collective influence on the perception of time. This thesis consists of three studies that explore temporal distortions during and after action, providing insights into the roles of attention and multimodal sensorimotor integration. Specifically, Study 1 investigated the effects of saccades on the time perception distortions occuring after saccades and proposed that saccades induced a transient temporal attentional gradient, which brought to light a new view on the duration perception of post-saccadic events. Study 2 explored the general overestimation in duration reproduction, a phenomenon observed in various studies yet remains unresolved, and proposed an account of attentional sharing between the action execution and the monitoring of the passage of time during the reproduction process. Study 3 delved into the delay adaptation across different modalities in a sensorimotor closed-loop action and suggested that the temporal delay adaptation was shaped by the sensorimotor integration based on the sensorimotor reliability, with a higher weight on the tactile modality than the visual modality. In summary, these studies collectively contribute to a deeper understanding of the intricate relationship between attention, action, and time perception, offering novel insights into the mechanisms governing the temporal experiences within the fabric of the multisensory reality.

Contents

Chapter 1

General Introduction

We, as human beings, inhabit a three-dimensional spatial realm, enabling us to sense depth, distance, and spatial connections through our senses. Yet, it is only with the fourth dimension, time, that we can fluidly traverse this three-dimensional expanse. This freedom of movement constitutes the essence of our actions. Our brain integrates all available information from this four-dimensional matrix - including sensory cues across modalities and motor signals - to forster a coherent perception aligned with our action.

When we act, attention surfaces, steering our focus and maintaining cognitive resources to process and prioritize information. Action and attention are closely and inevitably interlinked (Deubel & Schneider, 1996; Nobre et al., 2010; Shepherd et al., 1986). For instance, before starting motor actions, a shift in attention towards the target location is observed in both manual pointing movements (Baldauf et al., 2006) and saccadic eye movements (Deubel & Schneider, 1996; Posner, 1980; Shepherd et al., 1986). Due to the inherent limitations of attention as a cognitive resource, the ability to process sensory information becomes constrained. The distribution of attention across different sensory inputs can lead to a variety of temporal distortions. An attended event seems to last longer than a similar unattended one (Enns et al., 1999; Tse et al., 2004). Attentional focus also accelerates the processing of a primary attended event over unattended peripheral ones, illustrating a spatial gradient in visual attention (Downing, 1988; Mangun & Hillyard, 1988). Furthermore, initial or salient oddball events often feel extended compared to subsequent or standard ones (Kanai & Watanabe, 2006; Pariyadath & Eagleman, 2007; Rose & Summers, 1995).

Imagine a finger stirring water: then ensuing ripples echo the ramifications of actions. A solitary action can redirect attention, sending waves through our temporal perception. By meticulously examining the interplay between action and attention, we can discern potential temporal distortions that arise. Similarly, closely observing the temporal ripples associated with specific actions offers insight into underlying mechanisms of attention. Guided by this logic, this thesis focused on the nexus between action, attention, and time perception. It probes how actions sway attention and vice versa, exploring the interplay of time distortions. Central to this is the sensorimotor integration in time perception. On this ground, we investigated the subsequential temporal distortions induced by the action-induced attentional gradient, as well as the cross-modality sensorimotor integration through temporal discrepancies between action and sensory feedback.

Subsequent sections will first establish the foundation for action-induced time distortions, temporal bias and discrepancy, as well as methods of time perception studies. Following this, the pivotal role of attention gets its due spotlight. In the end, the introduction of the research questions and aims of the thesis will conclude the sections.

1. Time Perception

1.1. General Background

Time is an essential component in daily life. People rely on schedules to organize their day, consult timetables to catch trains, and set alarms to ensure they are timely for appointments. While the objective time on clocks offers precision to our routines, our perception of time, or subjective time, is malleable and varies depending on contexts. For instance, an exhilarating football game may seem to end in the blink of an eye, whereas waiting for a bus can feel interminable. In such scenarios, there is a discord between our perceived time and actual time.

The way we perceive time underpins human cognition and behavior. Unlike other senses rooted in specific sensory organs, time perception arises from a myriad of temporal cues from diverse events that engage the brain (Shi & Burr, 2016). Essentially, our sense of time is multisensory. As such, our subjective assessment of duration is not solely anchored in actual time elapsed but is also swayed by numerous other factors, like our situated environment, attention, emotions, movements, and our prior knowledge (for a review see Matthew & Meck, 2014).

Over past decades, research has highlighted myriad factors that can skew our sense of time. When evaluating time, individuals do not rely solely on the temporal information but also weave in non-temporal aspects (Hornik, 1984). An oddball stimulus, for example, feels lengthier than a regular one (Eagleman, 2008). Background context, such as the prior knowledge about durations can bias current time judgments (Shi & Burr, 2016). Even personal emotional states can color our time perception (Grondin, 2010; Droit-Volet, & Gil, 2009). For instance, Yamada and Kawabe (2011) employed continuous flash suppression to investigate the influence of invisible emotional stimuli on time perception and revealed an unconscious internal clock acceleration impacted by the negative emotions. As Jia and colleagues (2013) noted, event-irrelevant emotional visual stimuli can impact one's judgment in an audio-tactile temporal-order judgment task. Emotion's two fundamental dimensions - arousal and valence - also leave distinct imprints on our time perception. High arousal, negative valence events often seem prolonged, whereas pleasant, low-arousal events feel brief (Shi et al, 2012; Droit-Volet & Gil, 2009).

Actions and intentions hold particular intrigue when exploring timing and time perception. Earlier studies suggested that task-irrelevant actions or movements can affect the sense of time in action (Jia et al., 2015; Sebanz & Lackner, 2007). Voluntary eye movements can cause Chronostasis illusion (also known as 'Stop-clock' illusion), where the initial tick of a clock seems elongated when eyes shift from elsewhere to it (Yarrow et al., 2001). This phenomenon gives the impression that the clock initially momentarily halts before resuming (Yarrow & Rothwell, 2003). Haggard and Clark (2003) showed that the perceived gap between an individual's action and its effect gets shortened, a phenomenon termed intentional binding. This compression of perceived time stems from our innate desire to link causes with effects. In those studies, task-irrelevant actions inadvertently set the action context, thereby influencing our internal sense of time.

1.2. Action-induced Temporal Distortion

Action can induce both time expansion and time compression, akin to two sides of the same coin. There are several representative action-induced temporal distortions, which share overlapped effect periods. However, their distortions were inconsistent, comprising both expansion and compression illusions.

1.2.1. Temporal Compression

A typical time compression effect is reported around saccade (Morrone, Ross, & Burr, 2005). In the standard paradigm, participants were required to make a saccade and then compare two intervals separated by flashing bars. The test interval was presented shortly after presenting the saccadic target with a varied delay while the probe interval was invariably presented 2000 ms later. A time compression of around 50 ms was found from 150 ms before saccade to 150 ms after saccade approximately and maximized around the start of the saccade. It was saccade-specific as no effect was found in the blink and auditory click control conditions. This saccadic time compression was consistent with the saccadic space compression according to previous studies (Morrone, Ross, & Burr, 2005), but, surprisingly, contradicted with the Chronostasis illusion.

1.2.2. Temporal Expansion

The Chronostasis illusion is a typical time expansion illusion, which is also known as the “Stop-clock” illusion. When people make a voluntary saccade toward a clock, the clock seems to stop for a while before ticking for the second. In another word, a short period of time was perceived longer after the saccade. This illusion of time expansion was first reported by Yarrow and his colleagues (2001). A typical paradigm was to show participants several post-saccadic intervals with numeric or graphic stimuli and let them compare the durations of the first post-saccadic interval and the following standard interval (duration discrimination task). The first post-saccadic interval was perceived comparatively longer across participants and various durations (Yarrow et al., 2001; Yarrow, Haggard, & Rothwell, 2004). Such consistent expansion of subjective time was termed as the Chronostasis illusion.

A series of relevant studies were conducted to investigate the characteristics and perceptual mechanisms of the Chronostasis illusion by manipulating variables such as duration and action. This illusion was observed not only with voluntary saccades but also with other actions and across different modalities. For instance, Yarrow and Rothwell (2003) reported manual Chronostasis, which refers to a similar tactile time expansion induced by arm movement. Additionally, a common timing mechanism, rather than a unique visual mechanism, was suggested for the Chronostasis illusion through an auditory study (Hodinott-Hill et al., 2002). Analogous to the dead telephone phenomenon, auditory Chronostasis was observed by comparing the duration of gap intervals between tones during a concentration shift between ears.

One potential account of the perceptual mechanism behind the Chronostasis illusion is the shifted perceptual onset caused by uncertainty regarding the onset of the event (Yarrow et al., 2001, 2004; Yarrow & Rothwell, 2003) . For instance, when the Chronostasis illusion was induced by a saccade, whether the onset of the first post-saccadic interval was between or after the saccade was unclear for the saccade-maker. The onset was believed to shift backward to the onset of the saccade in order to compensate for the gap during saccade (Yarrow et al., 2001). Another proposed explanation for the Chronostasis illusion involves the internal clock theory. According to this theory, the internal clock accelerates due to post-saccadic arousal, resulting in the expansion of perceived duration. However, this explanation is considered less critical compared to the shifted onset account, primarily due to the consistent effects of Chronostasis (Yarrow et al., 2004). In addition, the shift of spatial attention was also deemed to be uncritical for the Chronostasis illusion in the early studies (Yarrow et al., 2001, 2004) but was admitted as cannot be fully ruled out in later studies (Yarrow, 2012).

1.3. Temporal Bias

In addition to the specific action-induced temporal distortions discussed above, there are also systematic temporal biases to consider. The occurrence of systematic errors in magnitude estimation can be attributed to the dynamic process of optimal probabilistic estimation and continuous learning of stimulus statistics (Glasauer and Shi, 2021). One notable example is the central tendency bias, which arises from the utilization and updating of prior information during magnitude estimation (Lejeune and Wearden 2009). Previous studies have demonstrated that incorporating prior experience can introduce this bias, resulting in a shift of the temporal bisection point towards the mean. This bias leads to the overestimation of small stimuli and underestimation of large stimuli when the spacing or distribution of sample intervals is manipulated, which manifests as a flattened slope of the line in data visualization. Building upon these findings, Glasauer and Shi (2021) investigated the relationship between central tendency and sequential dependence in magnitude reproduction. Their results challenged the assumption of static priors and proposed a new unified model that accounts for individual variation in biases by considering sensory precision and beliefs about temporal continuity. The study revealed that individual differences in central tendency and sequential dependence reflect variations in the underlying generative model, which is not static but updated on a trial-by-trial basis.

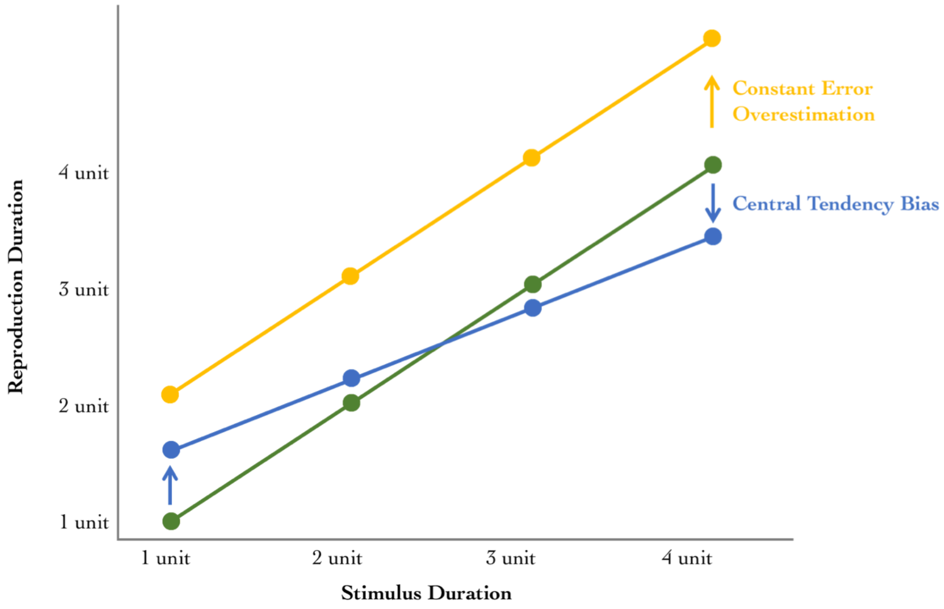

Figure 1. Simulated depiction demonstrating central tendency bias and constant overestimation.

Besides this well-established central tendency bias which leads to changes in the slope, there is also evidence of a constant error contributing to changes in the intercept (Figure 1). One frequently reported constant error is an overestimation observed in the reproduction task. It leads to an upward shift of the intercept while maintaining a constant slope and further induces a leftward shift in the indifference point. For instance, in a reproduction task conducted by Grondin and colleagues (2012), a constant error was observed across the entire range of tested durations (1000 to 1900 ms), when participants indicated interval onset and offset using two space-key presses in response to successive tones representing standard intervals. However, the exact cause of this error formation was not clearly explained. Similarly, Bausenhart, Dyjas, and Ulrich (2014) found a similar overestimation when participants reproduced a standard duration in comparison with a reference duration, particularly when the standard duration was presented in the second position. However, the discussion primarily focused on the differences between reproduction positions, attributing it to a "negative time-order error" where the first interval was underestimated in comparison to the second interval, without providing a comprehensive explanation for this overestimation phenomenon. While previous studies have often reported overestimation as a consistent error, there remains a dearth of investigation and discourse regarding the underlying mechanism driving this phenomenon. It is crucial to investigate whether this constant overestimation stems from experimental randomization protocols that diverge from natural conditions. Based on this understanding, further exploration of the underlying mechanism is warranted.

1.4. Temporal Discrepancy

Despite the action-induced temporal distortion and systematic error in temporal tasks, humans constantly encounter and navigate through abundant temporal information in their daily lives and have to process multiple timing inputs simultaneously. The integration of various sensory and motor temporal inputs is an essential ability to form coherent perception (Buhusi & Meck, 2005; Merchant & Yarrow, 2016). An example of integrating temporal inputs can be observed in the sport of tennis, involving both explicit and implicit timing tasks. When playing tennis, athletes must skillfully coordinate various temporal aspects. They visually track the trajectory of the incoming ball, audibly perceive the sound of the ball being struck, tactually feel the impact and movement of their racket, and execute motor actions to hit the ball with precise timing and force. The actions and sensory inputs from multiple modalities provide crucial temporal information for executing precise shots and ensuring a smooth gameplay experience.

Despite the variability in the nature of tasks and timing across sensory and motor processes, individuals often experience a coherent perception of time when engaged in multisensory inputs during a tennis match. This phenomenon can be attributed to the brain's ability to integrate and process temporal information from different sources, allowing players to anticipate and respond effectively to the dynamic nature of the game. The brain combines all available information to enhance the reliability of temporal estimates, as suggested by the Bayesian inference model (Ernst & Banks, 2002; Shi et al., 2013).

It is important to note that temporal information from multisensory inputs and sensorimotor actions may not always be perfectly synchronized, leading to temporal discrepancies. Temporal discrepancies, such as observing a mismatch between video and sound when watching a live sports event on television, can lead to a sense of cognitive dissonance (Festinger, 1962). As the brain expects the visual and auditory inputs to be synchronized, one may quickly notice a delay between the actual action on the field and its corresponding broadcast on the screen when there is a mismatch between the audio commentary and the visual action. The brain tries to resolve the state of cognitive dissonance induced by the temporal discrepancy through integrating information to construct a unified and cohesive perception of the event.

Interestingly, individuals have the ability to adapt to temporal discrepancies to create a self-consistent interpretation of the world. For example, in a study by Cunningham et al. (2001), participants adapted to a delay in visual feedback during a simulated shooting video game. They were able to adjust to the delay, but their performance significantly declined when the delay was removed. Another study found that participants recalibrated their perception of sensorimotor simultaneity after adapting to an action-feedback delay task (Stetson et al., 2006). Subsequently, when the delay was removed, participants perceived the action effect as occurring before their actions in a substantial number of trials. However, it remains unclear how these adapted discrepancies are incorporated into sensorimotor temporal perception and how it differs across different sensory modalities.

1.5. Methodology in Study of Time Perception

There are multiple types of temporal tasks developed to study how humans perceive time and the underlying temporal processing mechanisms. These tasks allowed researchers to investigate time perception in various contexts and aspects for a variety of purposes. For instance, some tasks test the length of interval directly while some other tasks test the temporal order of the events. The temporal order judgment task is commonly employed to examine perceived temporal order both within and across different sensory modalities. Participants judge the order of two events with manipulated inter-stimulus intervals, focusing on their sequence rather than their duration (Kanabus et al., 2002; Jia et al., 2013). With a specific focus on the perceived duration, the present studies in this thesis applied the duration discrimination and reproduction tasks as stated below.

1.5.1. Duration Discrimination Task and Psychometric Function

The duration discrimination task assesses the perceived duration through presenting participants two intervals for comparison. Either one or both durations of the two intervals vary across trials, and participants judge which interval is longer. In a standard paradigm, the two intervals consist of a reference interval with a fixed duration and a test interval with varied durations, of which participants are not made aware. The presentation of the reference and test intervals can be consecutive or with gaps in between. The order of presenting the intervals is flexible and can be tailored to the specific study aim, without strict guidelines dictating whether the reference interval should precede or follow the test interval.

The task follows a two-alternative forced-choice paradigm, where participants compare the durations of two intervals and indicate which one they perceive as longer (or shorter). The differences between the two intervals can vary from less than 100 ms to several seconds. The test duration is designed with multiple levels, ranging from considerably shorter than the standard reference duration, to equivalent to it, and to notably longer than the standard duration. On this basis, the psychometric function is utilized to determine the transitional threshold between short and long judgments, and to assess the temporal discrimination sensitivity.

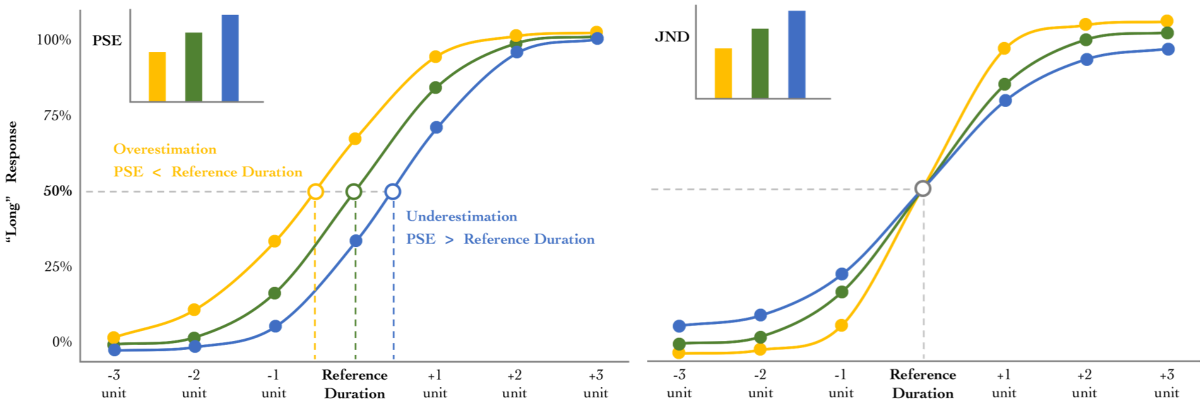

Figure 2. Simulated depiction demonstrating fitted psychometric curves with varied PSEs and JNDs. The curves shift horizontally along the duration axis with different PSEs (left panel). A lower PSE shifts the curve to the left, indicating a tendency to overestimate the test durations, while a higher PSE shifts the curve to the right, indicating a tendency to underestimate the test durations. The steepness of the curve varies with different JNDs (right panel). A smaller JND results in a steeper

curve, indicating better sensitivity to duration differences, while a larger JND results in a shallower curve, indicating more difficulty in discriminating between durations.

To be specific, participants’ responses indicating the longer interval are converted into mean proportions of "long" responses for each duration level. As the difference between the test and reference durations increases, participants' certainty in their responses strengthens, leading to more extreme proportions (approaching 0 and 100 percent). The psychometric curve is fitted with the lapse and guess rate and appears to be the representative S-shape (Figure 2). The two key parameters were obtained accordingly, the point of subjective equality (PSE) and the just-noticeable difference (JND). The PSE measures the transitional threshold between the short and long judgments, while the JND measures the temporal discrimination sensitivity.

This type of method allows researchers to accurately assess the perceived duration differences, and therefore, is used extensively to explore temporal distortions. It is worth highlighting that this task is purely perceptual, devoid of any action involvement. In other words, participants exclusively perceive the duration during the presentation of stimuli without any intervening actions. Such direct comparison method facilitates the detection and sensitivity of small differences at the millisecond level within short intervals. For instance, in representative Chronostasis illusion studies, reference duration can be set at 500 ms or 1000 ms, while test durations vary between 100 - 900 ms or 400 - 1600 ms (Yarrow et al. 2001; Yarrow et al. 2004). Moreover, a 50 ms compression was accurately detected within a 300 ms time window in the saccadic comparison effect (Morrone et al., 2005). Overall, the duration discrimination task is practical for estimating perceived duration and detecting temporal differences.

1.5.2. Duration Reproduction Task

The duration reproduction task provides an alternative method for measuring perceived duration. Participants are presented with a target duration and are required to reproduce it directly (Ganzenmüller, Shi, & Müller, 2012). The reproduction approaches varied across studies. One type of approach involves the unfilled interval method, which achieves reproduction through segmentation. After presenting the target interval, participants either stop a self-started test interval when it is perceived to be as long as the target interval, or start and stop a test interval to achieve an equivalent duration. This type of reproduction measures the duration of an interval with its onset and offset.

Another reproduction approach involves filled interval reproduction. Participants reproduce the target interval through tasks such as continuous button press, which produces an equivalent filled test interval. In contrast to the purely perceptual duration discrimination task, this filled interval reproduction task hinges on participants' action of reproducing the duration. The reproduction process encompasses two subtasks, executing the reproduction action and monitoring the passage of time. The duration reproduction task serves as a valuable method for gathering insights into the neural mechanisms underlying interval timing. Taking into account the sensory and motor temporal discrepancy discussed earlier, the filled interval reproduction task offers an effective approach for integrating sensory and motor information within a single paradigm, thereby facilitating the investigation of sensorimotor integration.

2. The Role of Attention and Action

Attention and motor action are closely intertwined and likely inseparable (Deubel & Schneider, 1996; Nobre et al., 2010; Shepherd et al., 1986). Prior to the initiation of the action, attention is directed towards the target location, for both saccadic eye movements (Deubel & Schneider, 1996; Posner, 1980; Shepherd et al., 1986) and manual pointing movements (Baldauf et al., 2006). Additionally, the allocation of attention can result in various distortions of time perception. For example, when an event is attended to, it is perceived as lasting longer than an unattended event of the same duration (Enns et al., 1999; Tse et al., 2004). Moreover, a specifically attended event is processed more rapidly than surrounding unattended events, indicating a spatial gradient of visual attention (Downing, 1988; Mangun & Hillyard, 1988). Furthermore, the initial event or an unexpected event that captures attention is perceived as longer in duration compared to subsequent events (Kanai & Watanabe, 2006; Pariyadath & Eagleman, 2007; Rose & Summers, 1995).

2.1. Temporal Attentional Gradient in Action-end Effect

Considering the temporal compression and expansion effects discussed in the previous section, one notable difference is the contrasting effect on perceived time. The compression effect is evident up to 150 ms after the saccade, with no expansion observed up to 500 ms after saccade, whereas the Chronostasis illusion reveals an apparent expansion of the post-saccadic first event. The role of attention had been discussed, however, with no sufficient finding for excluding or specifying the role of attention (Morrone et al., 2005). In general, the underlying causes of the differences are still unknown. Morrone and colleagues conceded that “Chronostasis may be related in some way to the compression and inversion effects reported here, but the connection is not obvious” (Morrone et al., 2005, p. 953).

The primary emphasis in most Chronostasis studies has been on examining sensory mechanisms at a lower level to explain (perisaccadic) Chronostasis, with a deliberate avoidance of explanations involving attentional mechanisms (Yarrow, 2010; Yarrow et al., 2001). The systematic discussion of attention's role in relation to Chronostasis was lacking, with only limited evidence available concerning the involvement of spatial attention (Yarrow et al., 2001, 2004, Yarrow, 2012). For instance, Georg and Lappe (2007) conducted a comparison of stimulus presentation locations at the saccade landing position to investigate the relationship between attention and saccade-induced Chronostasis. They found that Chronostasis was primarily observed at the saccade landing position, where attention was presumed to be focused (cf. Deubel & Schneider, 1996), rather than at the midway point on the saccadic trajectory. In contrast to this, Yarrow (2010) reported that Chronostasis remained unaffected when participants judged the duration of letter probes that did not appear at the saccade landing position. Furthermore, Knöll et al. (2013) systematically varied event onset, in addition to location (saccade start-, mid-, and end-position), and discovered that Chronostasis persisted for events occurring up to 50 ms after the saccade offset, with a similar pattern observed across all positions. However, no conclusive evidence emerged to either dismiss or precisely define the specific role of attention in relation to Chronostasis.

Most studies investigating Chronostasis concentrated on the temporal distortion of the first perisaccadic event, which is sufficient for studying the Chronostasis effect on the basis of the common shifted perceptual onset account. However, the extent to which this action-end effect lasts beyond this first event remains uncertain. Whether saccades can induce additional distortions is crucial for understanding the role of attention in the Chronostasis.

Similar to the spatial gradient of attention proposed by Mangun and Hillyard (1988), it is conceivable that goal-directed actions could engender a temporal gradient. Specifically, allocating attentional resources to the initial event may restrict the resources available for processing subsequent events, resulting in an uneven distribution of attention across time. In a similar vein, this bears resemblance to the well-known "attentional blink" phenomenon, where individuals often struggle to process a second target that immediately follows a first target (Duncan et al., 1997; Shapiro et al., 1997). This difficulty is believed to stem from the engagement of attentional and/or working memory resources by the initial target, rendering them unavailable for encoding the second target. Importantly, it is worth mentioning that the attentional blink phenomenon primarily highlights a constraint in attentional selection pertaining to the targets, which does not inherently necessitate an explicit motor action. For instance, the response to the first target can be verbal and delayed until after the completion of the visual sequence comprising both target and non-target events.

Referring to the Chronostasis experiments, the attentional blink phenomenon can potentially contribute to the first interval overestimation. This is achieved by influencing the timing of the second interval, particularly when the two intervals are closely spaced in time. The timing of the first interval is paused at the signal indicating the first interval offset and the second interval onset. The recorded time stored in working memory is later used for comparison with the duration of the second interval. The demanding nature of this attentional process can potentially disrupt the timing of the second interval, resulting in the loss of internal clock ticks and consequently leading to an underestimation of the duration of the second interval. This, in turn, contributes to the relative overestimation of the first interval.

Another explanation, distinct in nature yet seemingly similar on the surface, involves the concept that the saccadic action (i.e., eye movement toward the event being timed) generates a temporal gradient of attention, where attention influences the gate capacity through which pulses generated by the internal clock can pass (as proposed by Zakay and Block's attentional gate theory in 1996). Such a saccade-induced temporal gradient would cause an expansion of the first interval (more clock ticks) and a compression of the second interval (fewer clock ticks), resulting in an underestimation of the duration of the second event. Consequently, both the attention-blink and the saccade-induced temporal-gradient accounts indicate that when the reference interval for duration judgments is situated at the second temporal position, the underestimation contributes to perisaccadic Chronostasis, which corresponds to the overestimation of the duration of the first event.

2.2. Attentional Sharing and Switching in Reproduction

Given the aforementioned constant overestimation observed in the reproduction task, it is imperative to consider the role of attention allocation. The unique characteristics of the duration reproduction task, which distinguish it from other timing tasks, is incorporating an action component. While the encoding process remains similar among timing tasks, involving initial perception and independent encoding of temporal information, the decoding process becomes more demanding in reproduction tasks. In contrast to duration discrimination tasks that focus on comparing encoded temporal information and making temporal judgments, the duration reproduction task necessitates the estimation of perceived duration alongside the execution of a motor response to reproduce that duration. Consequently, the reproduction task encompasses two synchronized components: the action for reproduction and the progression of time during the reproduction process.

Expanding on this groundwork, it becomes imperative to investigate the allocation of attention between the two subtasks during the reproduction process in order to gain deeper insights into the occurrence of constant overestimation. Both the reproduction action and the passage of time during reproduction require attentional resources, which are inherently limited. This allocation of attention between the subtasks can lead to overestimation. One conceptualization suggests attention switching between the two subtasks to monitor the reproduction task, resulting in a constant overestimation independent of the standard duration. Alternatively, the attentional sharing account proposes that when attention is shared across the subtasks to monitor reproduction, the limited attention resources diminish monitoring of the internal clock, resulting in the loss of counting time. As a compensatory response, the reproduction duration becomes longer, leading to a constant overestimation. Unlike the absolute overestimation postulated by the attention switching account, the attentional sharing account suggests a ratio-based overestimation. The degree of overestimation maintains a consistent ratio relative to the reproduced duration: constant for the same standard duration, increasing for longer reproduced durations, and decreasing for shorter reproduced durations.

By understanding how attention is distributed between the reproduction action and the passage of time, the mechanisms underlying the observed overestimation can be unraveled. This investigation will shed light on the intricate relationship between attention allocation and the constant overestimation, paving the way for a more comprehensive understanding of the underlying cognitive processes involved in duration reproduction tasks.

3. Aim of thesis

Building upon these backgrounds, this thesis consists of three studies to investigate the role of action and attention in time perception.

The perception of time can be distorted by saccadic actions. For example, in the phenomenon of chronostasis, also known as the stopped-clock illusion, the first event after a saccade appears to last longer. Previously, only the events occurring immediately after the saccades were studied and the impact of saccades on subsequent events has never been explored. Furthermore, the predominant focus in most Chronostasis studies has been on low-level sensory mechanisms to account for the phenomenon, with attentional mechanisms being deliberately overlooked (Yarrow, 2010; Yarrow et al., 2001). Study 1 investigated the effects of saccades on the time perception distortions occuring after saccades and attentional mechanisms associated with it. It examined the action-induced temporal distortion (action-end effect) and proposed the saccade-induced temporal attentional gradient with a specific focus on the duration compression of the post-saccadic second event.

The proposed account of saccade-induced temporally uneven gradient of attention theoretically hypothesized an expansion of the first post-saccade event and a compression of the second post-saccade event, which led to an underestimated perceived duration of the second post-saccade event. To tackle this, Study 1 employed the duration discrimination task in two experiments to compare the subjective estimates of the time of first and second post-saccadic events (with fixation conditions as control). In Experiment 1, the position of the reference interval was varied to be either as the second post-saccadic event or a delayed event after a long gap. A larger Chronostasis effect was expected to be observed when the first post-saccadic was compared to the second post-saccadic event. Experiment 2 compared both first and second post-saccadic events to one identical delayed reference event after a long gap and expected to observe an underestimation of the second post-saccadic event.

The general overestimation tendency in the duration reproduction task has been observed in many studies, however was often treated as an incidental error, leaving the underlying mechanisms remaining unclear. Study 2 employed the Adaptation-Test paradigm to investigate the mechanisms underlying this general overestimation in the temporal reproduction task with a specific focus on the role of attention. Given the unique inherent nature of the reproduction task, the involvement of action, Study 2 involved two experiments to address the two potential factors possibly contributing to this general overestimation. Experiment 1 tackled the influence of different timing processes between sensory and motor timing through manipulating the temporal discrepancy between the reproduction action and the action output (shortened / synchronous visual feedback). Experiment 2 focused on distinguishing the two attentional accounts, specifically, whether attention is shared or switched between the two subtasks of reproduction (the reproduction action and monitoring the passage of time), through varying the test duration and the presence of accuracy feedback. The overestimation was hypothesized to be constant for different test duration under the attentional switching account and to vary with constant ratio under the attentional sharing account.

The execution of brief actions frequently incorporates various temporal cues that may not consistently align with one another. In a fundamental action-effect relationship, there is often a delay in the manifestation of the effect. However, how our brain integrates this delay across diverse modalities within a sensorimotor closed-loop action remains relatively less explored. By gaining a deeper understanding of the integration of motor and multisensory timing, Study 3 employed the Adaptation-Test paradigm together with the temporal reproduction task on the basis of Study 2, manipulating the delayed sensory feedback in both visual and tactile modalities, to explore the aftereffects of such delay adaptations. A greater incorporation of delay was anticipated in the tactile reproduction than visual reproduction, manifesting as a more pronounced increase of reproduction duration as the delay increased.

Chapter 2

Study 1

The saccade-induced temporal attentional gradient: Duration compression of the post-saccadic second event

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https://github.com/msenselab/saccade-induced-temporal-grading

Abstract

Rapid eye movements can distort our perception of time, as evidenced by the phenomenon of Chronostasis, where the first event following a saccade appears to last longer than it actually does. Despite extensive research on this phenomenon, the effect of saccades on post-saccadic events subsequent to the first one has never been investigated. To address this, in the present study we compared the subjective estimates of the time of first and second post-saccadic events, with fixation (i.e., no-saccade) conditions as controls. We found saccadic eye movements not only to affect the perceived duration of the first post-saccadic event (Chronostasis), but also that of the second event: when the second event immediately followed the first, it was subjectively compressed, And when the second event was used as the (constant) reference interval, Chronostasis was enhanced. Remarkably, the compression effect persisted even when potential “attentional-blink”-induced processes, that might affect timing at the transition from the first to the second event, were eliminated. To explain our findings, we propose that saccades induce a transient temporal attentional gradient that results in an overestimation of the first and an underestimation of the second interval when the two intervals are temporally (near-) contiguous.

Keywords: Chronostasis, time distortion, attentional blink, attentional gradient

Introduction

Subjective time is sensitive to various types of contextual modulation. When becoming engrossed in reading, time seems to fly by. Actions, such as pressing a key or catching a ball, can also affect the timing of subsequent events. One classic example of this is the stopped-clock illusion, also known as Chronostasis (Yarrow et al., 2001): when making an eye movement to look at a ticking clock, the second hand appears to stop momentarily before continuing to move, and the first second after the landing of the eye is perceived as longer than the following seconds (Knöll et al., 2013; Yarrow, 2010; Yarrow et al., 2001, 2004). In a typical Chronostasis study, participants are presented with a digital counter (initially set to ‘0’) in the visual periphery, to which they have to make a voluntary saccade. Immediately after the saccade lands on the counter, it begins incrementing (‘1’, ‘2’, …), where the duration for which each digit stays on represents an interval. The first duration, the test or ‘target’ interval, is variable, while the subsequent duration, the ‘reference’ interval, is fixed. Participants judge whether the test interval is longer or shorter than the reference interval. One common account of the Chronostasis illusion is that saccadic eye movements create retinal blur and give rise to saccadic suppression, resulting in uncertainty as to the onset of visual events (e.g., interval onsets). To deal with this, the visual system simply assumes that the post-saccadic image has remained constant throughout the saccade, that is: the event onset is antedated to the saccade onset, giving rise to an apparent expansion of the event (Yarrow et al., 2004).

Actions can influence the perception of time not only by causing a time expansion, but also by causing compression. For instance, Morrone and colleagues (2005) observed that the duration of a short interval during a saccade is perceived as shorter than its actual duration. They attributed this to a slowdown of the neural clock during saccade execution, which is at variance with the explanation of Chronostasis advocated by Yarrow and colleagues (2004). At present, there is no unified account of time-expansion and -compression phenomena, despite several attempts to formulate such an account (e.g., Georg & Lappe, 2007; Knöll et al., 2013). Morrone and colleagues conceded that “Chronostasis may be related in some way to the compression and inversion effects reported here, but the connection [to saccade-induced compression] is not obvious” (Morrone et al., 2005, p. 953). To disentangle these apparently opposing effects, Knöll and colleagues (2013) systematically investigated the spatio-temporal topography of Chronostasis. They found that, rather than being limited to the target location of the saccade, overestimation also occurred for peri-saccadic events (with an onset from 100 ms before to 50 ms after the saccade) at the initial fixation location or positions midway on the saccadic path. Chronostasis could even be induced by a reduction of stimulus visibility (by means of a rapidly flippable mirror in front of participants' right eye, mimicking the visual effect of saccadic movement) in the absence of a saccade. This led Knöll et al. to argue that overestimation of the duration during the perisaccadic period is "a passive result of how the time of a stimulus onset is predicted by the visual system in general" (Knöll et al., 2013, p. 64).

Most studies of Chronostasis have focused on low-level sensory mechanisms to account for (perisaccadic) Chronostasis, deliberately avoiding explanations in terms of attentional mechanisms (Yarrow, 2010; Yarrow et al., 2001). In part, this was based on finding that Chronostasis was little affected by whether or not participants had to make a voluntary shift of attention, in response to an arrow cue, to the target location before they executed the saccade (Yarrow, 2010; Yarrow et al., 2001). However, attention and motor action are tightly, and likely obligatorily, coupled (Deubel & Schneider, 1996; Nobre et al., 2010; Shepherd et al., 1986): attention is shifted toward the target (location) of the motor action prior to the actual commencement of the action, and this is the case with both saccadic eye movements (Deubel & Schneider, 1996; Posner, 1980; Shepherd et al., 1986) and manual pointing movements (Baldauf et al., 2006). Also, allocation of attention can lead to various time distortions. For instance, an attended event is perceived as lasting longer than an unattended event of the same duration (Enns et al., 1999; Tse et al., 2004). Also, a focally attended event is processed faster than unattended events in its vicinity, consistent with a spatial gradient of visual attention (C. J. Downing, 1988; Mangun & Hillyard, 1988). Furthermore, the first event or an oddball event that captures attention is perceived as longer than subsequent events (Kanai & Watanabe, 2006; Pariyadath & Eagleman, 2007; Rose & Summers, 1995). To examine the relationship between attention and saccade-induced Chronostasis, Georg and Lappe (2007) compared the location of stimulus presentation at the saccade landing position with that at the midway point on the saccadic trajectory. Choronstasis was found to be prominent only at the saccade landing position, where attention was assumed to be focused (cf. Deubel & Schneider, 1996), rather than at the midway position on the saccadic trajectory. At variance with this, Yarrow (2010) reported Chronostasis to be unchanged when observers judged the duration of letter probes that did not appear at the saccadic landing position. Also, systematically varying event onset (in addition to location: saccade start-, mid-, and end-position), Knöll et al. (2013) found Chronostasis to be evident for events that occurred as late as 50 ms after the offset of the saccade (with a similar profile for all positions).

While most studies on Chronostasis have focused on the time distortion of the first perisaccadic event, it remains unclear whether saccades can cause further distortion beyond this event. Analogously to the spatial gradient of attention (Mangun & Hillyard, 1988), goal-directed actions may induce a temporal gradient: allocating attentional resources to the first event may limit the amount of resources available for processing subsequent events, leading to an uneven distribution of attention over time. In some sense, this is similar to the classic ‘attentional-blink’ phenomenon: participants are typically poor at processing a (second) target that follows a first one with little delay (Duncan et al., 1997; Shapiro et al., 1997) – which is attributed to attentional, and/or working-memory, resources being engaged by the first target and so being unavailable for encoding the second target. Of note, though, the attentional blink reflects a limitation in target-related attentional selection, which in itself does not necessarily require an overt (motor) action (e.g., responding to target 1 may be verbal and delayed until after the end of the visual stream of target and interspersed non-target events). In Chronostasis experiments, blink-type processes may actually contribute to the overestimation of interval 1, by impacting the timing of interval 2, especially if the two intervals are temporally contiguous. Upon the signal indicating the end of interval 1 (and the start of interval 2), the timing of interval 1 must be stopped and the recorded time (or some trace of the whole interval) stored in some sort of working memory for comparison with the second interval. This attention-demanding process may interfere with the timing of interval 2, for instance causing a loss of internal-clock ticks and thus leading to an underestimation of the second interval (thus contributing to the relative overestimation of interval 1). Another, on the surface similar but fundamentally different, conceptualization would be that the saccadic action (i.e., the eye movement to the to-be-timed event) creates a temporally uneven gradient of attention, where attention influences the capacity of the gate which pulses generated by the pacemaker pass through (see, e.g., the attentional gate theory of Zakay & Block, 1996a). Such a saccade-induced temporal gradient would then lead to an expansion of interval 1 (more clock ticks) and a compression of interval 2 (less clock ticks), both giving rise to an underestimation of the second event’s duration. Consequently, with both the attention-blink and the saccade-induced temporal-gradient accounts: if the reference interval for duration judgments is placed at the second temporal position, the underestimation may contribute to perisaccadic Chronostasis, that is, overestimation of the duration of the first event.

On this background, we conducted two experiments to investigate saccade-induced duration distortions that occur beyond the post-saccadic first interval, with a focus on the post-saccadic second interval. To ensure comparability with standard Chronostasis studies, we employed essentially the same paradigm, but critically, in Experiment 1, we varied the positioning of the reference interval, which could either immediately follow the test interval (No-Gap condition) or be delayed by two seconds (Gap condition). We expected Chronostasis to be increased when the reference follows the test interval without gap, which would be consistent with both accounts sketched above. In Experiment 2, we directly compared the first or, respectively, second interval after the saccade to a fixed reference interval temporally remote from the saccade. Given that the reference interval is separated in time from both the first and the second test interval, the timing of the reference interval should not be affected by an 'attentional blink'. However, if saccades induce an uneven temporal attentional gradient, the second post-saccadic event should be underestimated relative to the reference event – consistent with account 2 above.

Experiment 1

Methods

Participants

Twenty-one health participants, all with normal or corrected-to-normal vision, were recruited (mean age: 26.0 years; 9 females and 12 males). The sample size was determined based on previous studies (Morrone et al., 2005; Yarrow et al., 2001), which had an average of 16 (range: 4 to 30) participants. To have sufficient power with a similar design, the sample size was increased to 21 participants. Participants were not aware of the purpose of the experiment. The study, including Experiment 1, was approved by the Ethics Committee of the LMU-Munich Faculty of Psychology and Pedagogics. Participants provided informed consent prior to the experiment, and were compensated at a rate of 9 Euro per hour for their service.

Apparatus

The experiment was conducted in a quiet and dark laboratory cabin. Participants sat in front of a display monitor (ViewPixx LCD, VPixx Technologies Inc.; screen refresh rate: 120 Hz), with a viewing distance of 60 cm maintained by a chinrest. Their eye movements were tracked and recorded by an EyeLink 1000 system (SR Research Ltd.), with a sampling rate of 1000 Hz. Behavioral responses were collected via a standard keyboard. The experimental program was coded in Matlab with the PsychToolbox (Brainard, 1997; Pelli, 1997) and the Eyelink toolbox (Cornelissen, Peters, & Palmer, 2002).

Stimuli and Procedure

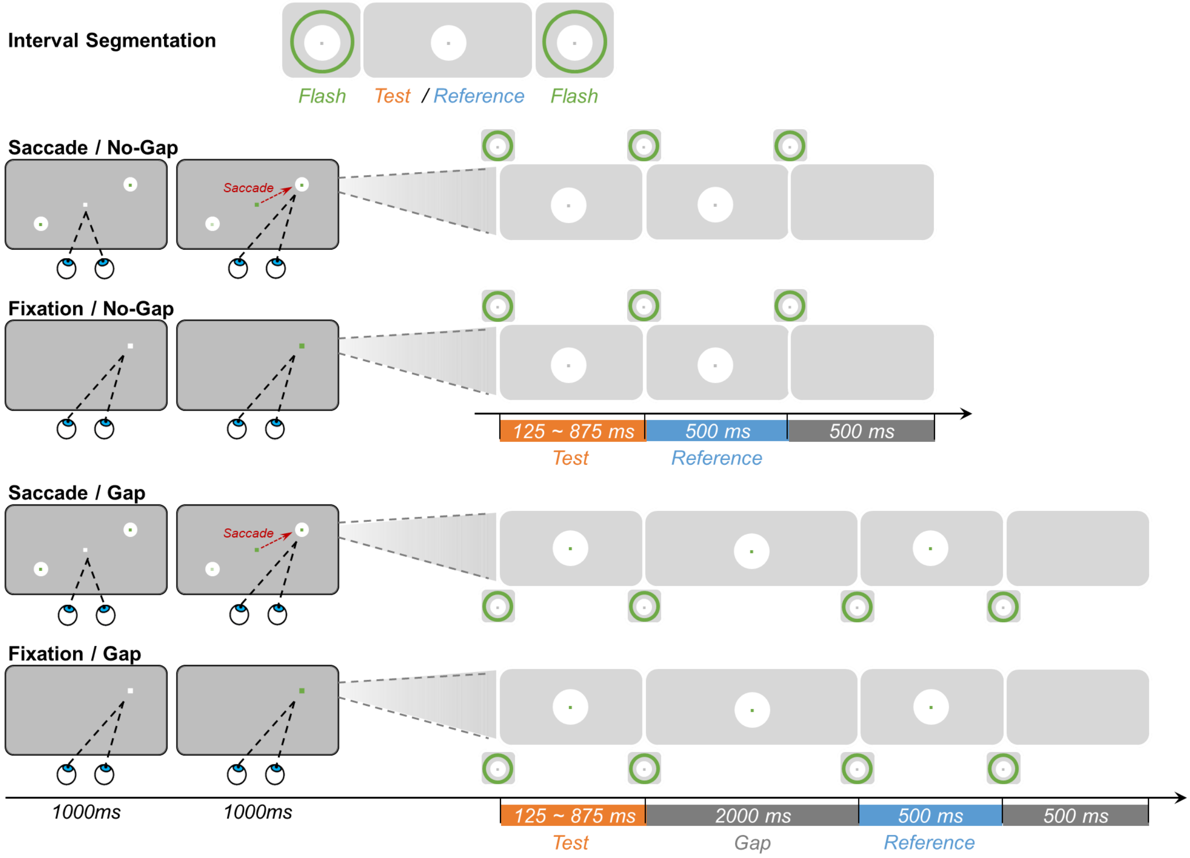

Fig 1. Schematic illustration of the procedure of Experiment 1. Experiment 1 comprised four blocked conditions: Saccade/No-gap, Fixation/No-gap, Saccade/Gap, and Fixation/Gap. The top row illustrates the interval segmentation for all conditions. In the bottom four rows, the left panels show the displays for the ‘eye-movement’ phase at the start of each trial (separately for the Saccade and Fixation conditions); and the right panels show the subsequent stimulus changes in central vision for the interval-comparison phase (separately for the Gap and No-Gap conditions). In the Saccade conditions (1st and 3rd row), participants fixated a central white marker dot, which (after 1000 ms) turned green, cueing a saccade to one of the two peripheral disk locations. Landing on the saccade target triggered the interval-comparison phase. In the Fixation conditions (2nd and 4th row), participants fixated the dot in one corner of the screen, which turned green after one second. In the interval-comparison phase (right panels), brief (25-ms) flashes of concentric green rings

demarcated the test and reference intervals. In the No-Gap conditions (upper two rows), three consecutive flashes demarcated the test and reference intervals, whereas in the Gap conditions (lower two rows) four flashes demarcated the test, a gap, and the reference interval, respectively. Participants indicated which interval (the test or the reference interval) was longer by pressing a corresponding button.

There were two saccade and two fixation conditions (see Fig. 1). In the saccade conditions, participants had to make a voluntary saccade, from a central white fixation dot (size: 0.1° of visual angle; luminance: 68 cd/m^2), toward one of two possible locations indicated by two white disks (1°, 68 cd/m^2). The disks were located diagonally opposite relative to the display center (randomly, either one left-down and the other right-up or, respectively, one left-up and the other right-down, at eccentricity of 10°), and which one of the two disks the (voluntary) saccade was made to on a given trial was chosen by the participant. A trial started with the central fixation marker (on a dark gray background, 5 cd/m2), prompting the participant to fixate the marker for 1 s (with a spatial-error tolerance of ±2° of visual angle). The dot then changed into green, providing the cue to execute the saccade. Once the eyes landed on the target dot, the irrelevant disk on the opposite side was extinguished immediately to minimize any potential distractions. At the chosen location, a green concentric ring around the target disk (30 cd/m^2) was flashed for 25 ms, indicating the start of the test interval. Following a randomly varying interval (duration selected from 125, 250, 375, 500, 625, 750, and 875 ms), a second flash (of a green ring around the disk) marked the end of the test interval. In the Saccade/No-gap condition (Fig 1, top row), the flash marking the offset of the test interval also indicated the onset of the (fixed-length) reference interval. In the Saccade/Gap condition, by contrast, a third flash was presented after a constant, 2000-ms gap to mark the onset of the reference interval (Fig 1, third row). In all conditions, the final flash indicated the end of the reference interval. Then, after a blank interval of 500 ms, participants were prompted with the displayed question “which interval lasted longer: the first or the second interval?”. Participants had to make a two-alternative forced-choice (2AFC) by pressing the left or right arrow key for the first or, respectively, the second interval as having been perceived as longer. Each test interval was repeated 20 times, in random order with the other test intervals.

To distinguish the time distortion induced by saccadic action, two baseline Fixation control conditions were introduced: one with and the other without a gap (as shown in the second and fourth row of Fig 1). In these conditions, participants were required to fixate a single dot without making any eye movements. The position of the dot was randomly chosen from the (four) possible landing locations in the saccade conditions. Participants were instructed to maintain fixation on this location throughout the entire trial. After one second, the color of the dot changed from white to green, indicating that the test and reference intervals would 'soon' be presented. Similar to the Saccade conditions, a white disk appeared (with the green dot staying on in the center) after 1000 ms, roughly matching the time taken for selecting the target disk and making a saccade to it in the Saccade conditions. The subsequent sequence of events was then the same as in the saccadic conditions.

During each trial, participants' eye movements were monitored. In the Fixation conditions, they had to keep their gaze within a specific area around the fixation marker (spatial-error tolerance of ±2° of radius) for the entire duration of the trial. In the Saccade conditions, they had to make the correct saccade towards the target and then maintain fixation within the designated area. Trials on which the participant blinked or fixated outside the designated area were considered invalid and immediately terminated, accompanied by a warning beep (5000 Hz, 31 Db) for 100 ms. Such failed trials (which occurred, on average, in 9.18%) were randomly retested at the end of each block to ensure that all conditions had an equal number of 140 valid trials.

Together, the experiment included four combinations of conditions, based on two actions (Saccade vs. Fixation) and two reference types (No-gap vs. Gap). These conditions were tested in blocks, with the order of four blocks randomly assigned to each participant but counterbalanced across participants. Henceforth, the four conditions will be referred to as Saccade/Gap, Saccade/No-gap, Fixation/Gap, and Fixation/No-gap, respectively. The entire experiment lasted approximately two hours, with participants taking breaks between blocks as needed.

Prior to the formal experiment, participants completed two training blocks (Saccade/Gap and Fixation/No-gap conditions) to become familiar with the tasks. Each training block included 20 test intervals (100 and 1000 ms, not included in the formal test), with the standard reference interval of 500 ms. To help participants understand the task, accuracy feedback was provided at the end of each trial, in the form of a warning beep (2000 Hz, 43 Db, 100 ms) upon an incorrect response (no such accuracy feedback was provided during the format test session). The formal experiment started when the accuracy rate was above

80%, otherwise, an additional round of training was added.[1]

Data Analysis

The ‘First’ vs. ‘Second’ responses (to the question which of the two intervals was longer) were transformed into ‘Longer’ vs. ‘Shorter’ judgments of the test interval relative to the reference interval. The mean proportion of ‘Long’ responses for each test interval was then calculated for each condition. Psychometric curves were estimated using the R package QuickPsy (Linares & López-Moliner, 2016) for each participant in each condition, with lapse and guess rates taken into account (the mean estimated lapse rate was 0.1 in Experiment 1, which was then taken as a reference for Experiment 2). The psychometric curves allowed us to obtain two key parameters: the point of subjective equality (PSE) and the just-noticeable difference (JND). The PSE indicates the transition threshold between short and long judgments, while the JND provides an index of temporal discrimination sensitivity. Finally, these parameters were examined in repeated-measures analyses of variance (ANOVAs) with the factors Reference Timing (with vs. without Gap) and Action (Saccade vs. Fixation).

Results and Discussion

Experiment 1 examined whether presentation of the fixed reference interval immediately following (vs. following with a delay) the variable test interval would enhance Chronostasis. Fig. 2A depicts the psychometric curves for one typical participant, with each curve representing the ratio of “long test interval” responses relative to the reference. A lower point of subjective equality (PSE) than the actual reference duration (500 ms) indicates an overestimation of the test interval, meaning that a shorter interval would be required to match the standard. The mean PSEs (with associated standard errors, ± SE) were 415 (± 21), 460 (± 14), 441 (± 18), and 496 (± 15) ms for the Saccade/No-gap, Saccade/Gap, Fixation/No-gap, and Fixation/Gap condition, respectively (Fig 2B).

The difference between the Saccade and Fixation conditions was significant, $F(1, 20)$ =

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[1] Participants who failed to pass the accuracy criterion after two rounds of training, as well as those whose eyes could not be reliably tracked by the Eyelink system (e.g., because they wore glasses), did not proceed to the formal experiment. Also, a number of participants exerted their right to quit the experiment without completing the total number of trials, stating mainly the demandingness of the task and tiredness as a reason. They were all nevertheless paid for their service at the standard rate. Overall, this led to the loss of 7 participants in Experiment 1 and 8 in Experiment 2.

5.64, *p* = .028, η_g^2= 0.04, with a reduction of 31 ms for the Saccade conditions, evidencing Chronostasis (Yarrow et al., 2001). The main effect of Reference Timing was significant, *F*(1, 20) = 6.41, *p* = .020, η_g^2 = 0.09: the test interval was perceived as longer when the reference immediately followed the test interval (No-gap condition), compared to when there was a 2-second gap between the two intervals (Gap condition). The Action × Reference Timing interaction was non-significant, *F*(1, 20) = 0.15, *p* = .703, η_g^2= 0.001.

For follow-up analysis, we conducted t-tests (two-tailed, adjusted for multiple comparisons) to examine whether the PSEs were smaller than the actual, 500-ms reference. The results revealed the PSEs to be significantly smaller in the Saccade/Gap condition (*t*(20) = -2.83, *p* = .014) and in both No-Gap conditions (Fixation: *t*(20) = -3.25, *p* = .008, Saccade: *t*(20) = -4.04, *p* = .003); however, the PSE was close to the actual 500 ms in the Fixation/Gap condition (*t*(20) = -0.28, *p* = .784). These results are indicative of a general tendency to (relatively) underestimate the second (i.e., reference) interval when it immediately follows the first (i.e., test) test interval.

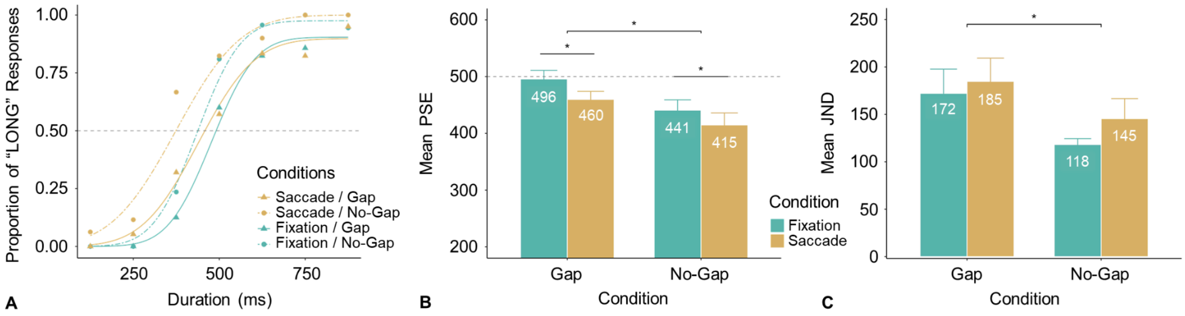

Fig 2. Results from Experiment 1. (**A**) Typical example of behavioral responses (dots) and fitted psychometric curves from one participant. Mean PSEs (**B**) and JNDs (**C**), and associated standard errors (SEs), for the four conditions, across all participants. The dashed horizontal line in (**B**) marks the reference interval (500 ms). The smaller the PSE, the more the dilation of the test interval, as it would require a shorter (test) duration to be perceived as long as the standard (reference) duration. (*: p < .05).

The mean JNDs (± SE) were 145 ± 21, 185 ± 24, 118 ± 6, and 172 ± 26 ms for for the Saccade/No-gap, Saccade/Gap, Fixation/No-gap, and Fixation/Gap condition, respectively (Fig 2C). A two-way repeated-measures ANOVA revealed the main effect of Reference Timing to be significant, *F*(1, 20) = 4.59, *p* = .045, η_g^2 = 0.06; the main effect of Action, *F*(1, 20) = 2.47, *p* = .132, η_g^2 = 0.01, and the Action × Reference Timing interaction, *F*(1, 20) =

0.20, p = .660, η_g^2 = 0.00, were non-significant. Introducing a gap induced additional memory decay, worsening temporal discrimination sensitivity.

In short, Experiment 1 revealed a significant Chronostasis effect (31 ms), along with a significant effect of the temporal position of the reference interval (50 ms). When the reference interval immediately followed the test interval, the latter was perceived as longer compared to when the reference was presented after a 2-second gap. Looked at in terms of the second (reference) event, the reference interval was ‘compressed’ relative to the first interval. While this ‘compression’ effect appears in part linked to the action, as evidenced by the lower PSE with vs. without a saccadic eye movement (415 ms vs. 441 ms), the main source of the ‘compression’ with two contiguous intervals may be an ‘attentional blink’ – potentially exacerbated by the intervals being defined by abrupt-onset flashes: salient stimuli that engage attention automatically (Remington et al., 1992; Yantis & Jonides, 1990). That is, reinforced by the first flash, attention is allocated to and engaged by the first interval, causing a blink-type difficulty with commencing the timing of the second interval – especially given that the second flash, demarcating the transition from the first to the second interval, prompts (executive) processes directed to the first interval. Attending to the second interval may therefore be delayed (by an ‘attentional blink’), causing the second interval to be underestimated (see also the ‘attentional-gate’ account of, Zakay & Block, 1996b). In contrast, when the reference appears two seconds after the end of the first interval, attention can be reallocated to the reference event without difficulty. This avoids the attentional blink, leaving a minor saccade-induced Chronostasis effect (36 ms, based on the PSEs of 496 ms vs. 460 ms in the fixation vs. saccade conditions).

To investigate the potential contribution of an attentional-blink effect, we conducted a control experiment without any eye-movement ‘action’ (i.e., the stimuli were presented at central fixation; see Appendix A for details). The results showed that the abrupt flash onset indeed significantly induced an attentional blink, causing the second event to be perceived as shorter than the first event (PSE of 389 ms, as compared to the fixed 500-ms test interval). This flash-induced attentional blink might potentially overlay any action-induced time distortions. When introducing conditions (in the control experiment) in which the test and reference intervals were defined by color identity, the two consecutive color-defined intervals were perceived as similar in duration: the PSE for the test interval was 494 ms, which is close to the actual (500-ms) duration of the reference interval. We attribute this to the (isoluminant) change from one to the other color generating fewer visual onset transients (compared to the abrupt-onset flashes) and so less confounding by blink-type processes. For this reason, we used color identity to define the interval duration in Experiment 2.

Experiment 2

Experiment 2 was designed to directly measure action-induced distortions to the second vs. first interval following the saccadic action, with the reference interval presented 1.2 seconds after the second interval. Assuming saccades induce an uneven temporal distribution of attention like the attentional blink, we expected the second post-saccadic event to be underestimated relative to the reference event.

Method

Participants

21 new participants (mean age: 26.7 years; 11 females and 10 males) were recruited for Experiment 2. All had normal or corrected to normal vision and color vision, and were naïve as to the purpose of the experiment. Before starting the experiment, participants provided informed consent. Payment was again at a rate of 9 Euro per hour.

Stimuli and Procedure

The setup as in Experiment 2 was similar to that in Experiment 1, with the following differences. The saccadic (target) disks were positioned 6° to the left and right of the central fixation point. Each trial started with the central fixation marker presented for 500 ms, followed by a white arrow cue (< or >) indicating the location of the target on a given trial. The target and non-target disks both (i.e., as a group) changed from white to green (or, respectively, from white to red) immediately after the saccade offset, marking the onset of the first interval. At a designated time, the disk changed to red (or, respectively, green), signaling the end of the first interval and the start of the second interval. Following another designated time (see details below), the disk turned white for 1200 ms to create a gap before the reference interval. The disk then changed color to either green or red marking the onset of the reference, depending on the selected test interval, which was blocked per 'session' (i.e., either the first interval was consistently the test interval in a session, or the second interval). Participants had to compare the test interval, either the first or second interval (which shared the same color with the reference interval, red or green) with the reference interval and judge which one was longer, by pressing the left or right arrow key.

In Experiment 2, the PSEs (and JNDs) were measured for two post-saccadic intervals: the first interval and the second interval (hereafter labeled S1 and S2, where S denotes the Saccadic conditions). The test and the reference intervals were assigned the same color, while the non-test interval used a different color. The colors were isoluminant and their assignment to the first and second intervals was counterbalanced across participants (i.e., half of the participants were presented with green and red as the first and second intervals in all conditions, while the other half were presented with red and green, respectively). The test interval varied randomly from 150 to 1050 ms in increments of 150 ms (7 levels), while the non-test interval and the reference were set to 600 ms[2] (see Fig 3).

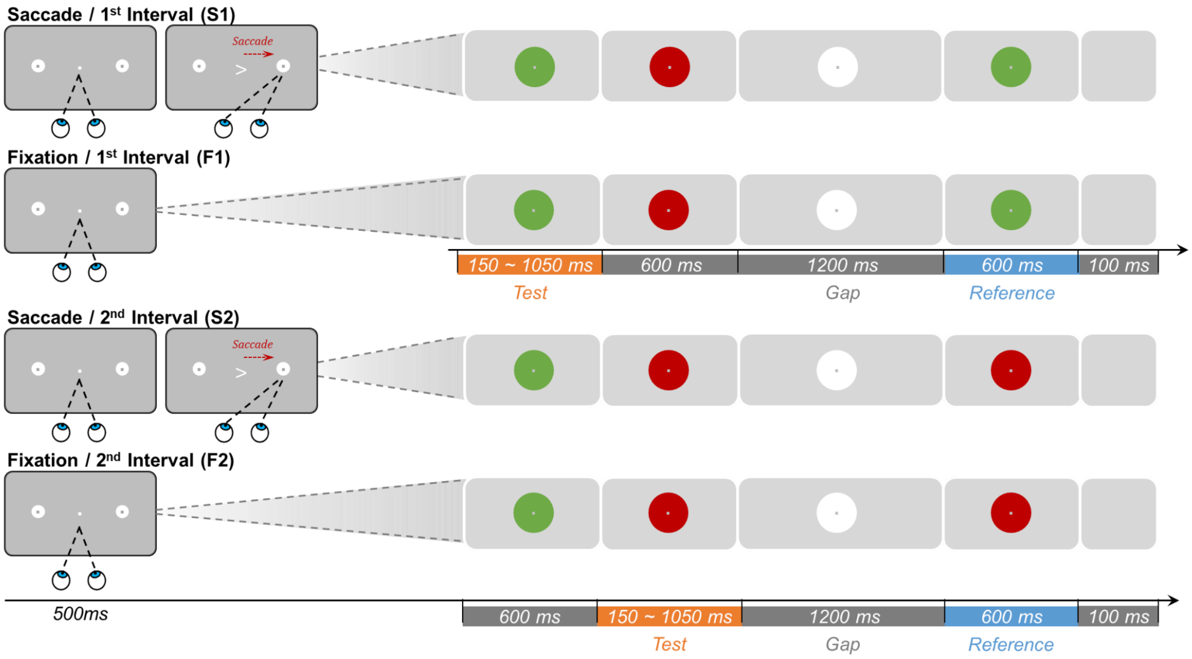

Fig 3. Schematic illustration of the procedure of Experiment 2. There were four blocked conditions: Saccade/1st Interval (S1), Fixation/1st Interval (F1), Saccade/2nd Interval (S2), and Fixation/2nd Interval (F2). The left panels illustrate the displays for the trial-initial action phase, separately for the Saccade and Fixation (action) conditions. The right panels depict the successive stimulus changes for the phase of interval comparison. In the Saccade conditions, participants fixated the central fixation dot for 500 ms, whereupon they were presented with a spatial arrow cue prompting them to make a saccade to the indicated target disk (1st and 3rd rows); landing on the saccade target then triggered the interval-comparison phase. In the Fixation conditions, there was no central change, requiring participants to maintain fixation in the center (2nd and 4th rows), and the interval-comparison phase began automatically after 500 ms of fixation. In the interval-comparison phase, the intervals were demarcated by changes of the disk color. In the S1 and F1

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[2] Given this, the non-test interval could potentially also have been used as the reference interval. This is, however, unlikely, as participants were instructed (and in the practice trials trained) to compare the two like-colored – test and reference – intervals.

conditions (upper two rows), the first interval shared the same color with the reference interval, and so interval 1 was the task-relevant test interval (blocked per S1 and F1 session). In the S2 and F2 conditions (bottom two rows), the second interval shared the same color with the reference interval, and so interval 2 was the task-relevant test interval (blocked per S2 and F2 session). The color of the reference interval varied across conditions (green or red), while the color of the gap interval was always white. Participants indicated which interval – the test or the reference interval – was longer by pressing a corresponding key.

There were also two analogous baseline conditions without eye movements, one in which the first interval was the test interval and one in which the second interval was the test interval (hereafter labeled F1 and F2, where F denotes the Fixation conditions; see Fig. 3, second and fourth rows). The procedure was identical to the saccade sessions (S1 and S2), except that observers were asked to maintain fixation on the central dot throughout the trial. After 500 ms fixation, the first two intervals and the reference were presented in the same manner as in the saccade sessions.

Each participant completed all four experimental conditions (S1, S2, F1, and F2) in a random order, with condition order counterbalanced across participants. Each session consisted of seven intervals that were randomly repeated 20 times, 10 per each side. As in Experiment 1, participants' eye-movements were monitored throughout each trial. Any trials with incorrect eye movements (on average, 12.77%) were retested in a random order at the end of each block, ensuring that all conditions had an equal number of 140 valid trials.

Results and Discussion

Fig. 4A depicts typical responses from one participant and associated fitted response curves, while Fig.s 4B and C show the average PSEs and JNDs across all participants.

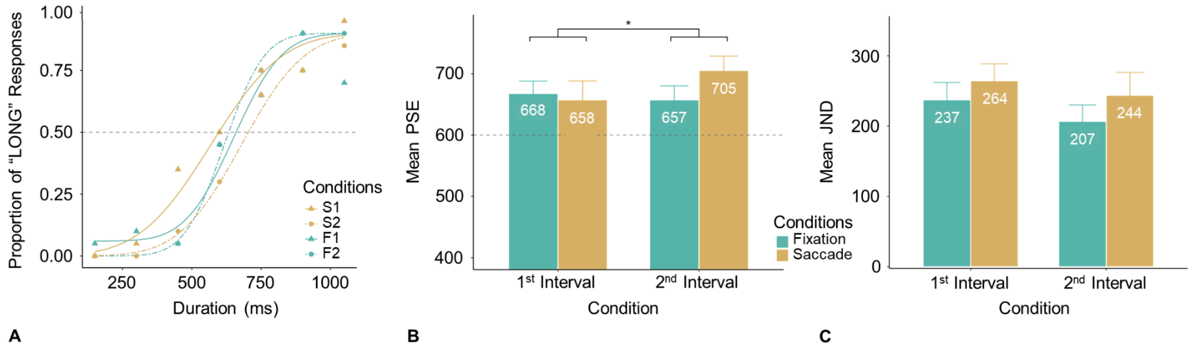

Fig 4. Results from Experiment 2. Typical example of behavioral responses (dots) and fitted psychometric curves from one participant (**A**). Mean PSEs (**B**) and JNDs (**C**) for the four conditions from all participants. The dashed horizontal line in (**B**) marks the reference interval (600 ms). The increased greater PSE value for the second test interval in the saccade condition (compared to the other conditions) indicates a compression of this

interval, as it would require a longer duration for it to be perceived as long as the delayed reference interval. (*: $p < .05$).

The mean PSEs (± SE) for all participants were 658 ± 31, 705 ± 23, 668 ± 20, and 657 ± 23 ms for the S1, S2, F1, and F2 conditions, respectively. A repeated-measures ANOVA revealed only the Action (Saccade, Fixation) × Test-Interval (1, 2) interaction to be significant, $F(1, 20) = 5.84$, $p = .025$, $\eta_g^2 = 0.02$; the main effects were non-significant: Action, $F(1, 20) = 1.09$, $p = .309$, $\eta_g^2 = 0.01$; Test-Interval, $\mathrm{F}(1, 20) = 1.03$, $p = .323$, $\eta_g^2 = 0.01$. The interaction was largely due to the ‘odd-one-out’ large PSE in the S2 condition, relative to comparable PSEs in the other three conditions. Further post-hoc comparisons revealed a significant difference between the S2 and S1 conditions ($t(20) = 2.00$, $p = .045$, *Cohen’s d* = 0.45) and between the S2 and F2 conditions ($t(20) = 2.12$, $p = .045$, *Cohen’s d* = 0.47), but not between the F1 and S1 conditions ($t(20) = -0.49$, $p = .627$, *Cohen’s d* = -0.11). This pattern confirms that the post-saccadic second interval (S2) was greatly compressed. However, we failed to find any significant Chronostasis. Given that the reference interval was constant (600 ms), we further conducted simple t-tests to examine the absolute over- or underestimates – which showed all PSEs to be larger than 600 ms ($ps < .05$). That is, regardless of the presence of a saccade, the first interval (F1 or S1) was perceived as shorter than the reference interval, even though the reference interval was separated from the end of the first interval by 1800 ms (which is similar to the 2000-ms separation in Experiment 1). In other words, when the first interval was judgment-relevant, it too was compressed (relative to the delayed reference interval) to some extent. We tentatively attribute this surprising finding to the presence of a second (irrelevant) interval intervening between the task-relevant first and the reference interval, which may have given rise to a recency effect for the last, reference interval (for more detailed arguments, see the General Discussion).

The mean JNDs (± SE) were 264 ± 24, 244 ± 33, 237 ± 25, and 207 ± 23 ms for the S1, S2, F1, and F2 conditions, respectively (Fig. 4C). A two-way repeated-measures ANOVA revealed no significant effects (Action, $F(1, 20) = 3.11$, $p = .093$, $\eta_g^2 = 0.02$; Test-Interval, $F(1, 20) = 1.91$, $\mathrm{p} = .183$, $\eta_g^2 = 0.01$; interaction, $F(1, 20) = 0.05$, $p = .818$, $\eta_g^2 = 0.00$).

Comparisons between Percentage Distortions

Comparisons between the Saccade and Fixation conditions revealed the saccade-induced expansion of the post-saccadic first interval (S1–F1) to be slight (percentage distortion: 1.7%); in contrast, there was substantial compression of the post-saccadic second interval (S2–F2; 8.0%), which was of a similar magnitude to the direct comparison between the two saccadic intervals (S2–S1, 8.0%). Interestingly, the percentage distortion was comparable to that seen in Experiment 1, where we compare the post-saccadic first intervals with and without gap (Saccade/Gap - Saccade/No-gap, 9.0%). This similarity reinforces a crucial observation from both experiments: the consistent underestimation of the second interval. Experiment 1 noted this when the second interval was the reference interval, and Experiment 2 confirmed it when the second interval was the test interval. Thus, these findings indicate that saccade-induced time distortions, rather than being just limited to the first post-saccadic event, also impact the second event.

General Discussion

The subjective perception of time can be distorted by actions (Merchant & Yarrow, 2016). Previous studies have shown that saccadic eye movements can either expand (Morrone et al., 2005; Yarrow et al., 2001) or compress (Morrone et al., 2005; Yarrow et al., 2001) the perceived duration of the peri-saccadic first event. In the present study, we investigated how making a goal-directed saccade influences the duration perception of subsequent events, particularly of the post-saccadic second interval, which is typically used as a reference interval in studies of Chronostasis (e.g., Georg & Lappe, 2007; Park et al., 2003; Yarrow et al., 2001, 2004).

Summary of Experiments and Critical Findings

Experiment 1 showed a greater Chronostasis effect when the reference interval immediately followed the post-saccadic first (i.e., test) interval (i.e., No-Gap), compared to when there was a 2-second gap between the two intervals. We considered two possible explanations for this overestimation of the post-saccadic time under No-Gap conditions. First, the post-saccadic interval may have been expanded by attention being shifted to this event, owing to the inherent coupling of spatial attention and saccadic eye movements (Deubel & Schneider, 1996; Shepherd et al., 1986). This would have resulted in a transient post-saccadic attentional enhancement of the first event and consequently a decline of attention to the (immediately following) second event, that is, a ‘compression’ of the post-saccadic second interval relative to the first interval. Second, attention may have been engaged by the first event, especially because this event was signaled by an abrupt-onset flash 'capturing' attention (Remington et al., 1992; Yantis & Jonides, 1990). This may have given rise to an 'attentional blink' at the end of the first interval, a control-demanding point (Kawahara et al., 2006) at which the 'clock' had to be stopped and the result buffered in working memory. These processes could have delayed the timing of – and thus effectively 'compressed' – the immediately following reference interval. In contrast, when the reference followed the target interval after a 2-second gap, the blink would have occurred during the gap and so have left the timing of the second interval unaffected. Of note, an 'attentional-blink'-type compression of the second (reference) interval could only explain part of the relative overestimation of the first (test) interval, as there remained a Chronostasis effect in the No-Gap saccade (vs. fixation) condition. A control experiment without eye movements (reported in the Appendix) confirmed that a blink-type effect was evident when the intervals were demarcated by salient abrupt-onset flashes, but not when they were demarcated by isoluminant color changes.

Given this, Experiment 2 was designed to more directly examine the hypothesis that saccadic actions induce a temporal attentional gradient that transiently enhances the timing of the first post-saccadic event, while (as the initial boost fades out) degrading the timing of the immediately following, second event. To investigate this, we introduced several changes to the experimental set-up compared to Experiment 1: Both the first and second intervals were test intervals – though blocked per condition, so participants knew which interval was task-relevant and to be attended and which one could be ignored. Additionally, the reference interval was presented with a gap after the end of the second interval, and the intervals were marked by isoluminant color changes rather than abrupt-onset flashes. The latter measures were implemented to minimize blink-induced distortions and so to isolate any temporal-gradient effects. According to the "temporal attentional-gradient" account, the second test interval should be compressed (relative to the reference interval), while the first interval should be expanded.

The results showed that the perceived duration of the first interval was similar in the Saccade as in the Fixation condition, failing to show significant saccade-induced Chronostasis. In fact, if anything, the first interval was underestimated ("compressed") compared to the reference duration, in both conditions. This is a finding that does not easily square with the "temporal attentional-gradient" account, requiring further discussion (see below).[3] Crucially, however, when the second interval was the test interval, the saccade caused a significant compression as compared to the fixation control condition, as predicted by the "temporal attentional-gradient" account.

One possibility why we found no saccade-induced Chronostasis effect for the first interval may have to do with the presence of a second (irrelevant) interval intervening between the task-relevant first and the reference interval. This may give rise to a recency effect for the last – the reference – interval, manifesting in a degree of 'compression' of the preceding intervals (which suffer from 'trace decay'). Consistent with this would be the finding that the underestimation of the first interval was similar to that of the second interval in the fixation condition. Alternatively, it is known that a group of intervals can be assimilated to the ensemble mean in low-level perceptual processing (Baykan et al., 2023; Burr et al., 2013; Nakajima et al., 1992; Ren et al., 2020). So, the significant compression of the second interval might assimilate the first interval, negating any minor Chronostasis that occurred to the first interval (as shown in Experiment 1). Also, as shown by Knöll et al. (2013), the Chronostasis effect can quickly disappear when the critical event is presented 50 ms after the saccade. These factors may all have contributed to the lack of saccade-induced Chronostasis in Experiment 2.

Theoretical Considerations

The present study sheds light on the intricate nature of subjective time distortions induced by saccades. Our results indicate that the stimulus onset, saccadic action, and the timing of the reference interval all play crucial roles in duration judgments. In Chronostasis experiments, a digital clock is often used to display a sequence of time intervals demarcated by the clock changing digits. Typically, the test interval is the first digit flip (from 0 to 1) that occurs after the saccade, while the reference interval is the interval immediately following the test interval – which is comparable to the No-Gap condition in our Experiment 1 (Georg & Lappe, 2007; Park et al., 2003; Yarrow et al., 2001). However, as we demonstrated in Experiment 2, the immediately following reference itself (i.e., the second interval) can be impacted by the saccade, as saccade-coupled attention may create a

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[3] In any case, our observed underestimation of the first interval would also be in line with Morrone et al.'s (2005) and Yarrow et al.'s (2001) finding of saccadic compression rather than Chronostasis.

temporal attentional gradient that boosts processing temporarily in the peri-saccadic period, but compromises the processing of immediately following events. The ensuing compression of the post-saccadic second interval was evident in Experiment 2 when it was directly compared to the reference interval presented after a 1.2-seconds gap. Recall that Experiment 2 had two fixation baselines, which both produced comparable PSEs (668 ms and 657 ms for the first and the second interval, respectively). This suggests that without any eye movements, the two intervals were perceived similarly (albeit shorter than the reference interval, which followed the second interval after a gap). Therefore, the greatly increased compression of the post-saccadic second interval (PSE of 705 ms) could only have been caused by the preceding saccadic eye movement. Unlike the post-saccadic first interval, whose onset was highly uncertain due to the saccade, the onset of the second interval occurred well beyond the peri-saccadic time window (600 ms after the saccade). Accordingly, active compensation for the stimulus onset (Yarrow et al., 2001) or low-level sensory factors (Knöll et al., 2013), which have been proposed to account for Chronostasis, cannot readily explain the compression of the post-saccadic second interval.

As a limitation, we note that the compression of the post-saccadic second interval only contributes to (rather than fully explains) the Chronostasis effect, as previous studies have reported robust Chronostasis illusions when the reference was temporally further removed from the saccadic action, separated by a gap of 500 ms or even 1000 ms (e.g., Knöll et al., 2013; Yarrow et al., 2004).

One possible explanation for the compression of the post-saccadic second interval is an uneven spatio-temporal attentional gradient tied to the saccadic eye movement. Spatially, attention is concentrated on the landing position of the saccade (i.e., the saccadic target) and decreases from there gradually (Mangun & Hillyard, 1988). This gradient also accounts for the line-motion illusion (Downing & Treisman, 1997; Hikosaka et al., 1993), in which a flash preceding the onset of a closeby line leads to subjective motion of the line outwards from the position of the flash. Temporally, planning and executing a voluntary eye movement to a target location is coupled with an attention shift to the saccade target (e.g., Deubel & Schneider, 1996; Shepherd et al., 1986), giving rise to a relatively transient post-saccadic attentional enhancement of objects or events at this location (see also Müller & Rabbitt, 1989). Thus, the first post-saccadic event occurring there would benefit from this enhancement, while the second event would fall into a trough (perhaps analogous to the "inhibition-of-return" effect in the spatial domain; e.g., Klein & Ivanoff, 2008, for a review), compromising its temporal processing and leading to it being perceived as shorter than its actual duration.

Overall, this account is consistent with previous findings that attention modulates the Chronostasis effect. For example, Chronostasis was diminished when the peri-saccadic event was presented spatially outside the focus of attention, at a midway position on the saccadic trajectory (Georg & Lappe, 2007; but see Knöll et al., 2013). Here, we find that a saccade-induced temporal attentional modulation extends beyond the post-saccadic first event. Future work is required to substantiate this account. For instance, future studies could vary the onsets of the first and second second intervals to track the duration of the transient boost and the attentional trough induced by saccades. Further, investigating phase oscillations in the electroencephalogram, which have been linked to attentional blink (Zauner et al., 2012) and temporal expectation (Cravo et al., 2013; Nobre & Van Ede, 2018), might shed light on neural mechanisms underlying the modulation of post-saccadic time estimation.

To sum up, saccadic eye movements affect not only the perceived duration of the first post-saccadic event (Chronostasis), but also of the subsequent events. Our findings indicate that if the second post-saccadic event follows immediately upon the first event, it is subjectively compressed – enhancing the Chronostasis effect when the second event is used as a reference interval. This compression is demonstrable even when 'attentional-blink'-type distortions are minimized or eliminated. We propose that saccades induce a transient temporal attentional gradient, resulting in an overestimation of the first interval and an underestimation of the second interval immediately after the saccade.

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Appendix A. Baseline Control Experiment

Baseline Comparison

According to the findings of Experiment 1, the flashes could have created abrupt changes that captured attention involuntarily, which could have led to a temporary inability to perceive the second event (also known as attentional blink). As a result, the second event was perceived as shorter than the first event. Given that our brain appears to prioritize attending to new object onsets over feature changes of existing objects (Yantis & Jonides, 1990), using color feature changes may generate less attentional capture than abrupt flash onsets. Therefore, in this control experiment, we compared the perceived duration between intervals defined by color changes vs. intervals defined by ring flashes.

Method

Participants

20 new healthy participants, with normal color vision, were recruited (mean age of 27.1 years; 12 females and 8 males). All participants were naïve as to the purpose of the experiment. They provided informed consent prior to testing, and were remunerated at a rate of 9 Euro per hour.

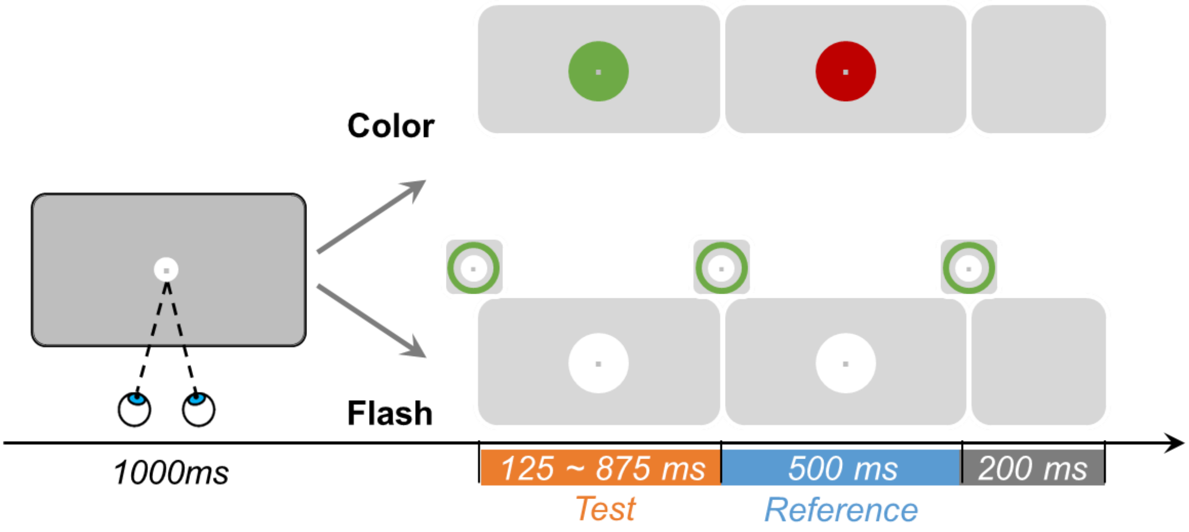
Apparatus

The experiment was conducted in the same experimental cabin using the same hardware without Eyelink.

Stimuli and Procedure

The conditions in this control experiment were essentially the same as in the No-Gap/Fixation condition of Experiment 1, with the following differences. Given that there were no saccade conditions, the white disk and fixation dot were presented in the screen center. Participants were instructed to fixate the center dot throughout the trial. There were two conditions, Flash vs. Color (Fig. A1, right bottom vs. upper panel), which were tested in separate blocks, with the order counterbalanced across participants. In the color condition, the start of the first – ‘test’ – interval was signaled by the central disk changing color (from white) to either green (for one half of the trials) or red (for the other half). The end of this interval and the start of the second – “reference’ – interval was signaled by another color change, from red to green or, respectively, green to red (where the colors assigned to the test and reference intervals were randomized across trials). The seven test intervals were randomly repeated 20 times each for both the color and flash blocks, resulting in 140 trials per block and 280 trials in total. Before formal testing in each (Flash, Color) condition, participants underwent a brief training block, in which the test durations were either 100 or 900 ms (presented in random order). Participants received accuracy feedback after each training trial, and the passing criterion was set to 80% accuracy in their decisions on which of the two intervals (the test or the reference interval) was longer. The number of training trials was initially set to 10, but increased automatically by another 10 trials if participants failed to pass the criterion.

Fig. A1. Schematic illustration of the procedure.

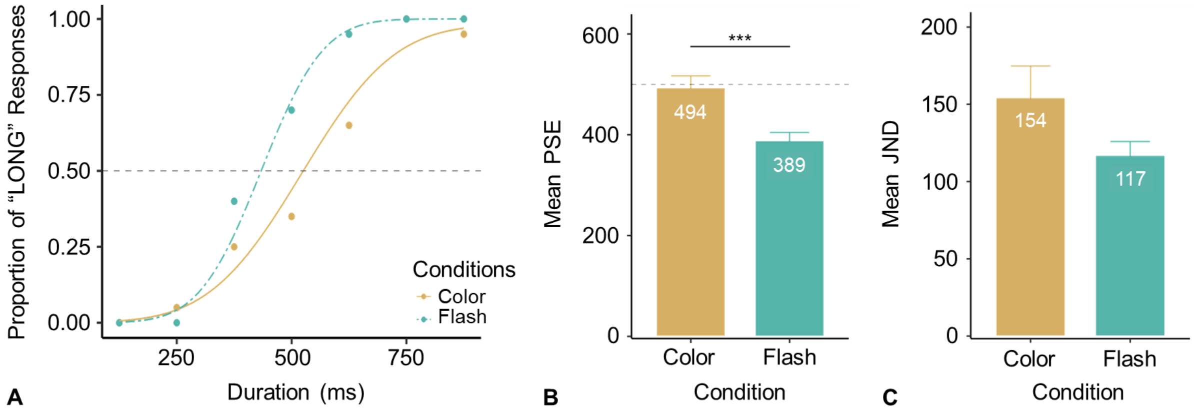


Note: A target disk with a center dot displayed in the screen center throughout the trial and participants kept fixated on the dot. The test and reference intervals appeared after 1000ms fixation, which were demarcated either by color or by the flash. In the color condition (upper row), the disk changed the color from white to a color then to another color, either green-to-red or red-to-green. In the flash condition (lower row), three concentric green flashes demarcated two intervals. The illustration on the right panel shows the stimulus changes in central vision for the interval-comparison phase*. Participants compared the durations of the test (orange) and reference (blue) intervals and chose the longer one by pressing a corresponding key.*

Results and Discussion

In order to ensure high-quality data, participants' performance was considered valid only if they were able to identify 125 ms as 'short' and 875 ms as 'long' (in comparison with the 500-ms reference interval) above 75% correct. Out of the 20 participants, only 3 did not meet this criterion and so their data were excluded from further analysis. Fig. A2 shows the proportion of ‘long’ responses and the associated psychometric curves from a typical participant.

Fig A2. Results from Experiment 2.



*Note: (**A**) A typical example of behavioral responses (dots) and fitted psychometric curves from one participant. (**B**) and (**C**) The mean PSEs and JNDs for the two conditions. The dashed horizontal line marks the reference interval (500ms). *: p < .05; **: p < .01, ***: p < .001)*

The mean PSE (with associated standard error) was 494 (± 23) for the Color condition and 389 (± 16) ms for the Flash condition. A t-test revealed the PSE to be significantly lower (105 ms) in the flash vs. the color condition, $t(16) = 4.95$, $p < .001$. This suggests that time distortions caused by the attentional blink were more pronounced due to the flashes as compared to the color changes. This also confirms the finding of Experiment 1, where the PSE (in the No-Gap/Fixation condition) was shorter than the reference duration of 500 ms. The mean JNDs (± SE) were 154 (± 20) and 117 (± 9) for the Color and Flash conditions, respectively; the difference was non-significant, $t(16) = 1.74$, $p = .102$, indicative of comparable discrimination difficulty.

To summarize, the results of the control experiment showed that replacing flashes with isoluminant color changes to establish intervals significantly reduced time distortion caused by the attentional blink. In fact, with color changes defining the intervals, the onset bias was effectively eliminated, as the PSE (494 ms) did not differ from the 500-ms standard ($t(16) = -0.28$, $p = .786$). Given this, we used color changes to define the target and reference intervals in Experiment 2.

Chapter 3

Study 2

Overestimation in time reproduction: Influences of accuracy feedback and attentional sharing

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Author note

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Abstract

Duration reproduction is often subjective to biases, with a general tendency to overestimate durations, which has been observed in many studies. Yet, this overestimation is frequently dismissed as a nuisance error, and its underlying mechanisms remain elusive. Here, we conducted two experiments to investigate this general overestimation in duration reproduction. To pin down the origin of the error, we manipulated the reproduction output through shortened visual feedback in Experiment 1, while varying the presence of accuracy feedback in Experiment 2. Across both experiments, we observed a consistent overestimation in reproduction when accuracy feedback was absent. This overestimation, amounting to approximately 13.5% on a ratio basis across different durations and sessions, was unaffected by shortened visual feedback. We propose that this consistent overestimation is likely due to the attentional sharing between the action execution and the monitoring of the passage of time during the reproduction process.

Keywords: duration reproduction, constant overestimation, attentional sharing

Introduction

In everyday life, we are immersed in a sea of temporal information. How we perceive, process, and integrate this temporal information is fundamental. For a trivial task, such as catching a flying ball, we need to constantly estimate the approaching time and adjust our own response. Researchers of time perception have developed various timing tasks, such as duration reproduction, temporal discrimination, and categorization (including temporal bisection or generalization), to facilitate this understanding.

An interesting phenomenon is that we generate estimation errors across various durations of which we are not explicitly aware. Two types of biases have been identified in time estimation. The first, commonly known as the central tendency bias, has been well-documented 150 years ago (Glasauer & Shi, 2021; Hollingworth, 1910; Lejeune & Wearden, 2009). The central tendency bias is exhibited when participants are asked to judge a set of durations. Shorter durations are often overestimated and long durations underestimated. This type of bias has been extensively studied, with a typical explanation being that we implicitly construct a prior centered around the set of durations. This prior is then integrated with the current duration (Bausenhart et al., 2014; Cicchini et al., 2012; Glasauer & Shi, 2021; Jazayeri & Shadlen, 2010; Shi, Church, et al., 2013; Shi & Burr, 2016), causing judgments to gravitate toward a mean duration. Varying the spacing or distribution of sample intervals can shift the temporal bisection point, a middle point of judgments between the given ‘short’ and ‘long’ standards, toward the ensemble mean (Baykan et al., 2023; Zhu et al., 2021).

The second type of bias, often referred to as a constant error or general bias, involves a general overestimation or underestimation in time perception (Craig, 1973; Grondin, 2001, 2012). For instance, intervals perceived as “filled” are often deemed longer than “unfilled” intervals (Craig, 1973), and auditory intervals are typically perceived longer than visual ones (Wearden, Goodson, et al., 2007). Reproducing a given auditory interval usually leads to an overestimation (Grondin, 2012; Shi, Ganzenmüller, et al., 2013). In a series of reproduction tasks where participants were asked to reproduce durations ranging from 1000 to 1900 ms, Grondin (2012) found consistent positive errors in reproducing intervals, except for the longest 1900 ms interval. Reproducing a one-second auditory interval with a simple button press could result in a 40% overestimation (Shi, Ganzenmüller, et al., 2013). Similar constant errors were also observed when participants reproduced a standard duration presented together with a comparison duration, particularly when the standard was presented second (Bausenhart et al., 2014). Although such general bias is common in duration judgments, it often garners less attention in interpretation and is treated as nuisance error and occasionally removed before further analysis (e.g., Cicchini et al., 2012). The prevailing explanation for this general bias is based on the internal-clock model. It postulates that either the speed of the clock varies (Wearden et al., 1998), or the timing of switch onset and offset differs (Craig, 1973).

In the case of the duration reproduction task, there are several factors that could contribute to a general bias. One noticeable difference between the duration reproduction task with other timing tasks is the involvement of action. It has been postulated that sensory modalities and the motor system may have distinct timing systems, and that these systems might process timing in a distributed manner (Bueti et al., 2008; Mauk & Buonomano, 2004). The timing of the motor system may be slower than the auditory or visual clocks, leading to consistent over-reproduction. A different, yet closely related, theory is the attentional sharing account (Fortin, 2003; Lejeune, 1998). When attention is shared between two subtasks, monitoring the passage of time and reproduction action, for instance, the limited attention resources could result in less attention being dedicated to monitoring the passage of time. Consequently, ‘ticks’ may be lost, leading to an overestimation as reproduction time lengthens to compensate for the misstated counts. Contrasting the attention sharing account, attention might also switch between motor action and monitoring the passage of time (Zakay & Block, 1996). Attention could initially be focused on the action onset, then shift to time monitoring. When the duration approaches the target duration, attention would return to the action for stopping reproduction. Such attentional shifts can also cause general bias, differing from attentional sharing. Alternatively, it is also possible that attention remains on motor timing without switching to reproduction feedback, resulting in a general bias solely caused by the motor system. Notably, the attentional shift account predicts a constant error, independent of reproduced durations, while the attentional sharing theory suggests that the error would be proportional to the test duration.

On this premise, this study designed two experiments to investigate mechanisms underlying constant overestimation in the temporal reproduction task. One approach to distinguishing these alternative accounts involves manipulating temporal discrepancies between the action and action output. If reproduction relies solely on the motor timing system, the reproduced duration would base on the action itself, unaffected by variations in the action output (such as a delayed visual output). For instance, a shortened visual output wouldn't cause the reproduced duration to shrink. Conservely, if reproduction hinges on action output, adapting to a shortened visual output would shorten the reproduced duration. If attention is shared between action and action output, the reproduced duration would be overestimated with simultaneous action output according to the attentional sharing account, but would be partially shortened after adapting to a shortened action output. We tested this in Experiment 1. In Experiment 2, we varied test durations to discern the role of attention. This was achieved by introducing a short and a long duration and varying the presence of accuracy feedback. If attention switches between the two subtasks, the overestimated duration should remain constant for both short and long durations. Alternatively, the overestimated duration should vary when reproducing the short and long standard durations, maintaining a constant ratio to the reproduced duration.

Experiment 1

Method

Participants

A total of 20 volunteers, aged 19 to 31 (average of 23.55, 9 females and 11 males), were recruited for Experiment 1. Each participant had either normal or corrected-to-normal vision, and was naive to the purpose of the study. The sample size was determined by previous studies (Ganzenmuller, 2013), in which a group of 12 participants had yielded significant findings concerning under- and over-estimations. All participants signed the informed consent form prior to 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.

Apparatus

The experimental code, developed using the Psychopy (Peirce et al., 2019), controlled the presentation of visual stimuli on a ViewPixx LCD monitor (VPixx Technologies Inc.) with a refresh rate of 120 Hz. Behavioral responses were collected via a standard keyboard. The setup was housed in a sound-isolated dark cabin. The viewing distance was fixed to 60cm with the aid of a chin rest.

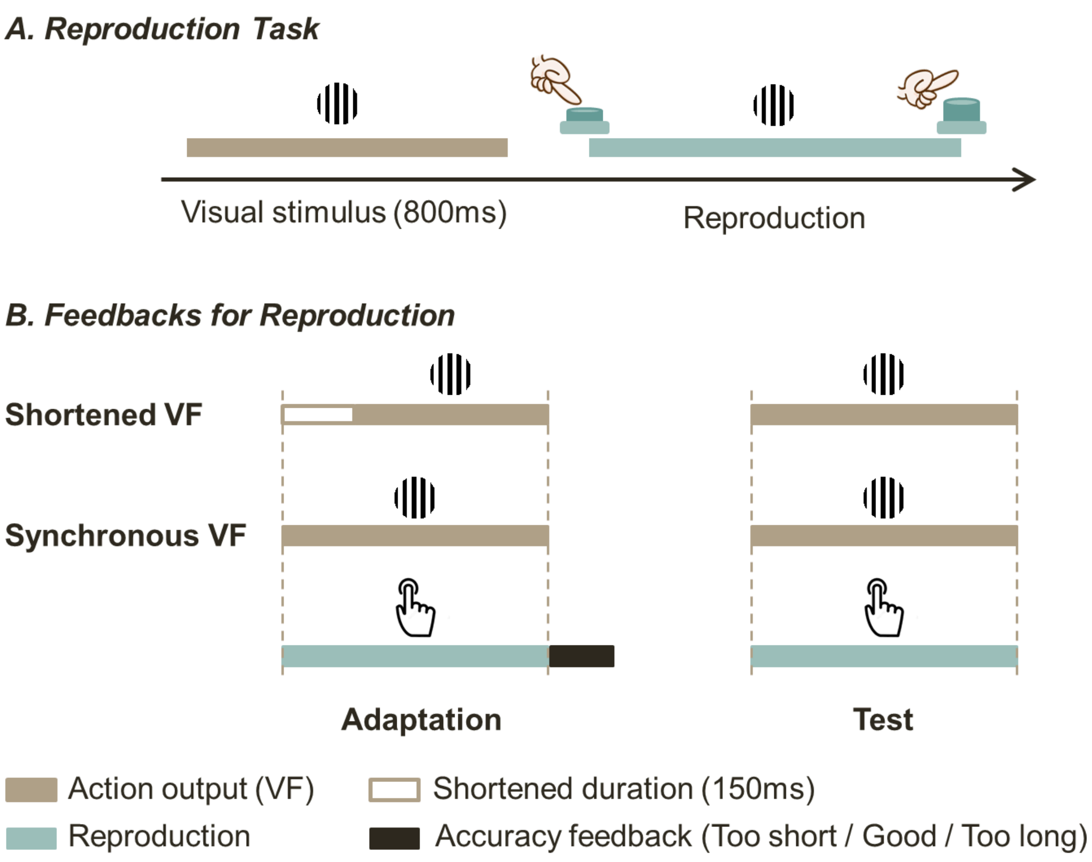

Figure 1. Schematic illustration of the paradigm in Experiment 1. The reproduction task **(A)** for each trial first presented a standard 800 ms target duration through a visual Gabor patch. After the visual stimulus disappeared, participants reproduced the target duration through pressing the spacebar. **(B)** Experiment 1 comprises two sessions, a shortened output adaptation (Shortened VF) and a simultaneous output adaptation (Synchronous VF). Each session comprised two phases: adaptation and test phases. In the session of the shortened output adaptation, the action output - visual feedback - started 150 ms later than the action onset, but stopped when the action stopped (left-upper panel). In the session of the simultaneous output adaptation, the reproduction was synchronized with the visual feedback. Upon the completion of the reproduction, an accuracy of the reproduced duration was provided (too short, long, or too long) based on the tolerant range of 10% error. The accuracy feedback was absent in the test phase.

Stimuli and Procedure

A duration reproduction task was used in Experiment 1 (Figure 1A). A typical trial started with a central fixation cross, prompting participants to fixate on it. After 400 ms, a Gabar patch (size: 1.7° of visual angle, spatial frequency: 0.08 cycles per degree) appeared centrally for 800 ms, serving as the target duration, before disappearing. Participants then, with self-paced, attempted to replicate the target duration by holding down the spacebar. A Gabor patch, identical to the initial one, appeared as visual feedback during the key pressing.

The experiment comprised two sessions, namely the synchronous visual feedback (VF) session and a shortened VF session. Two sessions were tested successively with a 5 min break in between, and their order was counterbalanced across participants. Each session consisted of two phases: an Adaptation phase and a Test phase. Both sessions began with the adaptation phases (Figure 1B, left panel) with 60 obligatory trials. The key difference between two sessions was that in the shortened VF session, the visual feedback started 150 ms later than the action onset, but stopped when the action stopped, while the visual feedback synchronized with the action onset and offset in the synchronous VF session. Participants received immediate accuracy feedback based on how closely they replicated the target duration with motor action. The acceptable tolerance range was set at 10%, spanning from 720 to 880 ms), known as the ‘good’ range. If the reproduced duration fell below this range, they received the text feedback ‘too short’. Conversely, if the reproduced exceeded this range, the textual feedback ‘too long’ was provided. Participants had to reach 80% of the last ten trials to the ‘good’ range to finish the adaptation phase. If not, ten more trials were administered. 75% of participants managed to reach the goal within 60 trials, and 85% reached the goal with one round of ten more trials. Only one participant required 30 more trials to reach the goal.

Reproduction in both test phases employed the same visual stimuli with the synchronous visual feedback (Figure 1B, right panel). This phase consisted of 13 mini-blocks, with 20 trials each. The first five trials of the mini-block were top-up adaptation trials, each with accuracy feedback after the task, while the rest 15 trials provided no accuracy feedback. The target duration was consistent in all trials types (800ms).

Data Analysis

The statistical analyses were performed using R (R Core Team, 2022). To ensure comparability across participants, only the final 60 trials of the Adaptation phase were included in the analysis, since some participants required more trials to meet the accuracy criterion. Additionally, the first trial of each sub-block in the test phase was excluded as they were influenced by the between-block break.

Result and Discussion

Experiment 1 investigated whether the shortened action-output (visual feedback) would affect the overestimation. During data preprocessing, one outlier was identified and excluded according to the interquartile range (IQR) rule. Figure 2B depicts the mean reproduced duration as a function of the mini-block trial number within the testing phase, encompassing the five top-up adaptation trials (brown lines) and 15 test trials (green lines). Two noteworthy patterns emerged during the test: a consistent lengthening in reproduction for the synchronous VF test trials relative to the shortened VF test trials, and an overall upward trend throughout the test phase, highlighting a distinct general bias characterized by growing overestimation across consecutive trials. Figure 2A details the mean reproduced durations for the Adaptation (the last 60 trials) and Test phase (excluding the top-up adaptation trials), separated by the Shortened-VF and Synchronous-VF sessions. The mean reproduced duration (± SE) were 788 (± 7), 893 (± 14), 809 (± 8), and 834 (± 19) ms for the Synchronous-VF/Adaptation, Synchronous-VF/Test, Shortened-VF/Adaptation, and Shortened-VF/Test conditions, respectively (Figure 2B).

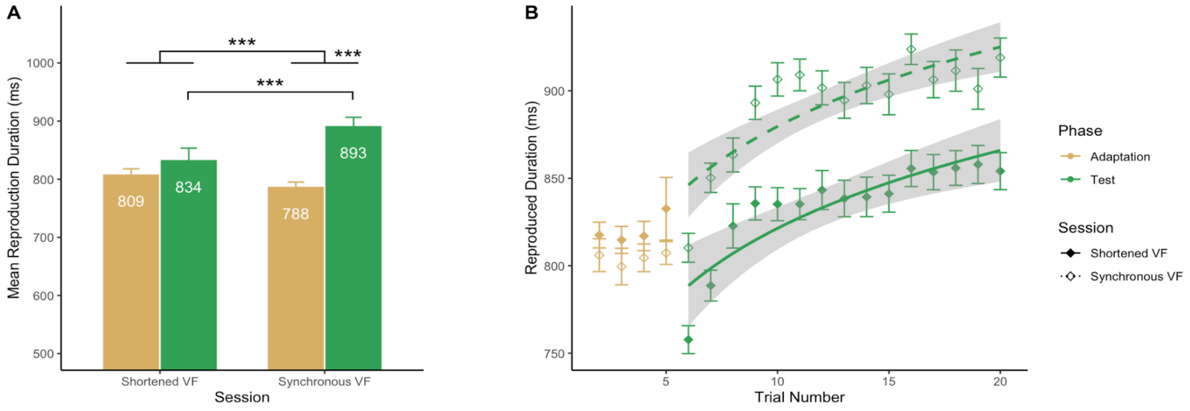

Figure 2. The general mean reproduction duration **(A)** for all four conditions (two sessions x two phases). The Trial-by-trial mean reproduction duration in the Test Phase **(B)**, comprising five top-up Adaptation trials and 15 Test trials in each sub-block. The fitted logarithmic regression model for the Test trials in both sessions **(B, right panel)**. The asterisks mark the significant interaction effect and between-condition differences (p < .001: ***).

A repeated-measure analysis of variance (ANOVA) with factors of Session and Phase revealed significant main effects for both Session ($F(1, 18) = 6.60$, $p = .019$, $\eta_g^2 = 0.03$), and Phase ($F(1, 18) = 17.69$, $p < .001$, $\eta_g^2 = 0.26$). This demonstrated a significantly lengthened reproduced duration in the test phase than in the adaptation phase, as well as in the Synchronous-VF session than the Shortened-VF session. Moreover, the Session x Phase interaction was also significant ($F(1, 18) = 28.82$, $p < .001$, $\eta_g^2 = 0.12$). Post hoc pairwise comparisons revealed the interaction was mainly contributed by the longer reproduced duration during the synchronous-VF test phase (ts > 4.8, ps < .001), the comparable reproduced durations between the adaptations and Shortened-VF test phase (ts < 2.56, ps > .079).

We then further estimated the reproduction growing curve from the mini-test blocks with a logarithmic regression model (Figure 2B, right panel):

$$\text{RT} = a + b \log(\text{Trial Number})$$

The curve was fitted separately to each session. Analysis of the logarithmic regression model revealed the following coefficient estimates for the two sessions. The mean intercepts were 673 and 729 ms for the shortened-VF and the synchronous-VF sessions, respectively. The former was significantly shorter than the latter ($t(18) = 2.41$, $p = .027$). The logarithmic slopes were comparable: 64.25 and 65.53 for the shortened-VF and synchronous-VF sessions, respectively. The slopes did not differ significantly ($t(18) = 0.12$, $p = .908$), indicating the growing overestimation was similar in two sessions in the absence of the accuracy feedback.

In short, Experiment 1 showed a significant influence of the shortened visual feedback on the duration reproduction in the test trials where accuracy feedback was not provided, suggesting that reproduction is not merely motor timing in the presence of action output. Rather reproduction is an integration of the motor and sensory feedback (Shi, Ganzenmüller, et al., 2013). The findings also demonstrated the effective updating of internal priors with accuracy feedback during the adaptation phase, as the accuracy feedback was based on purely motor action. However, this adaptation did not eradicate the general overestimation (absolute mean error of 109 ms) observed in the test phase when the accuracy feedback was omitted. In fact, reproduced durations gradually drifted back to overestimation, indicating reproduction is neither purely visual nor motoric timing. However, there remains several possibilities for the consistent overestimation error: attentional sharing between motor action and monitoring passage of time, or potential anchoring to one second as the test duration was 800 ms. We further distinguish these in Experiment 2.

Experiment 2

To rule out possible anchoring to one second, we tested two durations, one sub-second (800 ms) and one super-second (1200 ms) in Experiment 2. As we demonstrated that the accuracy feedback was a crucial factor influencing reproduction, we compared the presence and absence of the accuracy feedback as well in Experiment 2. Introducing both the short (800 ms) and long (1200 ms) durations permits us to distinguish two possible accounts: the attentional sharing account and switching accounts. If the general overestimation is a result of attentional switch, we expect comparable overestimation for both short and long durations. In contrast, if overestimation is driven by attentional sharing, we expected overestimation would be larger for the long compared to the short duration. However, according to the scalar property in time perception (Gibbon, 1977; Gibbon & Church, 1990; Ren et al., 2021; Shi et al., 2022), errors measured in ratio should be comparable for the two durations.

Method

Participants and Apparatus

Experiment 2 also recruited 20 volunteers to participate (21-33 years old, average of 25.6, 12 females and 8 males). The recruitment and compensation were identical to those in Experiment 1, and the experiment took place in the same cabin and under the same settings as in Experiment 1. The experimental program was also developed using the “Psychopy” package (Peirce et al., 2019) in PyCharm.

Stimuli and Procedure

The stimulus in Experiment 2 was the same Gabor patches as in Experiment 1. In addition to the 800ms target duration in Experiment 1, an additional 1200ms target duration was introduced in Experiment 2. These two target durations were tested in two separate sessions to avoid any central tendency effect. During the reproduction process, participants were presented with the same Gabor patch as visual feedback. Unlike Experiment 1, Experiment 2 did not involve any shortened visual feedback. Instead, the output of the action (i.e., visual feedback) was synchronized with the reproduction, meaning it began and ended simultaneously with the reproduction onset and offset. In addition, Experiment 2 compared the presence and absence of the accuracy feedback in the test phase.

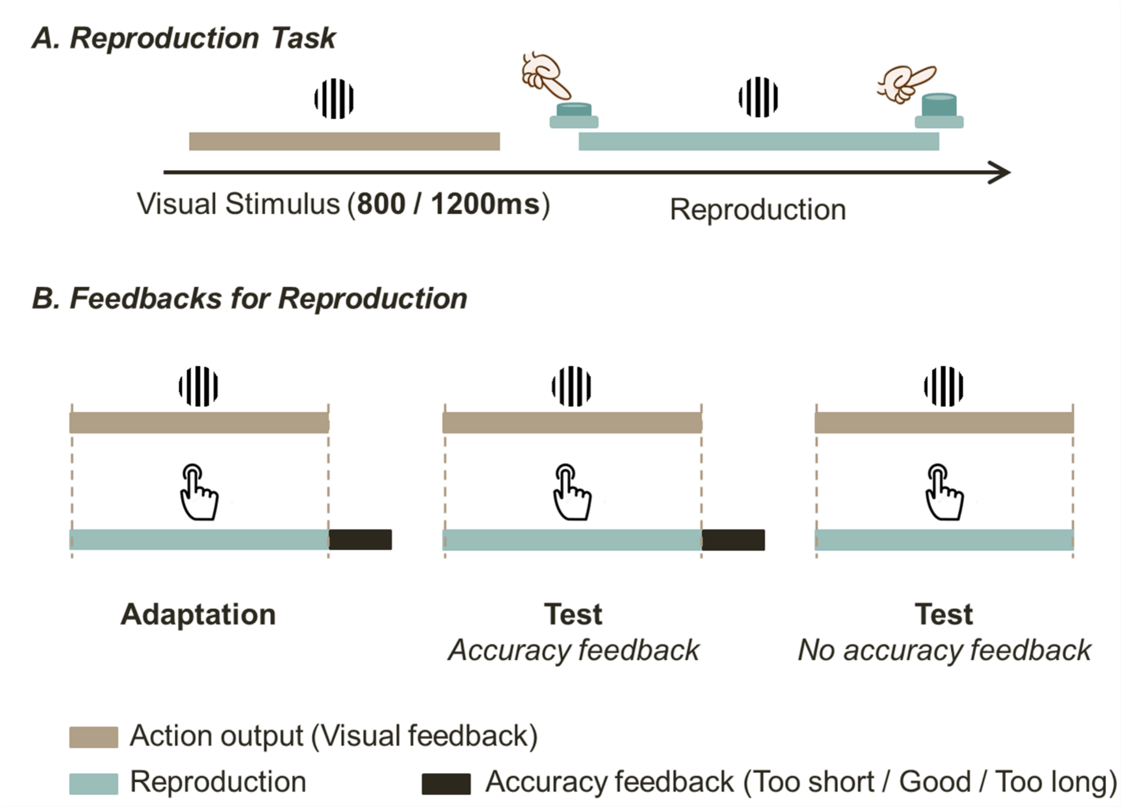

Figure 3. Schematic illustration of the paradigm in Experiment 2. The same reproduction task (**A**) was employed in Experiment 2 with two standard target durations, 800 ms and 1200 ms, tested in two separate sessions. Except for the standard duration, all settings in the two sessions were the same. The action output (visual feedback) was synchronized with the reproduction in both adaptation and test phases (**B**). Experiment 2 also applied the Adaptation-test paradigm. The test phase (middle and right panel) comprised four mini-blocks, two accuracy feedback and two no accuracy feedback blocks, presented alternatingly with an interleaved order. The accuracy feedback was only provided in the adaptation phase (left panel) and the accuracy feedback test blocks (middle panel).

Experiment 2 employed the same reproduction task as in Experiment 1, investigating how attention was allocated in reproduction with differentiated durations and the presence of accuracy feedback. Two sessions with different durations (800 and 1200ms) were tested in a succession with a 5 min break in between. The order of the two sessions were counterbalanced among participants. Each session consisted of two phases: an adaptation phase and a test phase. Like in Experiment 1, the adaptation phase included 60 mandatory trials, with an accuracy feedback by the end of each trial. The same criteria as in Experiment 1 were employed to determine the accuracy range and the requirements for passing the adaptation phase. The subsequent test phase consisted of four sub-blocks, each with 25 trials. Regarding the effect of the accuracy feedback, two types of test block were designed: those with accuracy feedback and those without. Specifically, the first and third test blocks supplied accuracy feedback at the end of each trial, while the second and fourth test blocks did not provide any accuracy feedback. This design formed three types of block within each session (800 and 1200 ms): Adaptation/Feedback, Test/Feedback, and Test/No-Feedback blocks.

Result

Figure 4 shows the mean reproduction durations for two separate durations (800 ms and 1200 ms) in three types of blocks: adaptation, test with accuracy feedback, and test without accuracy feedback. By visual inspection, reproduction was overestimated in the test without accuracy feedback blocks for both durations. The mean reproduced duration (± SE) were 800 (± 11), 806 (± 10), and 910 (± 22) ms for the 800 ms duration, and 1140 (± 10), 1162 (± 14), and 1291 (± 24) ms for the 1200 ms duration, for the adaptation, test with accuracy feedback, and test without accuracy feedback blocks, respectively.

A 2 (Standard-Duration: 800ms, 1200ms) × 2 (Phase: Adaptation/Feedback, Test/Feedback) ANOVA was conducted comparing the adaptation and test phase with different standard duration. The reproduction difference between 800ms and 1200ms standard duration was significant, ($F(1, 19) = 1420.06$, $p < .001$, $\eta_g^2 = 0.92$), with consistent longer reproduction duration in the 1200ms session compared to in the 800ms session. Neither the main effect of Phase ($F(1, 19) = 3.24$, $p = .088$, $\eta_g^2 = 0.02$) nor the interaction effect between the two main factors was significant ($F(1, 19) = 0.85$, $p = .368$, $\eta_g^2 = 0.01$), evidencing comparable reproduction in adaptation and test phase when accuracy feedback present in both sessions. A follow-up 2 (Standard-Duration: 800ms, 1200ms) × 2 (Accuracy-Feedback: Test/Feedback, Test/No-Feedback) ANOVA were conducted focusing on the Test phase with accuracy feedback presence and absence. It revealed significant main effect of both Standard-Duration ($F(1, 19) = 792.83$, $p < .001$, $\eta_g^2 = 0.84$) and Accuracy-Feedback ($F(1, 19) = 48.42$, $p < .001$, $\eta_g^2 = 0.35$), and non-significant interaction effect ($F(1, 19) = 1.05$, $p = .319$, $\eta_g^2 = 0.01$). These results are indicative of a general tendency of over-reproduction when the accuracy feedback is absent, independently to the standard duration of reproduction.

The mean standard deviation (SD ± SE) were 136 (± 10), 112 (± 8), and 138 (± 12) ms in the

800 ms session, and 151 (± 13), 165 (± 15), and 195 (± 17) ms in the 1200 ms session (Figure 4), for the Adaptation/Feedback, Test/Feedback, and Test/No-Feedback blocks, respectively. The ANOVA with factor of Standard-Duration and Phase revealed significant main effect for Standard-Duration ($F(1, 19) = 10.87$, $p = .004$, $\eta_g^2 = 0.10$) and non-significant main effect of Phase ($F(1, 19) = 0.28$, $p = .605$, $\eta_g^2 = 0.00$). The interaction effect ($F(1, 19) = 5.26$, $p = .033$, $\eta_g^2 = 0.03$) was significant. The interaction was largely due to the relatively large SD in the Adaptation phase of the 800ms session. Further post-hoc comparisons between the Adaptation/Feedback and Test/Feedback blocks revealed a significant difference in the 800ms session ($t(19) = 2.84$, $p = .011$, $BF = 4.909$) but not in the 1200ms session ($t(19) = -1.00$, $p = .331$, $BF = 0.360$). The large SD was mainly induced by the deviation in the early trials in the adaptation phase. The follow-up ANOVA with a specific focus on influence of accuracy feedback in the test phase revealed significant main effect for both Standard-Duration ($F(1, 19) = 23.38$, $p < .001$, $\eta_g^2 = 0.18$) and Accuracy-Feedback ($F(1, 19) = 13.14$, $p = .002$, $\eta_g^2 = 0.05$). The interaction effect between two main factors ($F(1, 19) = 0.08$, $p = .783$, $\eta_g^2 = 0.00$) was not significant. It revealed the sensitivity of reproduction performance on the continuous accuracy feedback calibration, suggesting a larger spreading reproduction when the accuracy feedback is absent and higher consistency when present. In summary, the results of Experiment 2 demonstrated that without immediate accuracy feedback calibration, the reproduction was overestimated.

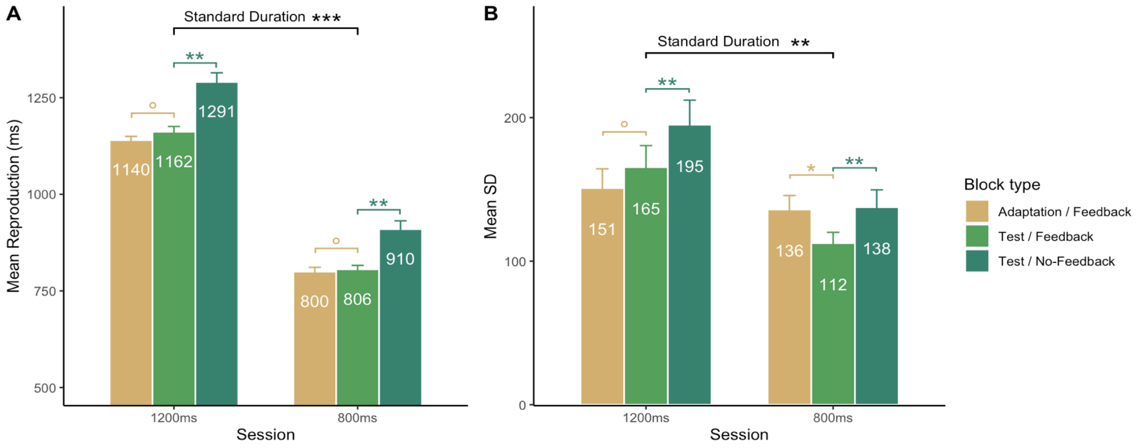

Figure 4. General mean reproduction duration (**A**) and mean standard deviation (SD) (**B**) in Experiment 2, for each session (800 / 1200 ms) and block type (Adaptation/Feedback,

Test/Feedback, and Test/No-Feedback). The asterisks mark the significant differences between conditions (p > 0.05: °; p < 0.05: *; p < 0.01: **; p < 0.001: ***).

Constant Overestimation Ratio

The key question to resolve in distinguishing between the two hypothesized attentional mechanisms: attentional sharing and switching - relates to whether overestimation is absolute or ratio-based. As shown in the above results, there was no significant difference between reproduced durations between the adaptation and test with the presence of accuracy feedback. However, a consistent overestimation occurred between the blocks with and without accuracy feedback, for both 800ms and 1200ms sessions. The average overestimation in the 800ms condition was 110 ms, representing 13.8% of the reproduced duration in the feedback blocks. Similarly, in the 1200ms condition, the overestimation was on average 150 ms and accounted for 13.2%. The absolute errors were significantly different between two sessions (*t*(19) = 2.14, *p* = .046, *BF* = 0.691), however, the ratio-based errors were comparable, *t*(19) = 0.28, *p* = .781, *BF* = 0.314.

Recall Experiment 1 had the absolute mean error of 109 ms, we compared the ratio-based errors between two experiments. The average ratio-based errors in the absence of accuracy feedback were 13.7% and 13.5% in Experiments 1 and 2, respectively. A Welch's t-test revealed they were comparable, *t*(46) = 0.09, *p* = .929, *BF* = 0.276, suggesting the general overestimation is comparable across different durations and experiments on ratio-based.

Discussion

In this study, we explored the underlying mechanisms responsible for consistent overestimation in time reproduction, focusing on the influence of both sensory and accuracy feedback during the reproduction process. Experiment 1 involved the shortening of a 150-ms action output (visual feedback), demonstrating that participants can calibrate their reproduction to motorically pressed duration for both shortened and synchronized action outputs if accuracy feedback was provided. When accuracy feedback was absent, however, reproduction progressively drifted back to overestimation in both scenarios. Interestingly, the difference between the shortened and synchronized conditions was consistently maintained across 20 trials in the mini-block. To rule out this drifting was caused by the anchoring effect (where subseconds and supper-seconds tend to anchor to a full second), we compared reproductions for both subsecond (800 ms) and supersecond

(1200 ms) durations in Experiment 2. Considering the pivotal role of accuracy feedback in Experiment 1, we also compared reproductions with and without accuracy feedback in Experiment 2. The results indicated a consistent overestimation across both durations, effectively negating the possibility of an anchoring effect. Furthermore, the overestimation, measured in a ratio basis, turned out to be comparable across the different durations and experiments.

In real-world situations, our actions and their effects are typically synchronized. When you press a light switch, the light comes on instantaneously. We only account for a delay when it is noticeable or when we have prior knowledge of it, such as knowing that hot water from a faucet will take a few seconds to flow. This implicit understanding of synchronized actions and effects often shapes how we act. Research has demonstrated that when a delay is subtly introduced between an action and its effect, it can profoundly influence our perception after we have adapted to it (Cai et al., 2012; Cunningham et al., 2001; Ganzenmüller et al., 2012; Shi et al., 2008; Stetson et al., 2006). For instance, when a 100 ms delay was injected between a button press and a subsequent flash, Cai et al. (2012) found that, following adaptation, a synchronized flash with the button press was perceived to have occurred earlier. This means that observers incorporated the 100 ms delay into the action-effect loop and recalibrated their action-effect prior. In Experiment 1 of our study, we also injected a 150 ms onset delay between the initiation of reproduction and its visual feedback. The focus on accuracy feedback was to direct observers' attention to their motor timing rather than visual feedback. However, we observed a consistent adaptation effect in the test phase: reproduction during the session with shortened visual feedback was 55 ms shorter compared to the session with synchronized feedback. This reduction in reproduction duration remained stable even without accuracy feedback and during reproduction reverting back the overestimation regime. These findings suggest that a delayed action output can recalibrate the internal prior of perceived duration. The effect was evident and sustained at least through the tested mini-block.

Another intriguing observation from Experiment 1 is the gradual return to an overestimation zone in both sessions. The reversion occurred during the absence of accuracy feedback. This progressively shift was unlikely to occur at the encoding stage, as the visual duration remained unchanged throughout the entire experiment, across two sessions. Rather, the most plausible explanation is that this general overestimation was a trait of the reproduction process itself, and it was constantly recalibrated when the accuracy feedback was provided. The reproduction in the synchronized visual feedback condition stabilized at 927 ms without accuracy feedback, resulting in an over-reproduction of 127 ms when compared to the physical duration of 800 ms. By observing this similar progressively reversion process, we can infer that a comparable overestimation likely remained in the shortened visual feedback condition, even after the prior had been updated during the adaptation to the shortened visual feedback.

So what could be the key factor causing such general overestimation observed during duration reproduction? As we have shown that reproduction with visual feedback cannot be solely attributed to motoric timing. Experiment 1, using shortened visual feedback adaptation, clearly illustrates that both the motor action and its effect (visual feedback) contribute to this general bias. In the introduction, we reviewed two potential explanations for this bias: attentional sharing and attentional switching (Fortin & Rousseau, 1998; Ganzenmüller et al., 2012; Zakay & Block, 1996). The attentional sharing hypothesis (Fortin, 2003; Fortin & Rousseau, 1998; Lejeune, 1998) suggests that attention is divided between action and timing process, resulting in an attentional lapse in monitoring the passage of time. According to the classic pacemaker-switch-accumulator clock model (Gibbon, 1977; Gibbon et al., 1984; Treisman, 1963) and attention gate theory (Zakay, 1989; Zakay & Block, 1996), attentional lapse causes fewer timing ‘ticks’ reaching the accumulator. The longer the duration is, the more ‘ticks’ that might be lost. On the other hand, the attentional switch assumes that switching latencies are affected by the task, such as switching from initiating the motor action to beginning to monitor the passage of time. And this switch effect only takes place at the opening and closing of the switch in the pacemaker-switch-accumulator model. Thus, the attentional switch hypothesis predicts that the overestimation should be consistent across different durations, as each duration is only influenced at its onset and the offset. It is worth noting that this interpretation of attentional switching can be seen as a special case of attentional sharing, where impacts occur only at the beginning and end. The interpretation of the ‘ticket’ loss caused by attentional lapse is closely related to the flickering switch account (Penney et al., 2000). According to this account, observers must maintain constant attention to a stimulus to keep the connection between the pacemaker and the accumulator. Without such attention, the switch may open spontaneously, reducing the number of pulses accumulated (Wearden et al., 2010; see also Wearden, Goodson, et al., 2007). In essence, both the flickering switch and attentional sharing accounts agree that attention is a pivotal factor for the general overestimation in duration reproduction.

In the present study, we observed the increased overestimation as the duration lengthened, which effectively dismisses the pure attentional switch hypothesis. Interestingly, across different sessions in both experiments, we observed that overestimates, calculated on ratio basis, were comparable, at 13.3% and 13.5% in Experiments 1 and 2, in the absence of accuracy feedback. Thus, our data seem to support the attentional sharing hypothesis (Fortin, 2003; Fortin & Rousseau, 1998; Lejeune, 1998) or the flickering switch account (Penney et al., 2000). However, we cannot entirely rule out that the possibility of the pacemaker speed of the temporal accumulation might slow down (Wearden et al., 2010; Wearden, Goodson, et al., 2007). This slowing down of pacemaker speed would mimic the prediction of the attentional sharing account (Fortin, 2003; Fortin & Rousseau, 1998; Lejeune, 1998) - a general overestimation is proportionate to the test duration. The present study, unfortunately, is unable to fully differentiate these two alternative explanations. Future research using extremely short or long durations (Wearden, Norton, et al., 2007) could further help untangle these two accounts.

However, insights might be drawn from a recent study (Ren et al., 2021). Ren and colleagues (2021) carried out a duration reproduction study across an extensive range, from 300 ms to 16 seconds. They observed consistent overestimation when durations were tested in blocks (separated into subsecond, seconds, and super-seconds categories to reduce the central tendency effect), except for the extreme long duration 16 seconds, where an underestimate was detected. Their findings implies that the general overestimation bias does not uniformly apply across all durations but is mainly confined to the sub-second and second ranges. For extremely long durations, the general bias appears to shift towards an underestimation. Such underestimation might partially be ascribed to the central tendency effect. As our day-to-day activities requiring critical actions usually fall within the subsecond and second ranges, this creates an implicit prior for action-related events in these time frames. When tasked with reproducing an extraordinarily long duration, this implicit prior likely influences the reproduction outcome. However, attentional lapse could also contribute to this underestimation. In the case of prolonged durations (such as 16 seconds), both attentional lapse and memory decay might affect the encoding and reproduction phases, and with significant impact of the former, resulting in an underestimation. Such underestimation phenomenon is challenging to explain solely with the slow-down pacemaker speed account, as it would predict the opposite outcome - overestimation.

In conclusion, here we observed a consistent overestimation in the reproduction of durations around a second, in the absence of accuracy feedback. The overestimation was approximately 13.5% on ratio basis across different durations and sessions, which was not influenced by shortened visual feedback. We propose that this consistent overestimation is a result of attentional sharing between action and monitoring of the passage of time during the reproduction process. Further research is needed to further disentangle roles of the pacemaker speed and attention in temporal reproduction.

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Chapter 4

Study 3

Aftereffects of Delay Adaptation in Visual and Tactile Duration Reproduction

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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 closed-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 indeed aligns with 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.

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).

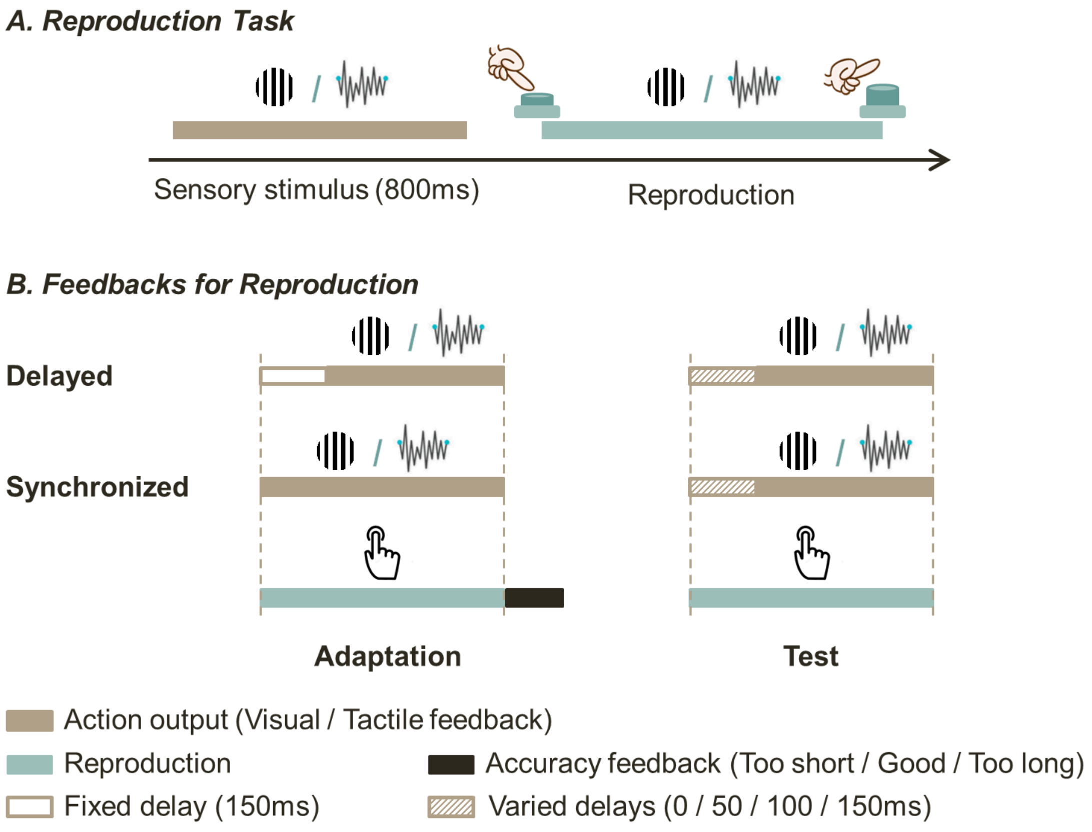

Figure 1. Schematic illustration of Experiments 1 and 2. The two experiments applied the same paradigm but differed in modalities of stimuli (Experiment 1: visual gabor patch; Experiment 2: tactile vibration). (**A**) A standard reproduction task, which comprised a 400 ms fixation, a 800ms standard duration 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.

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 ($F(1, 36) = 0.52$, $p = .475$, $\eta_g^2 = 0.01$) and the interaction between the two main factors ($F(1, 36) = 0.17$, $p = .678$, $\eta_g^2 = 0.00$). 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).

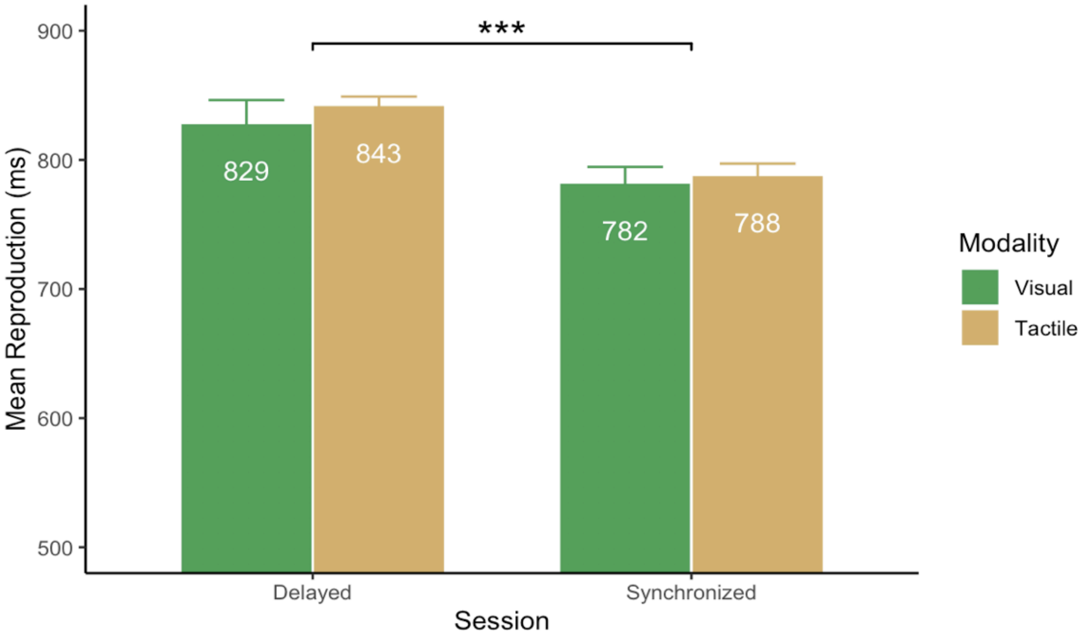

Figure 2. The mean reproduction duration from the Adaptation phases, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-session difference ($p < 0.001$: ***).

Prior Representation with 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.

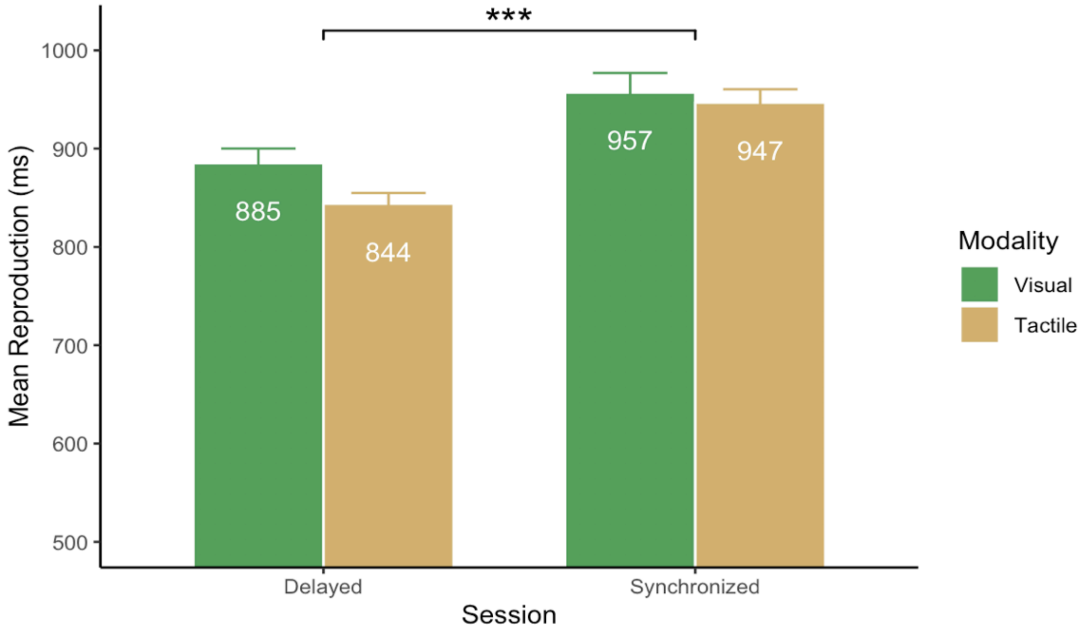

Figure 3. The mean reproduction duration from the test trials, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-session difference ($p < 0.001$: ***).

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 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.

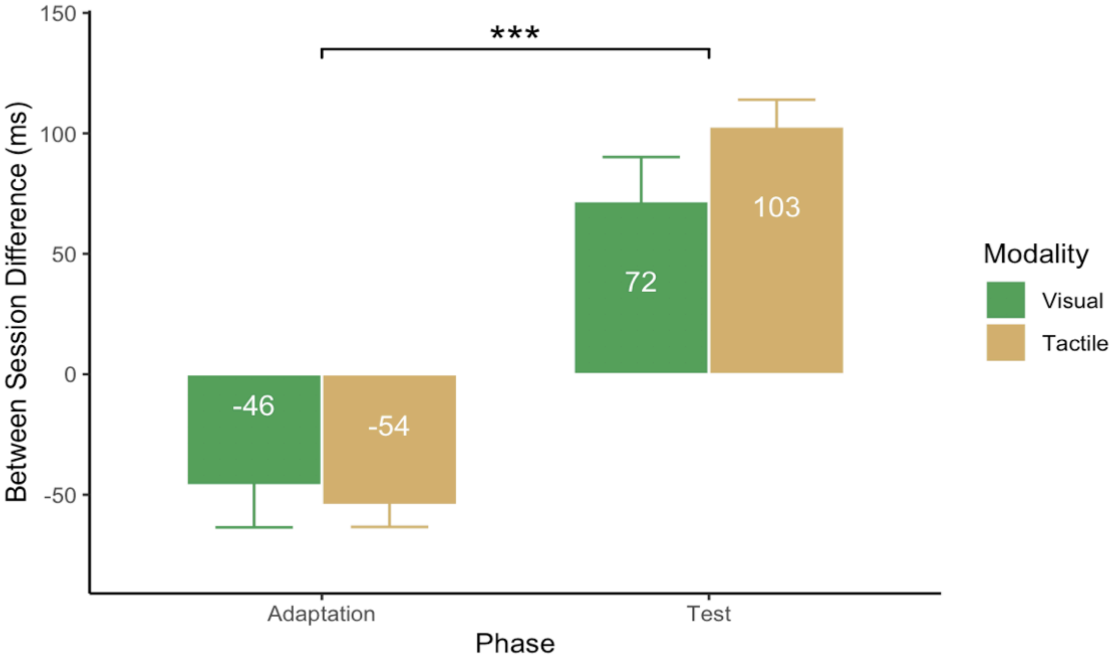

Figure 4. The mean reproduction duration differences between sessions (Synchronized - Delayed), separated for each phase (Adaptation / Test) and modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-phase difference ($p < 0.001$: ***).

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 4A), 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 ($t(18) = 2.52$, $p = .021$).

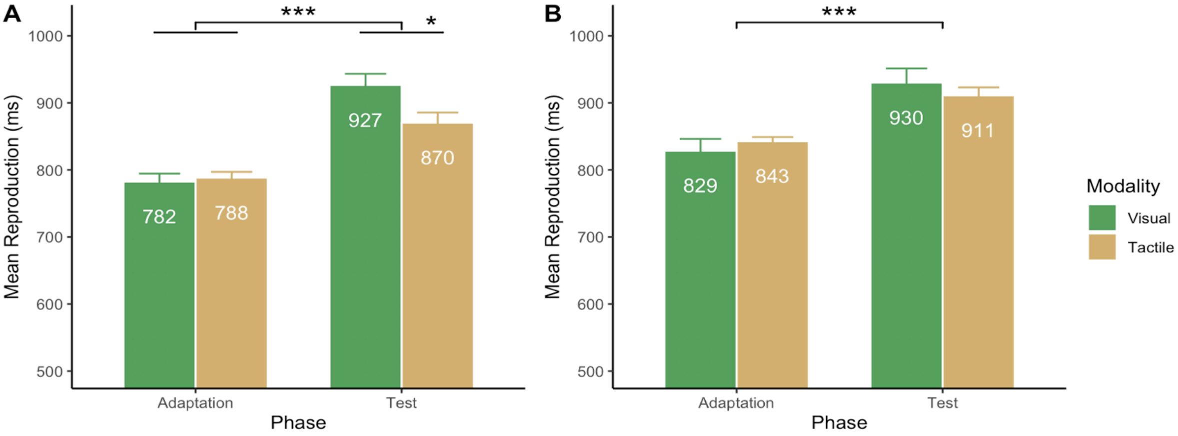

Figure 5. Constant overestimation from between-phases comparisons in both Experiment 1 (Visual) and Experiment 2 (Tactile). In synchronized feedback session (**A**), the general mean reproduction duration was compared between Adaptation trials and Test trials with 0 ms delay. In the delayed feedback 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 4B), 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.

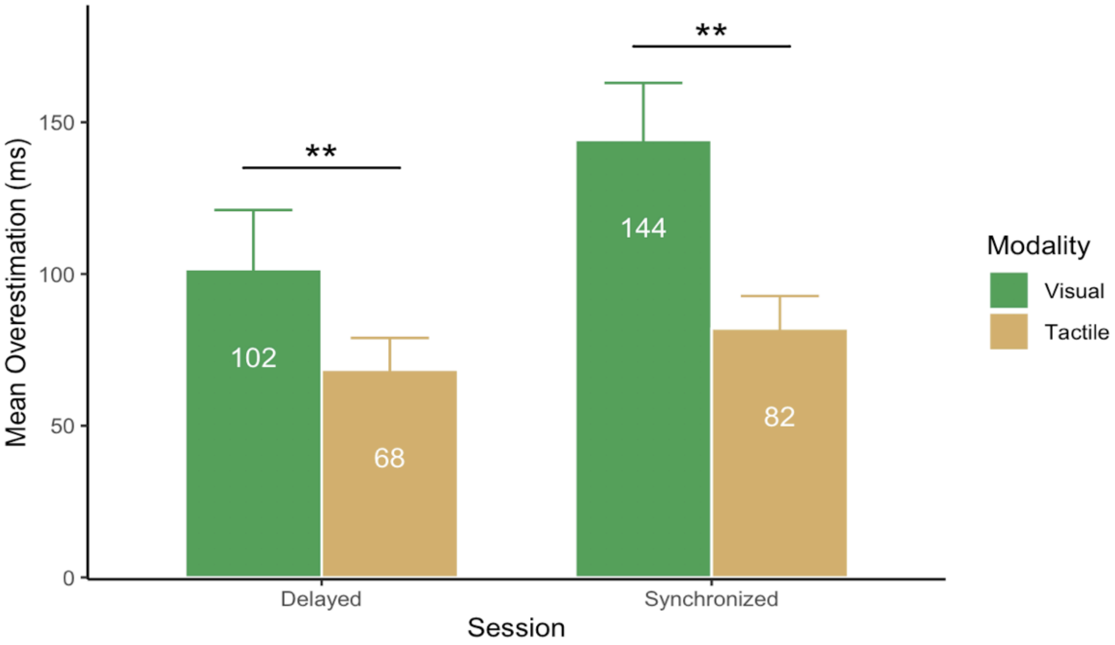

Figure 6. The mean overestimation in the Test phase relative to Adaptation phase, separated for each session (Delayed / Synchronized) and test modality (visual, Experiment 1, tactile, Experiment 2). The asterisks mark the significant between-modality difference ($p < 0.01$: **).

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. An 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, η_g^2 = 0.30, Delay Level, *F*(1, 36) = 272.64, *p* < .001, η_g^2 = 0.26.The main effect of the between-subject factor Modality, however, was non-significant, *F*(1, 36) = 1.92, *p* = .175, η_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, η_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, *F*s(1, 36) < 2.10, *p*s > .15, η_g^2s < 0.01.

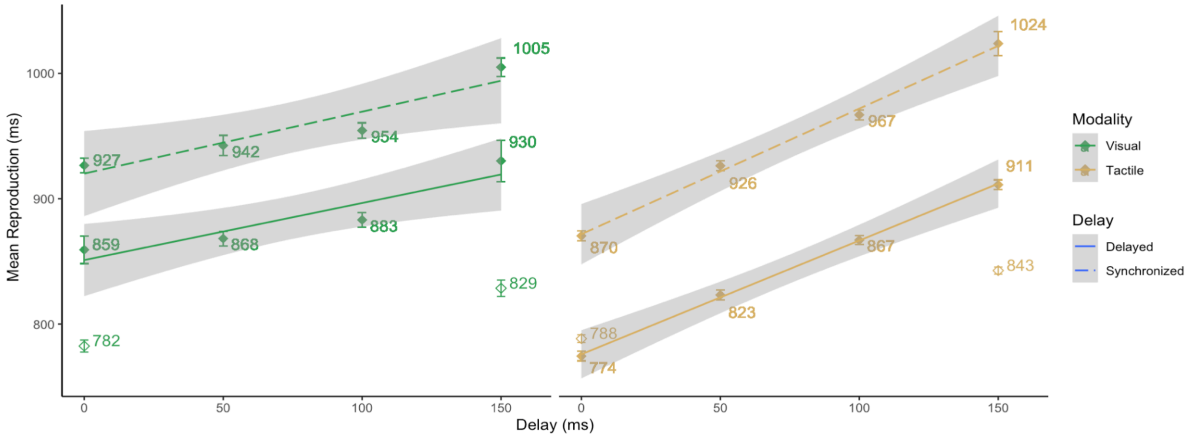

Figure 7. The mean reproduction duration for each delay level in both sessions (delayed, synchronized) and both experiments (Visual: left panel, Tactile: right panel). Each adaptation phase had one single mean reproduction duration for a fixed delay of either 0ms (synchronized) or 150ms (delayed). The 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.

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:

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

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

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.

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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Chapter 5

General Discussion

This thesis comprises three studies aiming for a better understanding from action to attention and time perception. Study 1 provided insights into temporal distortions and attentional gradient induced by saccade, while Study 2 and 3 shed insight on general bias resulting from attentional sharing and cross-modality sensorimotor integration during the temporal reproduction process.

1. Summary Findings

1.1. Study 1: Saccade-induced Temporal Attentional Gradient

Study 1 investigated the effects of saccades on the time perception distortions occuring after saccades and attentional mechanisms associated with it. Experiment 1 manipulated the temporal location of the reference interval relative to the post-saccadic first (test) interval, which either followed immediately or after a 2-second gap, and showed a greater Chronostasis effect when the reference interval was the post-saccadic second interval. Building upon this foundation, both post-saccadic first and second intervals were designed to be the test intervals in Experiment 2, compared to a fixed reference interval with a long gap after the second interval. It directly examined the temporal attentional gradient hypothesis which suggested a transiently enhancing of the first post-saccadic event timing and (as the initial boost fades out) a degrading the immediately following, second event timing. The findings challenged the current view by revealing that saccadic eye movements not only affect the perceived duration of the first post-saccadic event, immediately present at the saccade end but also subsequent events.

Importantly, contrary to the first event that is dilated, the second post-saccadic event is subjectively compressed, enhancing the Chronostasis effect when it serves as a reference interval. The compression effect persisted even when potential “attentional-blink”-induced processes were eliminated. We propose that saccades induce a transient temporal attentional gradient, resulting in an overestimation of the first interval and an underestimation of the second interval after the saccade. This study sheds light on the intricate nature of subjective time distortions induced by saccades. The present results indicate that the timing-related factors, such as stimulus onset, saccadic action, and the reference interval all play crucial roles in duration judgments. Remarkably, saccade-induced temporal attentional modulation was found to extend beyond the post-saccadic first event. It is an important contribution to the understanding of attentional mechanisms involved in saccade-related time distortions, and importantly, it brings to light a new view on the duration perception of post-saccadic events, unifying the existing data with the new results.

1.2. Study 2: Constant Overestimation in Reproduction

Multiple temporal biases can be induced in the temporal tasks (Glasauer and Shi 2021). Previous studies have reported an overestimation in the duration reproduction task (Grondin, et al. 2012; Bausenhart, Dyjas, & Ulrich, 2014), however only as a side error without clear discussion. Study 2 investigated the underlying mechanism of this constant overestimation, with a particular focus on both sensory and accuracy feedback during the reproduction. Experiment 1 manipulated the action output (sensory feedback) duration and showed a shorter reproduction duration after adapting to shortened action output. Additionally, a consistent overestimation occurred after both shortened and synchronized conditions when the accuracy feedback was absent. Experiment 2 applied a comparable temporal reproduction paradigm with synchronized action output to further investigate the two possible explanations for this overestimation. First, the anchoring effect towards one second was negated as the overestimation occurred consistently when reproducing both sub-second and super-second durations. Second, the attention was suggested to be shared rather than switched between action and monitoring the passage of time, as the overestimation was demonstrated to be consistent across different durations on a ratio basis (13.8%) rather than an amount basis. It is important to note that this constant overestimation was replicated in Study 3 in both visual and tactile reproduction tasks regardless of the temporal discrepancy between action and action output.

1.3. Study 3: Cross Modality Sensorimotor Integration

Humans have the ability of adapting to temporal discrepancy and integrating cross-modalities information to create a coherent perception. Study 3 investigated how the new sensorimotor relationships were adapted when varying temporal discrepancy appeared in the different sensory modalities (visual and tactile). It comprised two experiments applying a consistent Adaptation-Test paradigm with a duration reproduction task. It is important to note that Study 3 replicated the constant overestimation in reproduction tasks reported in Study 2. The reproduction duration was shorter after adapting to a temporal discrepancy between action output and motor reproduction, suggesting a successful adaptation effect in both visual and tactile modality. The sensitivity was found higher when the temporal discrepancy occurred between tactile and motor than between tactile and motor. The fitted linear regression model further supported this finding with a larger estimated slope for tactile modality, which represented a larger tactile weight of sensorimotor integration than visual weight.

2. Theoretical Considerations: Attention in Action and Time Perception

Attention is tightly coupled with action and plays a crucial role for accurate time perception and modulating the subjective experience of time (Deubel & Schneider, 1996; Nobre et al., 2010; Fleck, Bischoff, & O'Laughlin, 2001). The event duration tended to be overestimated when actively attended, resulting in a perceived lengthening of time, and conversely, be underestimated when the attention was diverted away from time, leading to a perceived shortening of duration (Kirsch et al., 2021; Konstantinova et al., 2019; Polti et al., 2018). Moreover, the influence of action on spatio-temporal perception is associated with attention throughout the entire action process, encompassing action planning, execution, and post-action phases (Mangun & Hillyard, 1988; Deubel & Schneider, 1996; Shepherd et al., 1986; Müller & Rabbitt, 1989). Expanding on this groundwork, the current studies explored and examined the role of attention both during and after action. Specifically, Study 1 put forth the temporal attentional gradient account to explain the action-end effect in temporal discrimination, whereas Study 2 proposed the attentional sharing account concerning the execution of temporal reproduction.

In typical Chronostasis experiments, sequential time intervals were displayed after saccade, with a specific focus on the temporal distortion of the first interval as the test interval, referencing the interval that follows immediately. Study 1 demonstrated that the saccade-coupled attention may create a temporal attentional gradient that can impact not only the first interval, but also the immediately following reference (second) interval. The processing of post-saccade events was temporarily boosted in the peri-saccadic period but compromised immediately afterwards. This greatly increased compression was only observed after eye movements but not in the fixation baselines and, therefore, can be solely attributed to the preceding saccadic eye-movement. The current accounts for Chronostasis, neither the active compensation for the stimulus onset (Yarrow et al., 2001) nor the low-level sensory factors (Knöll et al., 2013), can easily account for this compression, as the second post-saccadic interval onset can be perceived clearly without high uncertainty relative to the post-saccadic first interval onset which occurred within the peri-saccadic time window. Alternatively, Study 1's findings supported the attentional account of the uneven temporal attentional gradient, which suggested a transient post-saccadic attentional enhancement of the first post-saccadic event and a relative attentional fall of the second post-saccadic event, leading to a temporal processing compromission and consequently a shorter perceived duration. It is crucial to highlight that Study 1 not only sustained the role of temporal attentional modulation in the action end effect, but also extended this saccade-induced effect beyond the first post-saccadic event.

The allocation of attention plays an essential role in monitoring the sub-tasks of duration reproduction and exerting an impact on reproduction performance. Study 2 demonstrated a constant overestimation and proposed the account of attentional sharing between action and monitoring of the passage of time during the reproduction process. When some attentional resources were devoted to the action, attention lapse in the time process may cause over-reproduction (Zakay & Block 1996; Ganzenmüller et al. 2012; Fortin & Rousseau 1998). It should be noted that the attentional sharing account could explain the over-reproduction for those trials without accuracy feedback, but alternative accounts cannot be simply ruled out. One of such alternative explanations is that the overestimation could be induced by the additional switching cost when attention switches between the reproduction action and time process. This possibility was examined through varying the target durations. If the attention switches between the two subtasks of reproduction, an absolute amount of overestimation should be expected. On the contrary, if the attention is shared between the two subtasks, the overestimation should be expected to be larger with longer target duration, with a constant ratio to the reproduced duration.

The results showed that the overestimation only occurred when the accuracy feedback was absent and maintained a constant ratio of 13.8% to the reproduction duration rather than an absolute amount. These findings suggested the test effect of the accuracy feedback, which immediately calibrated the reproduction duration after each trial and dismissed the occurrence of overestimation. Of particular importance, the findings effectively differentiated between the two proposed attentional accounts, suggesting that overestimation was induced due to the attentional sharing rather than switching. To be specific, the constant overestimation was not constant with an absolute amount but with a constant ratio of the standard duration. It contradicted the account proposing attentional switching between two reproduction subtasks, which predicted an absolute overestimation as the switching cost, irrespective of the standard duration. The constant ratio, on the contrary, evidenced the shared attention across the different processes of the two subtasks to monitor the reproduction task. As the attention resource is limited, the shared attention led to less attention to monitor the internal clock, which resulted in the lost ticks and accordingly longer reproduced duration. The longer the standard duration to reproduce, the longer the overestimation would be. Additionally, the comparable ratio of the overestimation in both experiments suggested that the attentional sharing account fully explained the overestimation in both experiments, regardless of the variance in visual feedback.

3. Methodological Insights

3.1. Action-end Effect

Study 1 explored the perceived duration of events after saccade and proposed the saccad-induced temporal attentional gradient account. Drawing an analogy, it could be intriguing to extend this attentional perspective concerning action-end effects beyond saccade, encompassing other actions, particularly focusing on post-action events beyond the first one.

For instance, a typical post-action time compression effect, “intentional binding”, was first reported by Patrick Haggard and his colleagues (2002) as a novel measure of the sense of agency. It refers to the phenomenon that the subjective time in between people’s voluntary action and the consequent effect being perceived is shorter compared to the objective time. In another word, the voluntary action onset and consequent effect onset are perceived closer. The most typical paradigm adopted the Libet’s clock method (Libet et al., 1983).

Participants were instructed to make a voluntary or an involuntary action (induced by TMS) while watching a silent clock rotating at a constant speed. A tone would be presented after the action with a 250 ms delay. The task was to report the clock time for either the action or the tone. Compared to the involuntary conditions, the time of the voluntary action was always perceived later and the consequent tone was always perceived earlier (Haggard, Clark, & Kalogera, 2002). Similar time compression effect was also found in a more direct paradigm which estimated the duration of the delay interval directly (Moore & Obhi, 2012).

In general, intentional binding is a time compression effect induced by voluntary action. A series of relevant studies were conducted accordingly, investigating the characteristic and mechanism of this effect, however still lacking evidence for establishing the role of attention (Moore & Obhi, 2012, for a review). Taking into account the representative intentional binding paradigm, it could be valuable to include a comparable comparison, similar to that of Study 1, between the first and second post-action events (and potentially subsequent events). Furthermore, the temporal delay between the action and its subsequent effect to some extent aligns with the sensorimotor discrepancy manipulated in the Study 2 and 3, with a core distinction of being explicitly and implicitly noticed by the participants. It might provide an innovative and comprehensive perspective for integrating the three studies, encompassing cross-modality, sensorimotor processes, attention mechanisms, action-related effects, and time perception, paving the way for future research endeavors.

3.2. Duration Reproduction Task

3.2.1. Adaptation-Test Paradigm

Study 2 demonstrated the ratio-based constant overestimation in the visual reproduction task through an Adaptation-Test paradigm. It is important to note that, for the Experiment 1 synchronized condition, the task was the same for the Adaptation and Test phase, only differing in the accuracy feedback present and absent. The overestimation in the Test phase suggested that without immediate feedback calibration, reproduction of a visual event was overestimated. The same overestimation likely occurred in the shortened condition, yet, behaviorally failed to observe the difference between the Adaptation and the Test. Recall the duration reproduction task, which consists of the initial encoding the target duration and then the reproduction. During the Adaptation phase, unbeknown to participants, the visual feedback was shortened 150 ms. However, continuous accuracy feedback (with the motor duration, but not the shortened visual duration) calibrated the perceptual representation of the target duration to be shorter. Thus, the shortened encoding of the target duration and the later overestimation may cancel each other, yielding a non-significant difference between the Adaptation and the Test. It is demonstrated applying the constant overestimation ratio for the reproduction duration recalculation, subtracting the general bias induced by the absence of accuracy feedback (Figure 3). The 2 (Session: Shortened VF, Synchronous VF) × 2 (Phase: Adaptation, Test) ANOVA for the corrected reproduction in Test phases showed significant main and interaction effects: Session, F(1, 18) = 6.60, p = .019, g2 = 0.03); Phase, F(1, 18) = 6.72, p = .018, g2 = 0.12); Session x Phase interaction, F(1, 18) = 28.82, p < .001, g2 = 0.12). These findings further supported the significant overestimation when the accuracy feedback was absent as well as the shortened target duration encoding and the later over-reproduction canceled each other.

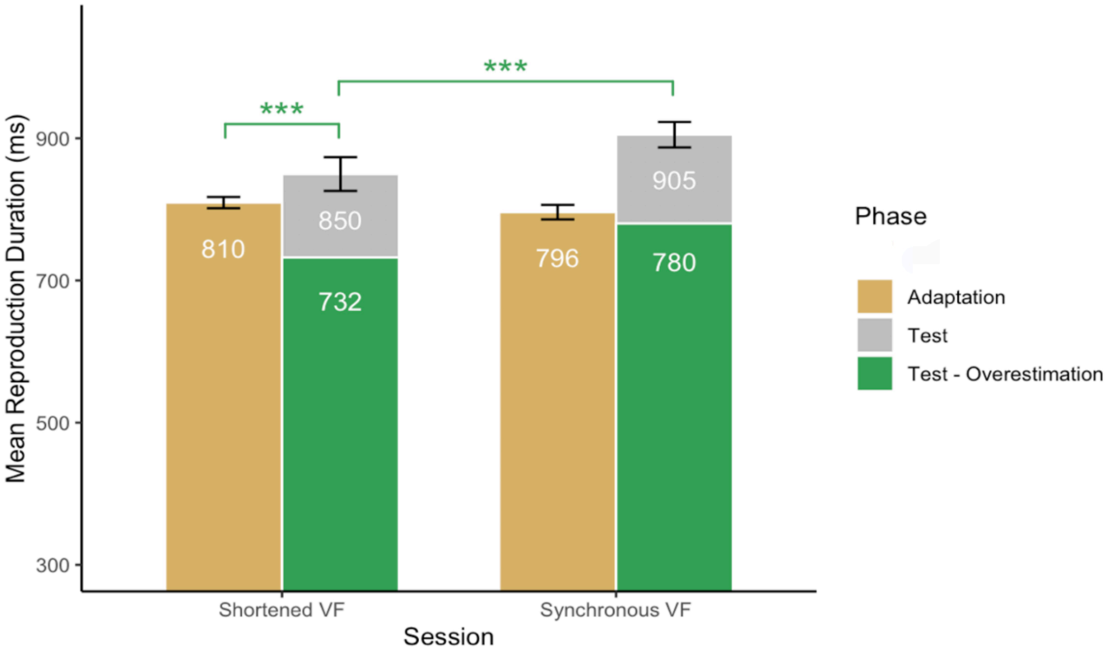

Figure 3. The recalculated overestimation and general mean reproduction duration for all four conditions in Study 2 Experiment 1 (two sessions x two phases). The asterisks mark the significant interaction effect and between-condition differences (p < .001: ***).

The above results distinctly presented a fundamental paradox within this Adaptation-Test paradigm. The reproduction performance is significantly influenced by the continuous accuracy feedback calibration. However, the inclusion of accuracy feedback is necessarily unavoidable in the Adaptation phase to ensure effective adaptation, while the exclusion of accuracy feedback is equally imperative for observing the target performance. One potential solution involves the post-correction based on the constant ratio of the overestimation. Nevertheless, this approach could potentially lack flexibility and adaptability across different modalities, study designs, and other contexts, potentially constraining the applicability. It is not also not feasible to determine a tailored overestimation ratio prior to every experiment. Building upon this foundation, it is crucial to be cautious during the study design phase to prevent the emergence of this paradox and the task-irrelevant overestimation. Moreover, when interpreting outcomes within such Test phases, it's imperative to emphasize relative comparisons between conditions rather than the absolute values, and to exercise caution against over-interpreting results across the Adaptation and Test phases.

3.2.2. Trial-by-trial Fluctuation

Another interesting finding in the duration reproduction studies is the trial-by-trial fluctuation observed for the length of the reproduced duration. The omission of this detailed finding in the aforementioned papers was due to its limited relevance to the research question and the lack of a significant difference between conditions. Nevertheless, the consistent nature of this pattern deserves a comprehensive discussion as well as dedicated studies designed to explore it further.

In typical psychological experiments, each manipulation is normally tested multiple times to achieve a relatively stable general performance to support theoretical exploration. Previous studies have well explored multiple factors which might affect trial-wise performance, such as trial sequence and prior information (Dyjas, Bausenhart, & Ulrich, 2012; Glasauer and Shi, 2022). In Study 2, Experiment 2 provided an unique example in the test phase, in which all trials within each sub-block were identical. The only manipulation was the accuracy feedback presence and absence across blocks. Nevertheless, considering the inherent nature of duration reproduction tasks (differing from force-choice tasks with constrained response options), it is impossible for participants to reproduce exactly the same duration in every trial, even with continuous calibration via accuracy feedback. Building upon this premise, a more detailed analysis delved into the inter-trial differences. The anticipation was that a trial-to-trial variability in reproduced duration would manifest in the blocks comprising accuracy feedback offered after each trial, compared to the blocks without accuracy feedback. This projection was grounded in the assumption that participants would adjust their responses for subsequent trials based on their own responses and the accuracy feedback received from the preceding trial. For instance, when provided with an accuracy feedback of “too long”, participants were expected to reduce their reproduction duration in the subsequent trial compared to the ongoing one. Such adjustment in trial-by-trial performance was not expected in the blocks where accuracy feedback was absent.

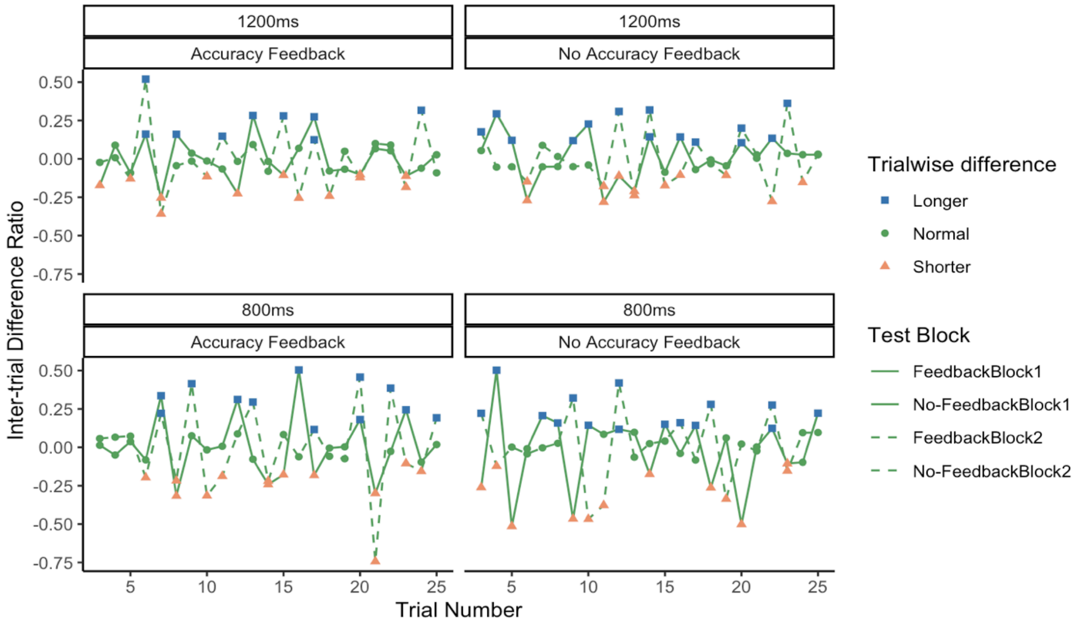

Figure 4. A typical example of the inter-trial difference from one participant. In both 1200 and 800 ms standard duration sessions, the Test phase comprised 4 sub-blocks, two accuracy feedback present and two absent blocks. The inter-trial difference was calculated and presented for each sub-block.

A supplementary trial-by-trial analysis was conducted for all Test trials in Experiment 2 Study 2. The inter-trial differences between Trial N and Trial N+1 was categorized into three types (Longer, Normal, and Shorter) with a reference range established at 10% of the standard duration. Those falling within the 10% range were categorized as "Normal." An increase exceeding 10% was categorized as "Longer", indicating that the reproduction duration in Trial N+1 was notably longer than in Trial N. Conversely, a decrease exceeding 10% was labeled as "Shorter", denoting a shorter reproduction duration in Trial N+1. As expected, rhythmic trial-to-trial fluctuations were evident in the accuracy feedback blocks, where the inter-trial differences alternated consistently between Longer and Shorter through the Normal category in both 800 and 1200 ms sessions (Figure 4, left panel). Interestingly, a comparable pattern was also observed in the blocks without accuracy feedback (Figure 4, right panel). This surprising finding might imply that while continuous calibration through accuracy feedback is crucial for maintaining accurate reproduction performance and preventing general over-reproduction (constant overestimation in Study 2), participants also appear to possess the capacity to implicitly recognize and self-calibrate reproduction within a narrow temporal range for consecutive trials.

4. Outlooks

Building upon the above theoretical and methodological discussions, there are several potential future studies proposed regarding the role of attention and the trial-by-trial fluctuation.

Focusing on the saccade-induced attentional gradient proposed in Study 1, it would be intriguing to further investigate the post-saccadic distortions in subsequent events. Expanding on the intentional binding effect discussed above, exploring the expansion of the attentional gradient account from saccade-induced situations to other actions could also yield valuable insights.

Additionally, the Study 1 and 2 proposed attentional gradient and attentional sharing accounts for the saccade-induced temporal distortion and general bias in reproduction predominantly rely on behavioral evidence. While the behavioral data provide valuable insights, the absence of complementary neuroscientific techniques, such as EEG, fMRI, or TMS could potentially constrain a comprehensive grasp and the opportunity to make causal inferences about the underlying neural mechanisms. Conducting further research that integrates both behavioral and neuroimaging methodologies would provide a more comprehensive understanding of the role of attention, thereby bridging the gap between behavioral observations and the underlying neural mechanisms. For instance, exploring attentional blink and temporal expectation associated with phase oscillations (Zauner et al., 2012; Cravo et al., 2013; Nobre & Van Ede, 2018) might provide insight into the underlying neural mechanisms for the time perception after saccade.

Regarding the trial-by-trial fluctuation observed in the duration reproduction tasks (Study 2 Experiment 2), the present findings are not sufficient to provide a comprehensive understanding of this trial-wise fluctuation. Further research incorporating a tailored trial-wise design could be helpful to offer a more insightful perspective on this phenomenon. For instance, it remains unclear whether such fluctuation is triggered by participants' implicit self-awareness of the deviated reproductions and corresponding effort to monitor more precise reproduction, or if it represents a natural variation inherent to the duration production process. A straightforward duration production task could be well-suited to differentiate between these two alternative explanations. If this trial-wise fluctuation is a natural variation, it should be observed not only in the reproduction task but also in the duration production task. Repeatedly producing a standard duration, either pre-learned or based on an intrinsic reference (such as one second), should be adequate. With a specific emphasis on the inter-trial difference ratio, potential variations in production duration between subjects or the overall over- or underestimation stemming from memory decay wouldn't impede the observation. Incorporating additional manipulations, such as modality type, sensory feedback, and varying pre-learned standard duration across independent blocks, could provide a more comprehensive perspective on this phenomenon.

5. Conclusion

To sum up, this thesis consists of three studies under the topic of action, attention, and time perception. Study 1 demonstrated that saccadic eye movements' impact on the perceived duration beyond the first post-saccadic event. The findings challenged the current view by revealing that saccadic eye movements not only affect the perceived duration of the first post-saccadic event, immediately present at the saccade end but also subsequent events. Importantly, contrary to the first event that was dilated, the second post-saccadic event was subjectively compressed, enhancing the Chronostasis effect when it serves as a reference interval. The compression effect persisted even when potential "attentional-blink"-induced processes were eliminated. A saccade-induced transient temporal attentional gradient was proposed to lead to an overestimation of the first interval and an underestimation of the second interval. Study 2 revealed a constant overestimation in the duration reproduction task when the accuracy feedback was absent, which remained consistent at approximately 13.5% across varying standard durations and sessions, irrespective of the shortened visual feedback. The proposed account for this constant overestimation was the shared attention between the two sub-tasks during the reproduction process, which were action and monitoring of the passage of time. Study 3 explored the sensorimotor integration for both visual and tactile modalities through manipulating the temporal discrepancy between action and action output. The overall findings suggested that the temporal discrepancy adaptation was influenced by the integration of multisensory timing and motor timing, which weighted differently across modalities, with a higher sensitivity on the tactile modality than the visual modality.

The present studies shed light on the intricate nature of subjective time distortions induced by saccades, brought a new view on the duration perception of post-saccadic events, and indicated that the stimulus onset, saccadic action, and the timing of the reference interval all play crucial roles in duration judgments. In addition, understanding how attention was distributed between the reproduction action and the passage of time allowed unravel the mechanisms underlying the observed overestimation. The investigation provided insight into the intricate relationship between attention allocation, constant overestimation, and cross-modality sensorimotor integration, paving the way for a more comprehensive understanding of the underlying cognitive processes involved in duration reproduction tasks.

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"Completing a PhD is no small feat; it requires years of dedication and countless hours of research. Your journey through this rigorous process is a testament to your resilience and relentless pursuit of knowledge."

—— Strongway

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“Let’s have a talk. You did much better than I expected this time. Do you know you are actually talented? You are young, passionate, and can have a long way to go in academia. I can give you some more suggestions if you would like.”

“PLS DO NOT MOVE THAT SET UP”

—— Lukasz

That was the last formal meeting we had, sitting together in person, though neither of us realized it at the time. And that was the written note you left for our cabin, the one we built together and you rebuilt again, before you moved to your new position, and before I finally managed to return to continue our study after the unexpected one-year pandemic gap.

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“You know you can do it.”

“It is you, yourself, who did it.”

—— Jan

It seems to be common to encounter a hard period during PhD study. As you told me, it was Strongway who came to you during your hard time and said, "Hey, shall we have one more try?" And it was you, Jan, who came to me during my hardest time and said, "Hey, let’s have one more try." Thank you for coming to me, for telling me you understand what is happening and how it feels, for sharing that you did it and you know I can do it too, and for guiding me through step by step. While you always told me it was my own effort that got me through, I would like to say that your support felt like a bright light in a dark space, lighting up a way out.

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"Morning~"

"Shall we start today's standup meeting?"

—— Yannan

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“CSC Scholarship, 4 Years”

“LMU-Abschlussstipendium, 3 Months”

“GSN-LMU Stipendium, 5 Months”

—— Scholarships

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