TEMPORAL RECALIBRATION: DOES AWARENESS INFLUENCE HOW WE PERCEIVE TIME?

By

Mikaela Bubna

Supervisor: Dr. Erin K. Cressman
Committee Members: Drs. Anthony N. Carlsen and Melanie Lam

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School of Human Kinetics
Faculty of Health Science
University of Ottawa

Statement of Contributors

I hereby declare that I am the sole author of this Master of Science thesis. My contributions include: A review of literature in the area of interest, participant recruitment, participant testing, data collection, data compilation, statistical analyses, and the write-up of this thesis document. All of these duties were performed under the guidance and mentorship of my research supervisor, Dr. Erin K. Cressman.

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Abstract

After exposure to a short, constant delay between voluntary movement and sensory stimuli, temporal recalibration (TR) arises to realign asynchronous stimuli. The objective of this study was to determine if awareness of the temporal lag between a motor response (i.e., a keypress) and a sensory event (i.e., a visual flash) is necessary for TR to occur. We further investigated whether manipulating the motor and judgment tasks required modifies the influence of awareness on TR due to the cognitive processes engaged. Participants (n = 22) were randomly divided between two groups (Group 1: Aware and Group 2: Unaware). The Aware group was told of the temporal lag between their keypress and visual flash at the beginning of the experiment, whereas the Unaware group was not. All participants completed 8 blocks of trials, in which the motor tasks (e.g., a single or repetitive tap), judgment tasks (e.g., judging the order of the keypress in relation to the visual flash or judging whether the two stimuli were simultaneous or not), and temporal lag between keypress and visual flash (e.g., a 0 ms or 100 ms lag) varied. TR was determined by comparing judgments between corresponding blocks of trials in which the temporal lag was 0 ms to 100 ms. Results revealed that both the Aware and Unaware groups of participants demonstrated TR across both motor and judgment tasks, and that the magnitude of TR did not vary across Aware and Unaware participants or tasks. Thus, results of the present study revealed that awareness of a temporal lag does not influence the magnitude of motor-sensory TR achieved.

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Chapter 1: Introduction

1.1 Introduction

When we type on a computer, we expect the appropriate letters to appear on the screen after a small, consistent, delay. What happens when the sensory feedback does not meet our expectations? For example, the wrong letter appears on the screen or the letter does not appear at the expected time. Do we still interpret the sensory information as arising as a consequence of our actions?

To act appropriately within our environment, we must understand the temporal relationship between our voluntary actions and resulting sensory feedback. Research suggests that one's perception of time can change with constant exposure to an increased lag between motor and sensory events (Stekelenburg et al., 2011; Sugano et al., 2010). For example, if someone completes several keypresses and there is a constant temporal lag (e.g., 100 ms) between their keypress and a letter appearing on the screen, they still associate the lagged sensory feedback (i.e., the letter appearing on the screen) as arising due to their action (i.e., the keypress). Time has been recalibrated, and sensory events once again become tied to motor actions.

It has recently been suggested that one must be aware of the temporal lag between one's actions and sensory feedback in order for time to be recalibrated (Tsujita & Ichikawa, 2016). The purpose of this project was to determine the validity of this hypothesis under task conditions that have previously demonstrated temporal recalibration (TR). In particular, we examined the role of

awareness in TR when the type of motor task (e.g., single tap versus repetitive tap), and perceptual judgment (temporal order judgment versus simultaneous judgment), are manipulated.

This thesis consists of four chapters. Following this introduction, Chapter 2 reviews the relevant literature critical for understanding the rationale underlying the current project. Chapter 3 consists of a manuscript outlining the thesis project, and Chapter 4 discusses our findings in greater detail, drawing conclusions regarding the influence of awareness on the magnitude of TR across varying motor and judgment tasks.

Chapter 2: Literature Review

2.1 Time Perception

Perceiving the relative timing of events is a complex task. Discrepancies in physical propagation speeds and neural processing latencies across different stimuli (e.g., light and sound), as well as the processes required to plan and initiate motor actions, makes perceiving the order of events ambiguous (Alais et al., 2010). While difficult, it is often necessary to judge the order of events to make real-world decisions. Imagine you are a wrestler competing in a match. The score is three-to-three, and time in the match is running out. You finally manage to push your opponent out of the ring, just as the buzzer goes off. What happened first? If you pushed your opponent out of the ring before the buzzer went off, you win the round. However, if the buzzer went off first, the match ends in a draw. As this example illustrates, perceiving the order of events is necessary for interacting with our environment in a meaningful way and creating salient and reliable experiences (Vroomen & Keetels, 2010).

While our bodies contain sensory systems for processing information related to touch, taste, sight, and audition, etc., there is not a single system dedicated to processing time. Instead, areas throughout the brain (e.g., the frontal cortex, basal ganglia, and cerebellum) have been implicated in time perception (Lee et al., 2007; Pouthas et al., 2000). Thus, how we perceive time is subject to distortion.

Common idioms such as “time flies when you’re having fun,” or “the watched pot never boils,” are examples of the prevalence of our flexibility in time perception. When you are having fun, you are not attending to time itself, rather you are focusing on the fun aspect, thus leading to the perception of a decreased duration of time. On the contrary, waiting for the water to boil will

lead to a perceived increased duration of the amount of time passing (Block et al., 1980). These common examples of experienced time distortions illustrate how the perception of time varies depending on cognitive processes engaged (e.g., attention). The next section will explore the perceived temporal relationship between two sensory events (e.g., lightning and thunder), as well as between a motor response and subsequent sensory event (e.g., keypress and visual flash).

2.2 Temporal Relationships Between Events

2.2.1 Sensory-Sensory

To perceive the order and synchrony of events, the brain must account for latencies between processing speeds for different sensory signals such as vision (e.g., light), audition (e.g., sound), and tactile sensation (e.g., touch). Vision is processed slower than audition, while tactile information is processed faster or slower depending on where stimulation occurs on the body (e.g., the neural signals from the nose will reach the brain faster than the neural signals from the toes; Keetels & Vroomen, 2012). Therefore, to establish the relationship between a visual and auditory event (e.g., did a basketball player release the ball before the buzzer sounded?), the brain must integrate information across these different modalities to make a decision. The complexity of sensory integration and individual differences in one's ability to reliably integrate sensory information has been known for a long time. Consider records from the 1700s, when an astronomer's assistant's job was to precisely record the time it took for a star to pass by a larger astronomical object, using a metronome's beat as a measure of time (Duncombe, 1945). Specifically, these assistants had to use visual and auditory information to accurately determine

the time at which the stellar transit crossed the wire on the telescope. While the task seems simple enough, assistants recorded different times, providing evidence that perceiving the relationship between sensory stimuli in a multisensory world is a complicated process, prone to discrepancies arising from individual differences.

2.2.2 Motor-Sensory

One's perception of the temporal relationship between voluntary actions and sensory feedback is also complicated and prone to error. The integration of motor intention, action output, and resulting sensory feedback is complex and plays an important role in how we interact with the external environment (Haggard et al., 2002). Thus, to elucidate the mechanisms that bind motor and sensory events together, researchers have manipulated the time of sensory events in relation to voluntary action. The next section will briefly review specific experiments that explore the perceived temporal relationship between motor action and sensory stimuli.

2.3 Intentional Binding

To understand how sensory events are linked to actions, it is important to first discuss the relationship between voluntary action and becoming conscious of it. Libet and colleagues (1983) put forth an innovative experimental paradigm to determine the onset of human consciousness for voluntary movement (Libet et al., 1983). To measure the time at which participants had the (conscious) intention to move, they presented participants with a clockface (i.e., Libet clock), with a rotating "minute" hand that completed a revolution every 2560 ms. Participants were to

watch the minute hand and flex their wrist whenever they felt like it. Following wrist flexion, participants indicated the positions of the minute hand when (1) they felt the urge to move and (2) when they actually moved (Libet et al., 1983). Using electroencephalography (EEG), Libet et al. (1983) showed that brain activity related to response preparation preceded participants' awareness of their intention to act. This finding demonstrates how we begin to evaluate our perception of events and that the intention to move and preparation of voluntary movement begins unconsciously.

To build off this seminal work, Haggard and colleagues (2002) adapted Libet's paradigm to examine one's perception regarding the timing of their voluntary movement and a sensory stimulus. Participants observed a Libet clock and judged the onset time of either their own voluntary movement, or an auditory stimulus (Haggard et al., 2002). The researchers found that when the motor and sensory events occurred in close proximity (i.e., a voluntary keypress was followed by a tone), the action was perceived as occurring later in time, and the tone was perceived as occurring earlier in time, compared to when only a single event occurred (e.g., keypress or tone). Based on these results, Haggard and colleagues (2002) concluded that the perceived timing between a voluntary action and sensory event is compressed in time (a phenomenon termed intentional binding), and that one's natural tendency is to perceive a sensory stimulus as a consequence of an intentional motor action.

2.4 Temporal Recalibration (TR)

Alternatively, Stetson and colleagues (2006) argue that changes in the perceived timing of motor and sensory events arise due to the realignment of signals that become asynchronous.

Sensory stimuli occurring immediately after a voluntary action (i.e., without a perceived lag) are interpreted as consequences of the action. If a constant temporal lag is then introduced between an action and subsequent sensory stimulus, one's perception of time will shift to make the relationship between events once more consistent with previous expectations (i.e., the sensory stimulus will once again be perceived as occurring without delay after the action), an effect termed TR (Stetson et al., 2006a). Stetson and colleagues (2006) demonstrated this phenomenon of TR in a reaction time (RT) experiment in which participants pressed a key in response to a go-signal and then indicated if a visual flash occurred before or after their keypress. Participants were exposed to two blocks which varied with respect to the temporal lag between keypress and visual flash (Stetson et al., 2006). Within one block of 100 trials, the visual flash was presented at a constant lag following participants' keypresses on the majority of trials (i.e., on 60 trials the flash occurred at 0 ms or 100 ms after the keypress). On the remaining 40 trials, the flash appeared at alternative lags, ranging from 150 ms before to 150 ms after the keypress. Stetson and colleagues (2006) then compared the point of subjective simultaneity (PSS), defined as the lag time at which participants indicated 50% of the time that the keypress occurred before (or after) the flash, between the two blocks. They found that the PSS was ~44 ms greater in the 100 ms block than the 0 ms block. This shift indicates that within the 100 ms block, visual flashes presented up to 44 ms after the keypress were perceived as occurring prior to the keypress on the majority of trials (these same flashes were perceived as being presented after the keypress in the 0 ms block; Stetson et al., 2006). The shifted timing of events thus indicates that TR has occurred, creating an illusory order reversal between movement and sensory stimuli on some trials. These findings have been replicated by Timm, Schönwiesner, SanMiguel, and Schröger (2014), who also observed TR in the order of ~40 ms. Moreover, this phenomenon has been

demonstrated in studies looking at the perceived relationship between sensory events (Machulla et al., 2016; Vroomen et al., 2004). These findings provide evidence that one recalibrates the perceived timing of a sensory event in relation to an action or initial sensory stimulus to minimize temporal discrepancies between one's actions and sensory stimuli (or between sensory stimuli).

2.5 Mechanisms Underlying Time Perception

TR is a well-studied, robust phenomenon, yet why or how it arises remains unclear. TR is hypothesized to arise due to the brain attempting to reduce the latencies between stimuli, thus binding together events that are generally associated with each other (Vroomen & Keetels, 2010). Previous research consistently shows that for TR to take place, the two events must occur within a short delay of each other, as the magnitude of TR deteriorates exponentially with an increased lag between the two events (Heron et al., 2009; Stetson et al., 2006a).

It has recently been proposed that in order for TR to arise, one must be aware of the temporal lag inserted between one's actions and sensory feedback (Tsujita & Ichikawa, 2016). However, this has yet to be examined across the different motor tasks (single vs. repetitive tap tasks) and perceptual judgments (TOJ vs. SJ) typically used in experiments demonstrating TR. In the next sections, we outline these tasks and suggest how the underlying processes engaged may be differentially influenced by awareness.

2.6 Single Tap vs. Repetitive Tap Tasks

Traditionally, two motor tap tasks, single tap tasks (as described above; e.g., Stetson et al., 2006) and repetitive tap tasks (as described below; e.g., Heron et al., 2009), have been used to examine TR. As previously stated, in a single tap task, participants are typically asked to respond as fast as possible to a go-signal. Following their response, they indicate the relative timing of a sensory stimulus with respect to their tap (Stetson et al., 2006a; Timm et al., 2014). In contrast, repetitive tap tasks generally ask participants to learn to tap at a given pace (i.e., with a given inter-tap interval (ITI); Sugano et al., 2010). Once participants can tap at the prescribed pace, participants are to maintain their tapping frequency while receiving sensory feedback (e.g., a flash) after each tap at a given latency (e.g., at a fixed lag of 0 ms or 100 ms). Participants are then asked to judge the timing of the last flash relative to their last tap, where the flash can occur before or after their tap (Sugano et al., 2010).

Heron, Hanson, and Whitaker (2009) were the first to study TR using a repetitive tap paradigm. In their experiment, participants were to choose and maintain a consistent tapping pace across sessions, while either visual, tactile, or auditory stimuli were presented at a constant lag (i.e., 25, 50, 100, 200, 400, or 800 ms) following four initial taps. On the fifth tap, the stimulus was presented at a random lag of 25, 50, 75, 100, or 125 ms after the action. Participants judged whether this fifth stimulus occurred before or after their tap. Results indicated that TR was greatest in magnitude when the constant lag between the first 4 taps and sensory stimuli was less than ~200 ms.

Sugano, Keetels, and Vroomen (2010) also used a repetitive tap paradigm to determine if TR transfers across sensory modalities (vision and audition). Participants were trained to tap with an ITI of ~750 ms and received either a visual (i.e., a flash) or auditory (i.e., a tone) stimulus

following each tap at a fixed lag (50 or 150 ms) for ~5 minutes of tapping (i.e., 240 trials). After this training period, participants tapped twice, with both taps followed by a flash or a tone. These last two tap-feedback pairings occurred either in the same modality that participants received during training (within-modality), or in the other modality (cross-modality), creating four different conditions (trained modality (visual or auditory) x tested modality (within-modality vs. cross-modality)). Participants made two judgments per trial, indicating whether the first stimulus occurred before or after their first tap, and whether the second stimulus occurred before or after their second tap (Sugano et al., 2010). Results demonstrated TR following training with the fixed lag. Moreover, TR was approximately 25 to 34 ms in magnitude across all types of trials, demonstrating transfer of TR from within-modality to cross-modality trials.

The magnitude of TR arising within repetitive tap paradigms varies greatly across experimental manipulations (e.g., ranges from 11 to 100 ms; Keetels & Vroomen, 2012; Tsujita & Ichikawa, 2016; Yarrow et al., 2013). These inconsistencies in the magnitude of TR could be due to variations in paradigm design, including the length of the training period (Stekelenburg et al., 2011; Sugano et al., 2010), or whether participants are to maintain their tapping frequency based on memory (e.g. Tsujita & Ichikawa, 2016) or an external pacer (e.g. a metronome; Motala et al., 2018).

In contrast, TR observed using the single tap task is consistently around 40 ms across experimental manipulations, including changes to the modality of the sensory stimulus provided (Timm et al., 2014), and the length of the adaptation/training period available (Vercillo et al., 2015). These variations in the magnitude and consistency of TR between the two motor tasks may be due to differences in the voluntary nature of the tasks. In particular, repetitive tap tasks have been suggested to engage more voluntary control, including additional brain processes

involved in motor planning and predictability compared to single tap tasks (Parsons et al., 2013). Thus, the repetitive tap task may be more cognitively demanding (e.g., engaging auditory rehearsal processes in addition to more striatal brain regions to remember the required tapping pace), as movements are driven internally, compared to externally driven movements in the single tap task as it is in reaction to a go-signal (e.g., engaging cerebellar brain regions; Rao, 1997).

2.7 TOJ vs. SJ Tasks

As mentioned earlier, temporal order judgments (TOJ) and simultaneous judgments (SJ) have both been used to establish TR. In a TOJ task, participants judge which one of the two events (e.g., keypress or flash) occurred first by choosing one of two options (e.g., keypress before flash or keypress after flash). In a SJ task, participants indicate whether two events occurred at the same time by indicating whether the events were simultaneous or not. Psychometric functions are then fitted to participants' responses across stimulus onset asynchronies (SOAs) to establish sensitivity parameters such as the PSS and temporal window of integration (TWI).

In a TOJ task (see example output in Appendix A), the PSS is an indirect measure of simultaneity. The PSS depicts the SOA at which the two stimuli (e.g., the action and sensory stimulus) are perceived as occurring at the same time (i.e., the SOA corresponding to when participants indicate the action came first 50% of the time; García-Pérez & Alcalá-Quintana, 2015; Kostaki & Vatakis, 2018). The just-noticeable difference (JND) and the TWI in the TOJ task reflect the discrimination sensitivity for reliably determining which event occurred first

(Kostaki & Vatakis, 2018), and are defined as the range between the SOAs corresponding to responding "keypress before flash" with 25% and 75% probability (Basharat et al., 2018). A lower value indicates that the participant is more sensitive to changes in SOAs (Kostaki & Vatakis, 2018).

In a SJ task (see example output in Appendix A), the PSS is a direct measure of simultaneity (Kostaki & Vatakis, 2018). It is computed by establishing the peak of the psychometric function fitted to the proportion of synchronous responses as a function of SOA (Kostaki & Vatakis, 2018). The JND of a SJ task is the smallest interval at which participants can reliably distinguish asynchronies between stimuli and corresponds to the standard deviation (SD) of the curve (Kostaki & Vatakis, 2018; Vatakis & Spence, 2010). The TWI for the SJ task represents the range of SOAs at which participants perceive two events as simultaneous and is typically represented by the SOA range from the PSS minus one SD to the PSS plus one SD (Harris et al., 2010; Kostaki & Vatakis, 2018; Sugano et al., 2010). Although the measurable parameters associated with these two judgments have different definitions, results from the tasks are often interpreted as meaning the same thing (Heron et al., 2009). In fact, it is only recently that studies have started to use TOJ and SJ paradigms within the same experiment and found that results differ depending on judgment required (Love et al., 2013; Machulla et al., 2016; Vatakis et al., 2008; Vroomen et al., 2004).

Given the differences in how parameters are defined between the two paradigms, it may not be surprising that TOJ and SJ tasks give rise to different results. That said, early work suggested that the magnitude of TR established via TOJ and SJ tasks was similar. For example, in 2004, Vroomen and colleagues revealed no significant differences in the magnitude of TR (as established via shifts in PSS) between TOJ and SJ tasks. Moreover, Machulla, Di Luca, and

Ernst, (2016) examined PSS and JND estimates for both TOJ and SJ tasks and found positive linear relationships between them, indicating a shared common process for TR. However, it is important to note that Machulla et al. (2016) had to use nonparametric statistics to overcome asymmetries in the functions fit to the PSS data for both the TOJ and SJ tasks, suggesting their results may have lower power.

In contrast to the above findings, Vatakis et al. (2008) found no correlation across TOJ and SJ tasks for shifts in the PSS and JND when TR was examined in a sensory-sensory paradigm. Similarly, a study examining TR in TOJ and SJ tasks in younger and older adults found that the mean PSS and TWI parameters for younger and older adults differed across tasks and that the PSS was not significantly correlated across the two judgment tasks for either age group (Basharat et al., 2018). In addition, Love and colleagues (2013) found no correlation between the PSS and TWI parameters across TOJ and SJ tasks. Interestingly, when participants were asked which task was more difficult, most participants indicated the TOJ task (Love et al., 2013). Together, these findings suggest that the two judgment tasks may engage different perceptual processes.

In addition to differences in behaviour, recent neurophysiological findings indicate that the two tasks engage different mechanisms. Using functional magnetic resonance imaging (fMRI), Binder (2015) found that although TOJ and SJ tasks use similar brain regions, the TOJ task recruits a greater cortical area, as well as more activation in the brain's cognitive areas (e.g., the prefrontal cortex, occipito-temporal regions, and the superior and inferior parietal lobules). These findings imply that the TOJ task requires supplementary brain resources compared to the SJ task, as suggested in Jaskowski's two-stage model. Jaskowski's two-stage model states there are two timing mechanisms that are needed to discriminate the order in which temporal events

are perceived (Jaśkowski, 1991). The first timing mechanism determines if two stimuli are simultaneous or not. If not, the second timing mechanism decides which event occurred first. Following this logic, the TOJ task would require additional (cognitive) processes compared to the SJ task, as shown by Binder (2015).

2.8 Awareness

Being aware of the temporal lag between motor and sensory events may modulate TR across single tap vs. repetitive tapping tasks, and TOJ vs. SJ tasks, given the different cognitive demands engaged across tasks as outlined above. Tsujita and Ichikawa (2016) suggest that awareness may be necessary for TR to arise, however, there is limited evidence to support this claim. Most studies investigating TR have not assessed or manipulated participants' awareness directly. Furthermore, given the lags used within previous paradigms (e.g., 100+ ms; Keetels & Vroomen, 2012; Stetson et al., 2006), it is unclear whether participants were ever aware of the lag between their keypress and sensory feedback. That said, recently, Tsujita and Ichikawa (2016) directly examined the influence of awareness on TR in a repetitive tap task, where participants made TOJs. Participants tapped at a specified frequency of 1.54 Hz (ITI of ~650 ms) and visual flashes followed their keypresses at a lag of 200 ms. Awareness of the 200 ms lag between the keypress and visual flash was manipulated by introducing the lag abruptly (and instructing participants that there was a lag), or gradually over blocks of trials (i.e., in the Unaware group, the lag between one's keypress and visual flash increased from 40 to 200 ms in 40 ms increments every 20 trials). Results indicated that the aware group showed TR (~99 ms), while the Unaware group did not demonstrate significant TR (~11 ms). The only other study to

examine awareness directly had participants adapt to asynchronous audio-visual stimuli and make SJs when they were aware or unaware of the lag between stimuli (Gallagher et al., 2014). Similar to Tsujita and Ichikawa (2016), the authors found TR only occurred when participants were aware of the temporal lag (Gallagher et al., 2014). These limited findings support the proposal that awareness of the temporal lag between one's motor action and sensory stimulus is necessary for TR to arise. However, to date, the influence of awareness on TR has not been assessed methodically across motor and judgment tasks.

2.9 Experiment Rationale

To summarize, TR has been observed across different motor and judgment tasks. Recently, it has been proposed that awareness of the lag between one's motor action (e.g., keypress) and subsequent sensory event (e.g., visual flash) are required for TR to occur. In this study, we will determine whether awareness is critical for TR, and if the role of awareness influences the magnitude of TR across the two different motor tasks (e.g., single versus repetitive tap) and judgment tasks (e.g., TOJ and SJ) typically used to examine TR.

In accordance with the proposal put forth by Tsujita and Ichikawa (2016), we hypothesize that awareness is necessary for TR to arise, such that TR will be present in participants that are made aware of a lag between their motor action and a visual flash and will not be present in participants who are unaware of the lag. It is further hypothesized that a larger magnitude of TR will be seen when the aware participants perform the repetitive tap task compared to the single tap task, as the repetitive tapping task requires participants to maintain an internal rhythm and hence is more cognitively demanding than the single tap task. It is also hypothesized that TR will

be greater in our aware participants completing the TOJ task compared to the SJ task, as the TOJ task has been suggested to engage more cognitive processes (e.g., dorsal premotor cortices), that do not overlap with the SJ task (Miyazaki et al., 2016; Rice & Stocco, 2019). If our hypotheses are supported, results would suggest that awareness drives TR and therefore how the magnitude of TR changes across tasks is tied to the engagement of higher cognitive processes.

Chapter 3: Manuscript

3.1 Introduction

In many everyday experiences, we perceive sensory events as arising as a consequence of our movements. For example, when typing on a computer, we expect letters to appear on the screen immediately after pressing a key. This temporal relationship between our action (i.e., pressing a key) and resulting sensory feedback (i.e., a character appearing on the screen) allows us to form a coherent representation of the temporal order of events in the world. Interestingly, it has been shown that the perceived temporal order between events can be disrupted by systematically manipulating the timing between events. In particular, researchers have shown that by introducing a constant temporal lag between an action (keypress) and a subsequent sensory stimulus (a visual flash appearing), one's perception of the relative timing of events can change. For example, if participants complete several keypresses, after which there is a constant temporal lag between their keypress and a flash appearing on the screen, they begin to associate the lagged sensory feedback (i.e., the flash appearing on the screen) as arising due to their action (i.e., the keypress) (Machulla et al., 2016; Stekelenburg et al., 2011; Stetson et al., 2006a; Sugano et al., 2010; Timm et al., 2014; Vroomen et al., 2004). Moreover, if the flash is to suddenly appear immediately after their keypress, participants now perceive the flash as occurring before their keypress. It is assumed that this temporal recalibration (TR) arises to minimize temporal discrepancies between one's actions and sensory stimuli, enabling one to still infer causality (Stetson et al., 2006a).

While the phenomenon of TR is well documented, the mechanism(s) underlying TR are unclear. TR has been shown to arise across paradigms employing various motor tasks (i.e., single

tap and repetitive tap tasks; Stetson et al., 2006; Tsujita & Ichikawa, 2016), as well as perceptual judgments (temporal order judgment (TOJ) and simultaneity judgments (SJ); Love, Petrini, Cheng, & Pollick, 2013; Machulla et al., 2016; Vatakis, Navarra, Soto-Faraco, & Spence, 2008; Vroomen et al., 2004). Within the single tap task, participants typically respond as fast as possible to a go-signal. Following their response, they indicate if a sensory stimulus (i.e., a flash) occurred before or after their tap (Stetson et al., 2006a; Timm et al., 2014). In contrast, within the repetitive tap task, participants learn and maintain a consistent tapping pace while a flash is presented at a constant lag following each tap (Heron et al., 2009; Keetels & Vroomen, 2012; Stekelenburg et al., 2011; Sugano et al., 2010; Tsujita & Ichikawa, 2016; Yarrow et al., 2013). Participants are then asked to judge the timing of the last flash relative to their last tap, where the flash can occur before or after their tap (Sugano et al., 2010).

In the single tap task, the magnitude of TR is consistently around 40 ms, regardless of the motor-sensory delay experienced (e.g., 100 - 200 ms; Stetson et al., 2006b), the modality of the sensory stimulus provided (Timm et al., 2014), and the number of training trials that participants completed with the delayed sensory feedback (Vercillo, Burr, Sandini, & Gori, 2015). In contrast to the consistency of TR observed in the single tap task, the magnitude of TR has been shown to vary greatly in the repetitive tap task depending on the motor-sensory delay introduced (e.g., ranges from 11 to 100 ms with motor-sensory delays between 80 – 150 ms; Keetels & Vroomen, 2012; Tsujita & Ichikawa, 2016; Yarrow et al., 2013). These inconsistencies in the magnitude of TR across repetitive tapping tasks could be driven by variations in paradigm design across experiments, including the length of the training period (Stekelenburg et al., 2011; Sugano et al., 2010), and/or whether participants are to maintain their tapping frequency based on memory or an external pacer (e.g. a metronome; Motala, Heron, McGraw, Roach, & Whitaker, 2018).

Furthermore, differences in result patterns between the single and repetitive taps tasks could be due to the cognitive resources required to complete the motor tasks. In general, repetitive tap tasks have been suggested to engage more voluntary control, and require additional cognitive demands (e.g., auditory rehearsal processes, requiring recruitment of striatal brain regions to remember the required tapping pace), as movements are driven internally, compared to externally driven movements in the single tap task (e.g., engaging cerebellar brain regions; Rao, 1997).

Within the two judgment tasks used to establish TR, individuals are asked to judge the relative timing of two events by indicating which event occurred first (e.g., keypress or flash; Temporal Order Judgment (TOJ)) or if the two events occurred at the same time Simultaneous Judgment (SJ). Following a series of responses, psychometric functions are fit to participants' responses across stimulus onset asynchronies (SOAs) to establish the point of subjective simultaneity (PSS). In a TOJ task, the PSS is an indirect measure of simultaneity, corresponding to the SOA at which the participants indicate the keypress (and flash) came first 50% of the time; García-Pérez & Alcalá-Quintana, 2015; Kostaki & Vatakis, 2018). In contrast, in the SJ task, the PSS is a direct measure of simultaneity, and is computed by establishing the peak of the psychometric function fitted to the proportion of synchronous responses as a function of SOA (Kostaki & Vatakis, 2018). While the PSS associated with the TOJ and SJ tasks have different definitions, results from the tasks are often interpreted as meaning the same thing (Heron et al., 2009).

Early work revealed no significant differences in the magnitude of TR established via TOJ and SJ tasks (Vroomen et al., 2004). In fact, positive linear relationships have been observed between the two types of responses (Machulla et al., 2016), suggesting that the TOJ

and SJ task assess similar perceptual processes. However, in contrast to these findings, researchers have shown no correlation between shifts in the PSS when participants completed TOJ and SJ tasks after adapting to audiovisual delays (Basharat et al., 2018; Love et al., 2013; Vatakis et al., 2008). Interestingly, when participants were asked which task was more difficult, most participants indicated the TOJ task (Love et al., 2013). In addition to the behavioural differences observed across TOJ and SJ tasks, recent neurophysiological findings indicate that the two tasks engage different neural mechanisms. Using functional magnetic resonance imaging (fMRI), Binder (2015) found that although TOJ and SJ tasks engage similar brain regions, the TOJ task recruits a greater cortical area, including cortical areas associated with cognition (e.g., the prefrontal cortex, occipito-temporal regions, and the superior and inferior parietal lobules). These findings imply that the TOJ task requires additional cognitive processes (i.e., increased neural mechanisms) compared to the SJ task (Binder, 2015).

Given the differing cognitive demands between the single tap vs. repetitive tap tasks, and TOJ vs. SJ tasks, awareness of the temporal lag between motor and sensory events may modulate the extent of TR observed across paradigms. In accordance with this proposal, Tsujita and Ichikawa (2016) recently suggested that awareness of the motor-sensory delay is necessary for TR to arise. In their study, awareness of the motor-sensory delay was modulated directly within a repetitive tapping task by introducing participants to a 200 ms lag between their keypresses and visual flashes either (i) abruptly and instructing participants on the presence of the lag (i.e., Aware group), or (ii) gradually over blocks of trials, in the absence of instructions (i.e., Unaware group). Participants then judged whether the flash occurred before or after their keypress (i.e., completed a TOJ). Results indicated that the Aware group showed TR (~99 ms), while the Unaware group did not demonstrate significant TR (~11 ms). Similar findings were observed

when participants adapted to asynchronous audio-visual stimuli (Gallagher et al., 2014). These limited findings support the proposal that awareness of the temporal lag between one's motor actions and resulting sensory stimuli is necessary for significant TR to arise. That said, awareness of the temporal lag may differentially influence results depending on cognitive processes engaged (i.e., motor task completed and perceptual judgment required). To date, the influence of awareness on TR has not been assessed methodically across motor and judgment tasks.

In this study, we looked to determine whether awareness is critical for TR, and if awareness modulates the magnitude of TR across the two different motor tasks (e.g., single versus repetitive tap) and judgment tasks (e.g., TOJ and SJ) typically used to examine TR. Two groups of participants (Group 1: Aware of the delay and Group 2: Unaware of the delay), completed 8 blocks of trials, in which the motor tasks (e.g., a single or repetitive tap), judgment tasks (e.g., judging the order of the keypress in relation to the visual flash or judging whether the two stimuli were simultaneous or not), and temporal lag between keypress and visual flash (e.g., a 0 ms or 100 ms lag) varied. In accordance with the proposal put forth by Tsujita and Ichikawa (2016), we hypothesized that a larger magnitude TR would be observed in participants that were made aware of a lag between their keypress and flash compared to our unaware participants. We further hypothesized that TR would be greater when the aware participants performed the repetitive tap task compared to the single tap task, as the repetitive tapping task requires participants to maintain an internal rhythm and hence is more cognitively demanding than the single tap task. It was also hypothesized that TR would be greater in our aware participants completing the TOJ task compared to the SJ task, as the TOJ task has been suggested to engage more cognitive processes (e.g. dorsal premotor cortices), that do not overlap with the SJ task

(Miyazaki et al., 2016; Rice & Stocco, 2019). Support for our hypotheses would indicate that awareness drives TR and the magnitude of TR differs depending on the engagement of higher cognitive processes.

3.2 Methods

3.2.1 Participants

Ideal sample size was originally determined to be 48 participants by performing a power analysis using G*Power Version (3.1.9.3; Faul, Erdfelder, Lang, & Buchner, 2007), with a desired power of 0.80, a probability of Type 1 error of 0.05, and an expected effect size of 0.14 with respect to the influence of awareness on TR in a motor-sensory repetitive tap task paradigm. Due to COVID-19 restrictions, data from twenty-three adult participants (19-37 years of age) were collected. Participant recruitment and data collection commenced after the Faculty of Health Sciences at the University of Ottawa approved a Safe Research plan and ethical approval was attained from the University of Ottawa's Health Sciences and Science Research Ethics Board.

Participants were randomly divided into two groups of participants (Group 1: Aware = 12 participants and Group 2: Unaware = 11 participants). Twenty-two out of the twenty-three participants were right hand dominant, as determined via the modified Edinburgh handedness inventory (Oldfield, 1971; see Appendix B). As well, participants reported having no history of neurological, sensory, or motor impairment, and normal or corrected-to-normal vision. Prior to testing, a questionnaire for musical ability was given (i.e., the Ollen Musical Sophistication Index; OMSI; see Appendix C), as research has demonstrated that trained musicians perform better in time discrimination tasks and may thus skew results (Krause et al., 2010). Based on this

questionnaire, only one participant in the Unaware group was deemed to be musically sophisticated (i.e., score > 500 on OMSI) and was kept in the analysis. Furthermore, video game experience was assessed by having participants report how many hours a week they play video games and what genres they play, as participants with considerable video game experience have been found to perform better at TOJ and SJ tasks than individuals without video game experience (Donohue, Woldorff, & Mitroff, 2010; see Appendix D). Based on our assessment, none of our participants were considered to be video game players and all were kept in the analysis.

Testing took place across two consecutive days, separated by approximately 24 hours, with each testing session lasting about 1.5 hours each day. The two days of testing differed with respect to the fixed lag presented between participants' motor response (i.e., keypress) and visual flash (0 or 100 ms)[1]. A lag of 100 ms was used as previous research has demonstrated that participants tend to not become aware of this lag between their motor action and sensory stimulus on their own accord (e.g., Van Vugt & Tillmann (2014) found that the threshold for becoming aware of a lag between action and tone was ~170 ms). At the end of the experiment, participants in the Unaware group completed a questionnaire (i.e., end of experiment probe; see Appendix E) that probed whether they became aware of the temporal lag. One participant in the Unaware group was classified as aware of the temporal lag, and they were not included in the analyses or results reported below. Thus, out of 23 participants, a total of 22 participants were included in our analysis.

[1] We recognize that on all trials there was an inevitable lag between one's keypress and the appearance of the visual flash due to computer/set-up hardware delays. Previous studies (e.g., Stetson et al., 2006; Tsujita & Ichikawa, 2016) report average delays between 35-59 ms, and do not include these system limitations when reporting the inserted lag between keypress and visual flash (i.e., report a fixed lag of 0 ms or 100 ms as we have done above). The delay between the tactile pad and PC set-up was 17-21 ms verified through Python and Arduino and the delay between the PC to the monitor was 3 ms. Similar to Stetson et al. (2006) we do not include this delay when reporting the inserted lab between keypress and visual flash.

3.2.2 Experimental Apparatus

Experimental testing took place in a dimly lit room. The experiment began when the participant was seated in a comfortable position, with their chin on a chinrest that was positioned 48 cm from a 24-inch LCD monitor (ASUS, refresh rate of 144 Hz; Figure 1). Participants performed the motor keypress task by placing the index finger of their dominant hand on the tactile pad (AT42QT1010 microchip), which was covered by a box to prevent vision of the limb (see Figure 1A). The index and middle fingers of their non-dominant hand were placed on yellow and blue response keys respectively to complete the judgment tasks (Figure 1B), and user's inputs were recorded in JAVA as cvs files. In the judgment tasks, the index finger was used to indicate "FLASH AFTER KEYPRESS?" (TOJ), or "NOT SIM" (SJ), while the middle finger was used to indicate "FLASH BEFORE KEYPRESS? (TOJ), or "SIM" (SJ).

Visual stimuli were created using Java software. Stimuli presented in the single tap blocks included a central cross (white cross; 2 by 2 cm) that served as a go-signal and a square (white or pink square; 2 by 2 cm) that was flashed for 50 ms, 0.5 cm above the fixation cross. In the repetitive tap blocks, a square (yellow or pink square; 2 by 2 cm) served as a pacing stimulus in the keypress training and adaptation blocks. A square (white square; 2 by 2 cm) was flashed for 50 ms in the practice and test blocks.

3.2.3 Procedure

All participants completed the blocks of trials as shown in Figure 2, which varied with respect to the motor task required (single tap vs. repetitive tap), judgment task to complete (TOJ

vs SJ), and the temporal lag between keypress and visual flash (e.g., a 0 ms or 100 ms lag). The order in which the blocks with varying motor tasks, judgments, and temporal lags were completed was counterbalanced across participants.

3.2.3.1 Single Tap Adaptation Block

An example participant started with the single tap task. The participant first completed a single tap adaptation block consisting of 50 trials, with a fixed lag of 0 ms (Row 1, Block I, Figure 3). To commence a trial, the words "Get Ready!" appeared on the display for 750 ms (Box 1, Figure 3). A blank screen was then presented for 500 - 1000 ms (Box 2, Figure 3), after which time a white cross was presented (Box 3, Figure 3). The cross served as the go-signal. Participants were instructed to press the tactile pad with their right index finger as fast as possible in response to the go-signal. A square immediately flashed above the go-signal (i.e., lag of 0 ms) after their keypress for 50 ms (Box 4A, Figure 3). Following the offset of the flash, the participant was provided with feedback related to their reaction time (RT) if it was out of range. Specifically, if their RT was 100 ms or less, the experimenter indicated the response was "Too fast." If their RT was greater than 1000 ms, the experimenter said, "Too slow." These trials were redone. Within the single tap adaptation block, participants also completed a secondary task. On each trial, following the presentation of RT performance feedback, participants indicated to the experimenter if the square that was flashed was white (38 of 50 trials) or pink (12 of 50 trials). These trials were included to ensure that participants paid attention to the presentation of the flash during the task. Following this verbal response, the trial was considered complete, and the next trial started immediately after the experimenter inputted the answer to the colour question.

3.2.3.2 Single Tap Practice and Test Blocks

Following the single tap adaptation block, the participant completed the practice (Row 1, Block II, Figure 3) and test TOJ (Row 1, Block III, Figure 3) blocks. These trials were similar to the single tap adaptation block, except that after each trial, the participants completed a judgment task about the timing of the appearance of the visual square in relation to their keypress. Participants completed 5 trials within the practice block; three in which the flash occurred approximately 200 ms before their keypress, and two trials in which it appeared 200 ms after their keypress. In the test block, the participant completed 100 trials, in which the flash had the same fixed lag as in the adaptation block (i.e., 0 ms after the keypress) on 60% of the trials. For the remaining 40% of trials, the flash was randomly presented at one of the ten following lags: ±15, 45, 75, 105, and 135 ms with equal probability, where the '+' sign refers to a lag presentation time following the keypress and the '-' sign refers to a lag presentation time before the expected keypress. The time of the expected keypress was predicted based on a participant's average RT on the previous five trials. Similar to the adaptation trials, the flash was presented for 50 ms. 350 ms after the keypress, the screen displayed "FLASH BEFORE KEYPRESS? OR FLASH AFTER KEYPRESS?" and the participant made an unspeeded TOJ with their non-dominant hand, pressing the blue key if they perceived the flash to come first, or the yellow key if they perceived their keypress to have come first (Box 6A, Figure 3).

Following the test block, the participant completed a single tap adaptation "top-up" block of 10 trials with a fixed lag of 0 ms (Row 1, Block IV, Figure 3). These trials were identical to the single tap adaptation block, but only white squares were flashed. Next, the participant completed the practice (Row 1, Block V, Figure 3) and test (Row 1, Block VI, Figure 3) SJ blocks. The SJ trials differed from the TOJ trials with respect to the judgment to be completed.

In particular, the screen displayed “SIM? OR NOT SIM?” and the participant pressed the blue key with the index finger of their non-dominant hand if they perceived their keypress to be simultaneous with the flash, and the yellow key with their middle finger of their non-dominant hand if they did not perceive the two events as simultaneous (Box 6B, Figure 3). The participant then took a break for a minimum of 5 minutes, before starting the repetitive tap blocks (Row 1, Figure 3).

3.2.3.3 Repetitive Tap Keypress Training Block

In the repetitive tap blocks (Row 2, Blocks I - VII, Figure 4), participants initially completed a keypress training block to learn to tap at the required pace (i.e., with the required inter-tap interval (ITI) of 650 ms). This training block was divided into two halves (Row 2, Block I, Figure 4). To commence a trial in the first half, the words “Get Ready!” appeared on the display. Participants tapped six times on the tactile pad with the index finger of their dominant hand in tempo with a yellow square that appeared in the centre of the display above the fixation cross (ITI of 650 ms). With respect to determining if participants matched the desired tapping pace, only the ITI between taps 2 to 6 were analyzed. If the participants tapped too quickly (i.e., ITI of less than 500 ms on one or more of the four intervals between the five keypresses), the experimenter said, “Too fast”, or if the participants tapped too slowly (i.e., ITI of greater than 800 ms on one or more of the four intervals between the five keypresses), the experimenter said, “Too slow” and the participant redid the trial. If the participant had one or more taps that were too fast, and one or more taps that were too slow, the experimenter said, “Out of range”, and the participant redid the trial. In order to complete this first half of the training and move on to the second half of the keypress training session, the participant had to tap within the required timing

range on eight out of twenty-five trials (Row 2, Block I, Figure 4). If a participant was not able to complete eight trials within 25 trials, they were asked to withdraw from the experiment. The second half of the keypress training block proceeded similarly to the first half, however, the yellow squares were not shown, and hence we assessed participants' ability to tap at the required pace from memory. Again, participants had to complete eight trials correctly (maximum attempts = 25 trials) (Appendix F).

3.2.3.4 Repetitive Tap Adaptation Block

The keypress training block was followed by the repetitive tap adaptation block of eight trials (Row 2, Block II, Figure 4) in which participants completed six taps per trial. In this block, participants were told to tap with the same pace they had learned in the keypress training block. However, on these trials, squares flashed for 50 ms following their keypresses at a fixed lag of 0 ms. The squares were white following the majority of taps but on a small subset of taps (1 or 2 taps per trial), the square was pink. In four of the trials, there were two pink squares, and for the other four trials, there was only one pink square (Box 3B, Figure 4). Following each trial, participants received feedback from the experimenter regarding the timing of their taps relative to the required pace, as in the training trials (Row 2, Block II, Figure 4). As well, they were required to verbally report the number of times a pink square was presented within a trial (i.e., 1 or 2 times).

3.2.3.5 Repetitive Tap Practice and Test Blocks

After completion of the repetitive tap adaptation block, participants completed the TOJ repetitive tap practice (Row 2, Block III, Figure 4) and test (Row 2, Block IV, Figure 4) blocks.

Similar to the repetitive tap adaptation block, the white square flashed with a fixed lag of 0 ms after their keypress on the first 4 taps (taps 1 through 4). However, no square was flashed following the fifth tap in order to prevent the use of timing intervals between feedback flashes as a cue for the judgment task (Box 5, Figure 4) (Tsujita & Ichikawa, 2016). A square flashed in association with the sixth tap. In the practice block (Block III, Row 2, Figure 4), there were two trials; one with the flash occurring 200 ms before the expected 6th keypress, and one with the flash occurring 200 ms after the 6th keypress. In the test block (Block IV, Row 2, Figure 4), the participant completed 100 trials. On 60% of trials, the square flashed at the fixed lag of 0 ms following the 6th keypress. On the remaining 40% of trials, the square flashed at the same alternate lags as described in the single tap task before or after the expected 6th keypress. The expected time of the 6th keypress was estimated within each trial by averaging the inter-tap intervals between the 2nd to 5th taps.

Following the 6th keypress, the screen displayed “FLASH BEFORE KEYPRESS? OR FLASH AFTER KEYPRESS?”, and the participant made an unspeeded judgment regarding the timing of the flash, pressing the appropriate key designated for the TOJ task (Box 9A, Figure 4). Following every 20 trials of the repetitive tap test block, the participant completed two training trials (one with the pacing stimuli and one without; Row 2, Block 1, Figure 4). Participants’ tapping pace was monitored and feedback was provided after both trials.

Following the test block, participants completed a repetitive tap “top-up” adaptation block of two trials (Row 2, Block V, Figure 4), in which they completed six taps per trial. In this block, participants were told to tap with the same timing they learned in the keypress training block. The squares flashed for 50 ms following all 6 keypresses at a fixed lag of 0 ms.

Next, the participant completed the practice (Row 2, Block VI, Figure 4) and test (Row 2, Block VII, Figure 4) SJ blocks. The SJ practice and test blocks were similar to the TOJ practice and test blocks, however, participants now judged if the events were "SIM? OR NOT SIM?" (Box 9B, Figure 4).

3.2.4 Instructions for Participants in the Aware Group

Specific instructions regarding the timing between the keypress and flash were only provided to participants in the Aware group, such that they were instructed on the relationship between their keypress and subsequent flash before the adaptation blocks in the experiment (Appendix G). For example, in the 0 ms fixed lag adaptation block, they were instructed that "The flash will appear immediately after your keypress with no lag." In the 100 ms fixed lag adaptation block, they were told that "The flash will appear at a slight lag, specifically 100 ms after you press the key." In contrast, participants in the Unaware group did not receive any information about the relationship between their keypress and subsequent flash. Only the Unaware group was probed on their awareness of the relationship between their response and flash at the end of the experiment on Day 2 by asking them if they noticed whether anything had changed between the two days of the experiment (Appendix E). If they answered yes, they were asked "What do you think was going on?" If they did not mention anything about the timing interval between their motor responses and flashes, they were prompted with the following question, "Were you aware there was a lag between your keypress and resulting flash on one of the testing days?" (Tsujita & Ichikawa, 2016). If participants indicated "Yes", they were asked, "Which day was the lag presented on?", and if they answered correctly, they were classified as aware. Otherwise, they were classified as unaware.

3.4.5 Data Analyses

3.4.5.1 Musical Sophistication

Based on the OMSI (Appendix C for evaluation and equation, Ollen, 2006), scores that were <500 were defined as “less musically sophisticated”, and scores >500 were defined as “more musically sophisticated”.

3.4.5.2 Video Game Playing Ability

Participants were asked to consider how often they play video games and the amount of experience they have, as well as report their level of expertise within different genres over the past 6 months. Video-game players were classified as participants who play at least two hours a week of first-person shooter games, as well as any type of action game (including first-person shooter, real-time strategy, and sports games) for a minimum of 4.5 hours a week. They also had to have played first-person shooter games for at least 5 hours per week at some point in their lives. Participants who did not meet the video-game player criteria were classified as non-video game players. These classifications are based on criteria as established by Donohue and colleagues (2010).

3.4.5.3 Dual-Task Performance (Adaptation Blocks)

To ensure that participants were attentive during the adaptation blocks, the percentage of correct responses regarding the square colour (single tap task) and the number of pink squares (repetitive tap task) were calculated for each participant (Figure 2, Row 1, Block I; Row 2, Block

II; Row 3, Block I; Row 4, Block II). A participant's data was only included in the subsequent analyses if they achieved an overall score of 90% or higher in the adaptation blocks for both motor tasks (single tap and repetitive tap). If their score fell below 90%, their data were excluded.

3.4.5.4 TOJ Task

For each participant, for all TOJ testing blocks, a sigmoid function (Eq. 1; Basharat et al., 2018) was fit to their responses (i.e., "flash after keypress"), across SOAs using Sigmaplot (version 14.0).

$$(1)\ y = \left(\frac{1}{1+e^{\left(-\frac{x-x\emptyset}{b}\right)}}\right)$$

Where *xø* is the PSS and *b* is the standard deviation. The PSS (*xø*) is the SOA corresponding to when the participant judged "keypress before flash" with 50% probability. Given that we are interested in the relationships between the TOJ and SJ tasks, the parameter *b* was used as a proxy for the temporal window of integration (TWI) as done by Basharat et al. (2018) in which the TWI represents the discrimination sensitivity of the PSS.

3.3.4.5 SJ Task

For each participant, for all SJ testing blocks, a Gaussian function (Eq. 2; Basharat et al., 2018) was fit to their responses (i.e., "simultaneous"), across SOAs using Sigmaplot (version 14.0).

$$(2)\ y = a * e^{\left(-0.5\left(x-\frac{x\emptyset}{b}\right)^2\right)}$$

Where *a* is the amplitude fixed to 1, *xø* is the PSS, and *b* is the standard deviation. The PSS (*xø*) corresponds to the SOA at the peak of the curve, at which participants judged "simultaneous" the majority of the time (Harris et al., 2010). Like mentioned above, the parameter *b* was used as a proxy for the TWI, in which the TWI represents the discrimination sensitivity of the PSS.

The best fit parameters corresponding to the PSS and TWI were established for each participant for each testing block. Values corresponding to data with a poor fitting function ($r^2 < 0.5$) were replaced using the multiple imputation strategy in SPSS (version 27). In total, 18 PSS and 18 TWI (~10.2%) values were replaced.

3.3.4.6 Statical Analyses

The PSS and TWI values were compared across Groups and tasks using a 2 group (Aware vs. Unaware) x 2 fixed lag (0 ms vs. 100 ms) x 2 motor task (single tap vs. repetitive tap) x 2 judgment task (TOJ vs. SJ) mixed analysis of variance with repeated measures (RM-ANOVA) on the last three factors. As well, the changes in PSS values from the 0 to 100 ms fixed lag trials and TWI values for the 0 ms fixed lag trials were compared for the two different motor tasks across judgement tasks (TOJ vs. SJ) using Pearson's correlation tests. Data from the 22 participants who were kept in the analysis (Aware and Unaware) were included in these correlations to determine the strength and direction of the relationship of TR between the two judgment tasks.

The significance value for all statistical tests was set at $p < .05$, and Bonferroni post-hoc tests corrected for multiple comparisons were used to find the locus of significant interactions for all pre-planned comparisons.

3.3 Results

In the future, it would be of interest to garner a greater sample size. Due to restrictions imposed by COVID-19, our sample size was limited, and thus we had an underpowered study, enhancing the probability of making a Type 2 error.

3.3.1 Dual-Task Performance

All participants in both the Aware and Unaware groups were able to correctly identify the square colour (single tap task) and the number of pink squares (repetitive tap task) during the adaptation blocks on over 90% of trials. Specifically, for participants in the Aware group, the mean percentage of correct responses was 99.82% (SD = 0.60) in the single tap task and 96.59% (SD = 5.84) in the repetitive tap task for the 0 ms lag trials, and 100% (SD = 0) in the single tap task and 98.86% (SD = 3.77) in the repetitive tap task for the 100 ms lag trials. Participants in the Unaware group reported correct responses on 99.16% (SD = 2.77) of trials in the single tap task and 100% (SD = 0) in the repetitive tap task for the 0 ms lag trials, and 100% (SD = 0) in the single tap task and 97.73% (SD = 5.06) in the repetitive tap task for the 100 ms lag trials.

3.3.2 Point of Subjective Simultaneity (PSS)

By looking at the shifts in the PSS from the 0 and 100 ms blocks of trials in Figure 5, we see that participants demonstrated evidence of TR across all motor and judgment tasks. In accordance with this observation, ANOVA revealed a significant effect of fixed lag [$F(1,20) = 9.336$, $p = 0.006$, $\eta p^2 = 0.318$], in which participants shifted their PSS by 18.6 ms on average from trials in which the fixed delay was 0 to when it was 100 ms. ANOVA also revealed that

there was no significant main effect of group [$F(1,20) = 1.643$, $p = 0.215$, $\eta p^2 = 0.076$], nor was there was a significant interaction between fixed lag and group [$F(1,20) = 0.410$, $p = 0.529$, $\eta p^2 = 0.020$], indicating that the magnitude of TR observed did not differ statistically with changes in participants' awareness.

ANOVA revealed a significant main effect of judgment task [$F(1,20) = 166.443$, $p < 0.001$, $\eta p^2 = 0.893$] and a significant interaction between motor task and judgment task [$F(1,20) = 4.741$, $p = 0.042$, $\eta p^2 = 0.192$]. In general, participants demonstrated a PSS closer to true simultaneity in the TOJ task (M = -30.6 ms) compared to the SJ task (M = 71.5 ms) across both motor tasks (both $p < 0.001$), and within the repetitive tap task (M = -22.1 ms) compared to the single tap task (M = -39.1 ms), across both judgment tasks (both $p < 0.001$). These trends in performance did not vary across groups (all p's > 0.05).

Pearson correlation analyses revealed a non-significant relationship between the magnitude of TR observed for TOJ responses compared to SJ responses for both motor tasks (single tap task: $R^2 = -0.105$, $p = 0.642$; repetitive tap task: $R^2 = 0.167$, $p = 0.457$).

3.3.3 Temporal Window of Integration (TWI)

The mean TWI across all blocks of test trials are shown in Figure 6. Mean TWI ranged from 25 ms to 105 ms across all blocks of trials. When comparing the TWI between groups, there was no statistical difference between participants who were aware of the temporal lag between their keypress and visual stimulus and those who were unaware [$F(1,20) = 0.004$, $p = 0.952$, $\eta p^2 < 0.001$]. The average TWI was similar across both groups (Aware M = 62.1 ms, Unaware M = 62.5 ms). ANOVA revealed a significant main effect of judgment task [$F(1,20) = 79.783$, $p > 0.001$, $\eta p^2 = 0.800$], in which participants had a smaller TWI in the TOJ task (M =

33.1 ms) compared to the SJ task (M = 91.5 ms). No significant interactions were observed (all *p*'s > 0.05). These results suggest that participants were less consistent in their responses for the SJ task compared to the TOJ task.

Pearson correlation analyses revealed a non-significant relationship between the TWI observed for TOJ responses compared to SJ responses for both motor tasks (single tap: R^2= -0.071, p = 0.752; repetitive tap: R^2= 0.162, p = 0.471).

Overall, awareness did not modulate the magnitude of TR or TWI across motor and judgment tasks. However, the different judgment tasks influenced the PSS, such that participants generally perceived simultaneity before physical simultaneity in the TOJ task, but perceived simultaneity after physical simultaneity in the SJ task. Differences between judgment tasks were also shown by the lack of significant correlations between judgments in relation to TR and TWI values, as well as the finding that participants had a larger TWI in the SJ task compared to the TOJ task. These results suggest that the judgment tasks tap into different cognitive processes (i.e., different neural mechanisms).

3.4 Discussion

The current study looked to establish whether awareness is necessary for significant TR to arise. Specifically, we investigated the role of awareness when the motor task (e.g., single tap versus repetitive tap), and perceptual judgment (TOJ versus SJ) were manipulated. Based on the findings of Tsujita and Ichikawa (2016), we predicted that TR would be larger in magnitude when participants were made aware of the lag between their keypress and visual flash, compared to participants who were unaware of the lag. Furthermore, we predicted that there would be a

larger magnitude of TR within the Aware group when completing the repetitive tap task compared to the single tap task and the TOJ task compared to the SJ task, as both the repetitive tap task and the TOJ task have been shown to recruit additional cognitive processes (Binder, 2015). We found that participants demonstrated TR across both motor tasks and perceptual judgments. In contrast to our predictions, the magnitude of TR did not differ statistically between groups. On average, the magnitude of TR was 18.6 ms across both motor and judgment tasks. These results suggest that awareness of the temporal lag does not influence TR, and TR can be induced regardless of participants' awareness of the temporal lay between their keypress and appearance of a visual stimulus.

Furthermore, awareness did not lead to significant differences in the TWI, indicating that Aware and Unaware participants demonstrated similar discrimination sensitivity for determining which event occurred first or if the events were simultaneous. Results did indicate significant differences between judgment tasks, such that perceived simultaneity within the TOJ task was closer to true simultaneity than within the SJ task, and the TWI was greater in magnitude in the SJ task compared to the TOJ task. Furthermore, no significant correlation was found for the PSS and TWI values across the two judgments for both motor tasks. These findings indicate that the two judgment tasks tap into different cognitive processes.

3.4.1 Awareness

Recent literature has suggested that awareness plays a critical role in TR, such that only participants who are made aware of the temporal lag between their motor action and visual stimuli demonstrate TR (Tsujita & Ichikawa, 2016; see also Gallagher et al. 2014). To directly induce awareness, Tsujita and Ichikawa (2016) instructed some of their participants of the 200

ms lag between their keypress and visual stimulus when completing a repetitive tap task and temporal order judgment. A second group of participants (i.e., Unaware participants) were not instructed about the lag and were instead gradually introduced to the 200 ms lag over 5 blocks of 20 trials (i.e., lags increased by 40 ms every 20 trials until the 200 ms lag was achieved). Their results indicated that only participants who were aware of the lag between their keypress and visual stimulus demonstrated TR (~99 ms), whereas the Unaware group did not (~11 ms). Tsujita and Ichikawa's (2016) results further showed that the TWI did not significantly differ between groups, indicating that there was no difference in sensitivity in completing the TOJ task between participants who were aware of the lag and those who were not. However, it is important to note that the authors only reported regression slopes of their different adaptation blocks to determine sensitivity, whereas, in our experiment, we calculated TWI values.

Research regarding the role of awareness on TR remains limited, as the Tsujita & Ichikawa (2016) study is the only published work in this area to date. Most studies examining TR do not directly manipulate or assess awareness. Given that previous studies examining TR tend to use delays of 100 ms (e.g., Keetels & Vroomen, 2012; Stekelenburg et al., 2011; Stetson et al., 2006a; Sugano et al., 2010), it remains unclear whether their participants became aware of the delay. According to Van Vugt & Tillmann (2014), participants generally become aware of a delay between their action and sensory event (i.e., tone) when the delay is 170 ms or more. Thus, it is likely that many participants in previous TR paradigms were unaware of the delay between their action and stimulus appearing.

We used a lag of 100 ms to reduce the likelihood of participants in our Unaware group becoming spontaneously aware of the delay. Our end of experiment probe revealed that, in general, participants in the Unaware group did not become aware of the lag between their

keypress and visual stimulus. Only one participant out of twelve became aware of the delay, and their data was removed from analyses. The eleven other participants remained unaware of the lag between their keypress and visual stimulus. Based on these participants' data, we found that there was no difference in their magnitude of TR, nor a difference in their TWI compared to participants in the Aware group. In general, all participants showed a TR of approximately ~19 ms, or in other words, a rightward shift of ~19 ms from the 0 to 100 ms lag trials (indicating that participants now perceived simultaneity 19 ms later in the 100 ms compared to the 0 ms lag trials).

In an attempt to explain why our results differ from Tsujita & Ichikawa (2016), we can look to differences in methodology. Across the two studies, the manner in which the temporal lag was introduced and the magnitude of the lag varied. Tsujita and Ichikawa gradually introduced a 200 ms lag to their Unaware group, and participants only completed a total of 20 trials with the 200 ms temporal lag (i.e., participants experienced 80 total tap-flash pairs). However, participants in our Unaware group were abruptly introduced to the lag (i.e., 100 ms), and completed all test and adaptation trials with this lag (i.e., participants experienced over 456 total tap-flash pairs). Thus, it is possible that the Unaware participants in Tsujita and Ichikawa (2016) did not have enough time to adapt to their temporal lag, and this could explain why they demonstrate significantly less TR than aware participants. Furthermore, it is important to note that the lag Tsujita and Ichikawa (2016) used (i.e., 200 ms) was double the lag we used (i.e., 100 ms). A lag of 200 ms has been shown to lead to greater TR than a lag of 100 ms (approximately 15 ms greater; (Heron et al., 2009), perhaps driving the differences between studies.

Similar to Tsujita & Ichikawa (2016), we also found no differences in TWI values across participants who were aware versus unaware of the temporal lag between their keypress and

visual stimulus (~59.9 ms vs. 61.6 ms, respectively). This is in agreement with a number of studies employing a motor-sensory task, in which they demonstrated no differences between the two lags (Stekelenburg et al., 2011; Stetson et al., 2006a; Sugano et al., 2010; Timm et al., 2014; Vercillo et al., 2015). Only one study to our knowledge demonstrated a difference in the TWI across the different lags, such that their TWI became larger as the lags increased (Keetels & Vroomen, 2012).

Taken together, when we manipulated awareness directly, we found that the magnitude of TR, as well as PSS and TWI values did not change significantly based upon whether participants were aware of the temporal lag between their keypress and visual stimulus. Given that we did find a significant difference between the two lags indicating evidence of TR, we can tentatively say that, based on our current data, awareness does not play a role in TR within a motor-sensory paradigm when a 100 ms lag is introduced abruptly

3.4.2 Motor Task

Two motor tasks commonly used in TR studies are the single tap task and the repetitive tap task (Heron et al., 2009; Keetels & Vroomen, 2012; Parsons et al., 2013; Stekelenburg et al., 2011; Stetson et al., 2006a; Sugano et al., 2010; Timm et al., 2014; Vercillo et al., 2015; Yarrow et al., 2013). Across the literature, the magnitude of TR in repetitive tap paradigms has been shown to vary. For example, Stekelenburg and colleagues (2011) demonstrated a magnitude of TR of ~9 ms for the repetitive tap task, whereas in Tsujita and Ichikawa's (2016) experiment, the magnitude of TR was ~99 ms. In contrast, the magnitude of TR has been shown to be more consistent across paradigms when the single tap task is used by experimenters. For example, multiple studies using the single tap task have found a magnitude of TR of approximately 40 ms

when a 100 ms delay is introduced (Stetson et al., 2006b; Timm et al., 2014; Vercillo et al., 2015). In our study, we found that the magnitude of TR was similar across both motor tasks once we collapsed across factors. The TR of 18 ms we observed is comparable in magnitude to other studies using a repetitive tap task (e.g., Keetels & Vroomen, 2012; Stekelenburg et al., 2011), but smaller in magnitude compared to studies employing a single tap task (e.g., Stetson et al., 2006b; Timm et al., 2014; Vercillo et al., 2015).

Variations in the magnitude of TR reported between motor tasks have been suggested to arise due to the differences in the voluntary nature of the tasks and therefore the cognitive processes engaged. For example, Lepage and colleagues have suggested that because of the sequential nature of a repetitive tap task, both processing related to maintaining the required tapping rhythm and determining the timing of the last tap to halt the sequence are required (Lepage et al., 1999). In contrast, because the single tap task is a discrete tap, participants are merely reacting to a single cue, and thus do not have to maintain rhythmic tapping. The proposal that the single and repetitive tap tasks engage different cognitive resources has been made by comparing findings across studies, varying in methodologies (Lepage et al., 1999). It is thus difficult to draw conclusions based on previous reports. We are the first to directly compare the magnitude of TR within the two motor tasks within the same experiment, thus ensuring that the tasks were similar in nature with respect to the experimental setup, visual stimuli displayed, the timing of events, the environment, the experimenter, etc. We found that the magnitude of TR, as well as TWI values, did not significantly differ across our single and repetitive tap tasks. Thus, this study, in which both motor tasks were examined in a single experiment, provides the first evidence that both motor tasks may engage similar cognitive resources (e.g., similar brain regions).

3.4.3 Judgment Task

It has been suggested that the TOJ and SJ tasks either measure different facets of time perception (Vatakis et al., 2008), or that they are processed differently in the brain (Basharat et al., 2018; Binder, 2015; Love et al., 2013). Previous findings have shown that the TOJ task is considered to be more difficult (Love et al., 2013), engaging a greater cortical area than the SJ task (Binder, 2015). To date, these differences in the two tasks have been founded on results in paradigms that examined the relationship between sensory events (e.g., the order of visual and auditory stimuli; Basharat et al., 2018; Binder, 2015; Love et al., 2013; Vatakis et al., 2008). This is the first study to directly compare TR as evaluated by TOJ and SJ tasks in a motor-sensory paradigm. We found no significant linear correlation between performance on the TOJ and SJ tasks with respect to TR and TWI values, indicating that these tasks are likely subserved by different cognitive processes.

Within our experiment, we also found a larger magnitude of TR within the SJ task compared to the TOJ task (M = 24.0 ms vs. M = 13.7 ms, respectively). This was contrary to our expectations, as we hypothesized a greater magnitude of TR in the TOJ task compared to the SJ task, given previous suggestions that the TOJ task engages more cognitive resources than the SJ task (Basharat et al., 2018; Binder, 2015; Love et al., 2013; Vatakis et al., 2008). Furthermore, we found differences in the accuracy of participants' estimates across the two judgment tasks. Participants were more accurate in judging physical simultaneity when completing the TOJ task (~ -31 ms) compared to the SJ task (~71 ms). In the TOJ task, participants tended to perceive simultaneity *before* it occurred. In contrast, when participants completed the SJ task, they perceived simultaneity *after* it occurred. Based on these results, it could be argued that

participants were more accurate in the TOJ task as they engaged additional or more cognitive processes than when completing the SJ task.

In agreement with our study, a similar pattern of results was also found in a sensory-sensory paradigm (i.e., audio-visual) by Basharat et al. (2018). They found that participants in the TOJ task perceived simultaneity prior to it occurring, and closer to true simultaneity, whereas when participants completed the SJ task, they perceived simultaneity following true simultaneity, and had greater errors in their estimates. They also found that the cortical responses for the audio (N1) and visual (P1) event-related potentials did not change between tasks, thus they suggested that the differences between the TOJ and SJ tasks arose during multisensory integration and that participants used different cognitive processes for the two judgment tasks (Basharat et al., 2018). Taken together, our results and those from previous studies (Basharat et al., 2018; Binder, 2015; Love et al., 2013; Vatakis et al., 2008), suggest that the differences between the TOJ and SJ tasks may arise because these tasks rely on different cognitive processes (i.e., different neural mechanisms).

Although many studies compare the PSS observed in TOJ and SJ tasks (Basharat et al., 2018; Donohue et al., 2010; Van Eijk et al., 2008; Vroomen & Stekelenburg, 2011), few studies examine the TWI across judgments. In the current study, we found that the SJ task had a wider TWI than the TOJ task, as seen previously by Love et al. (2013). The decreased sensitivity in the SJ task may be explained by the wording of the question “Simultaneous or not simultaneous?”, biasing the participant to think that the two events occurred at the same time (Vatakis et al., 2008). This bias can be further explained by the unity assumption, which states that when participants expect two different sensory stimuli (e.g., vision and audition) to “go-together” (e.g., watching a ball bounce and also hearing it hit the floor), they believe that both stimuli underlie

the same multisensory event (Vatakis & Spence, 2007). While we had a motor-sensory paradigm, our results imply a generalization of the unity assumption such that when participants are prompted about the simultaneity between their action and sensory stimulus, they are more likely to pair these two events together than perceive them as occurring at distinct (i.e., separate) movements in time.

3.4.4 Conclusion

This study demonstrated that TR is a robust phenomenon, present across motor tasks and perceptual judgments. Critical to the question of interest, we found that TR was not altered by participants' awareness of the lag between their keypress and visual flash in our small sample of data. Specifically, we found that participants demonstrated no significant differences between their magnitudes of TR regardless of whether or not they knew about the temporal lag between their keypress and visual stimulus across the different motor (i.e., single tap and repetitive tap) and judgment (i.e., TOJ and SJ) tasks that are commonly used within the TR literature. Our results demonstrated that participants had a PSS closer to true simultaneity in the TOJ task than the SJ task for both motor tasks. Furthermore, we did not find a significant linear relationship between TR observed in the TOJ and SJ tasks, and there were significant differences in both the PSS and TWI values between the TOJ and SJ tasks, suggesting that the TOJ and SJ tasks are likely subserved by different cognitive processes. As our results are purely behavioural, future studies should look to understand the mechanisms underlying TR by incorporating neurophysiological tools.

3.5 Figures

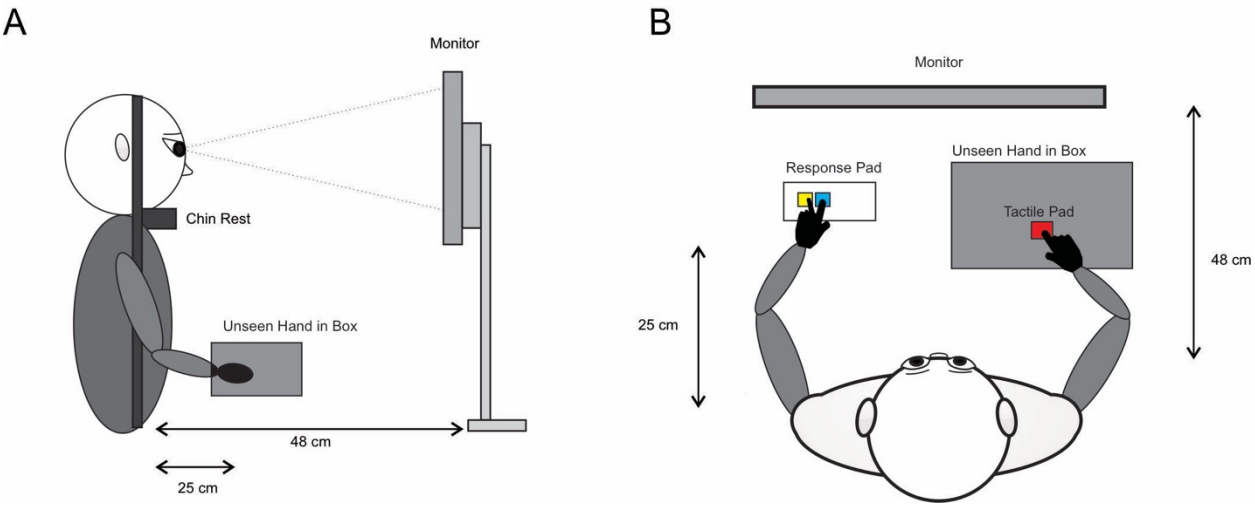


Figure 1. Experimental apparatus with dimensions. **A** Side view of experimental set-up with occluded vision of the hands. **B** Overhead view of experimental set-up.

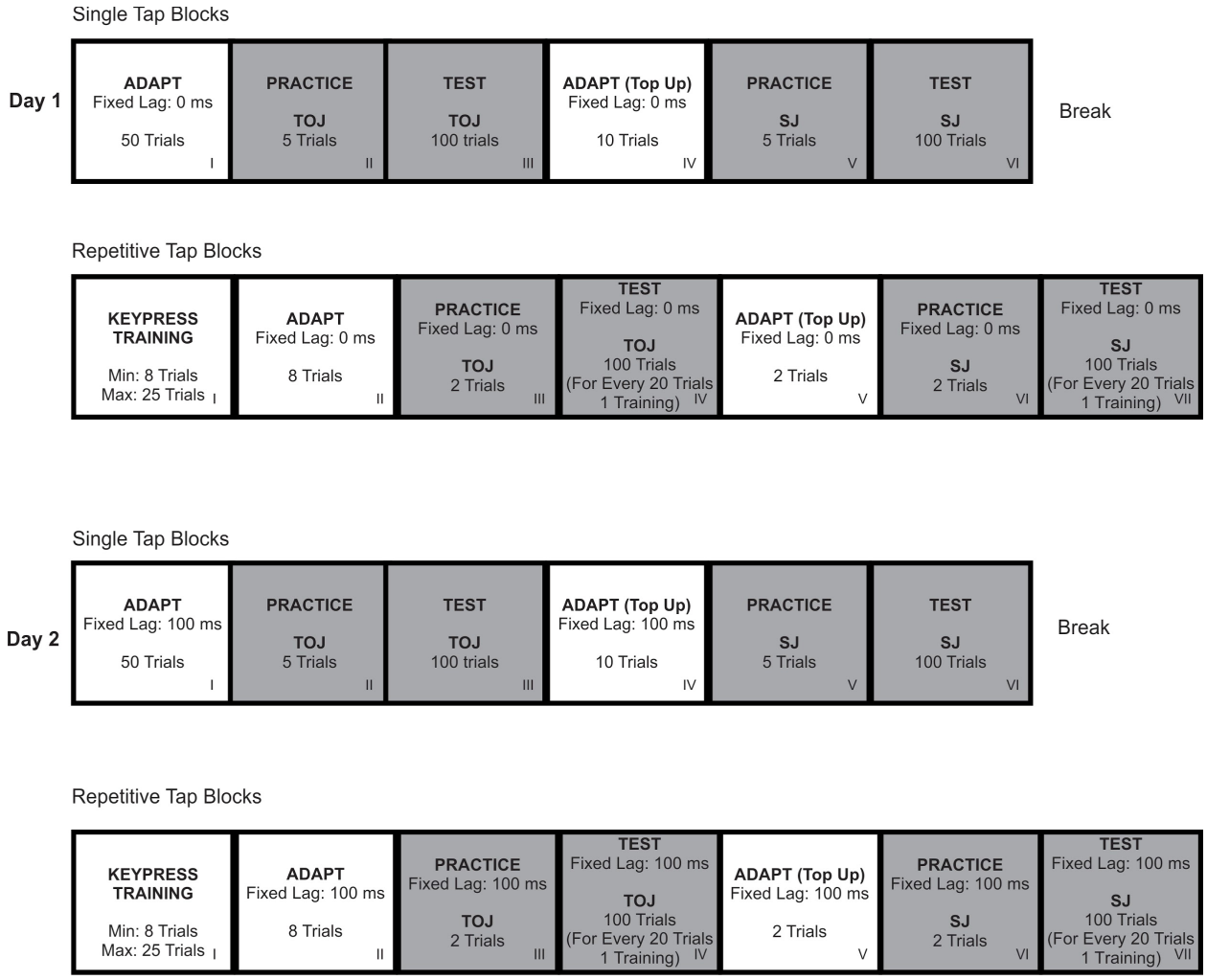


Figure 2. Example block progression for a participant in either the Aware or Unaware groups on Day 1 (top 2 rows) and Day 2 (bottom 2 rows). Within each testing Day, participants completed two motor tasks and two judgment tasks, separated by a 5-minute break minimum. The Days differed with respect to the fixed time lag (0 or 100 ms). The order in which participants completed the differing fixed time lags, motor tasks (Single Tap vs. Repetitive Tap), and judgment tasks (TOJ vs SJ) was counterbalanced across participants.

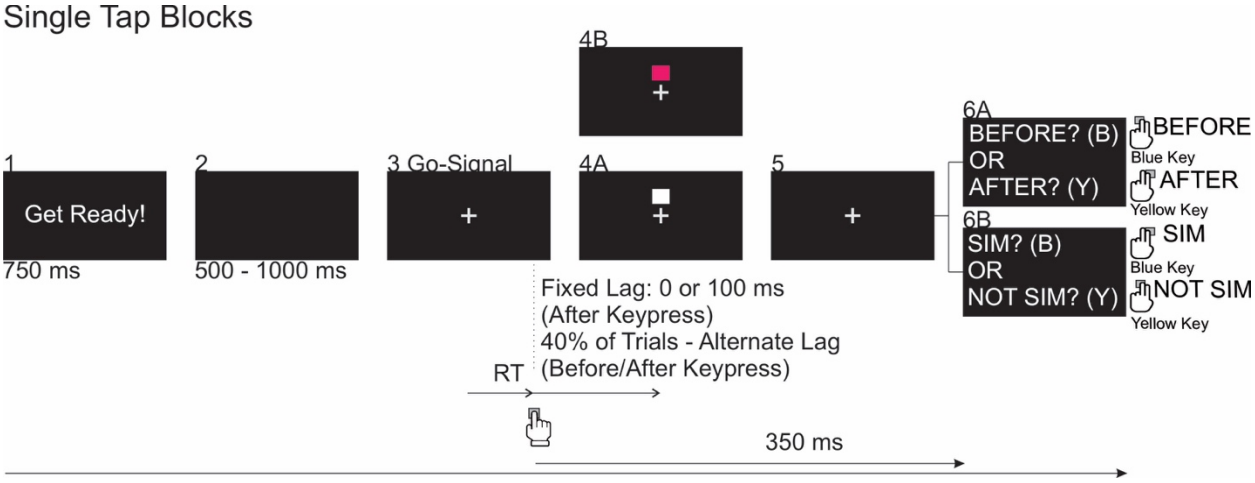


Figure 3. Blocks 1-5: Visual events occurring during the (50) adaptation trials in the single tap blocks. In the single tap practice and test blocks, participants completed Blocks 1-6. During these trials, the white square flashed at a fixed lag (0 ms or 100 ms) on 60% of trials. For the remaining 40% of trials, the white square flashed at one of 10 alternate lags relative to the expected keypress reaction time: ±15, 45, 75, 105, and 135 ms, where '+' corresponds to a lag presentation time following the expected keypress '-' corresponds to a lag presentation time before the expected keypress.

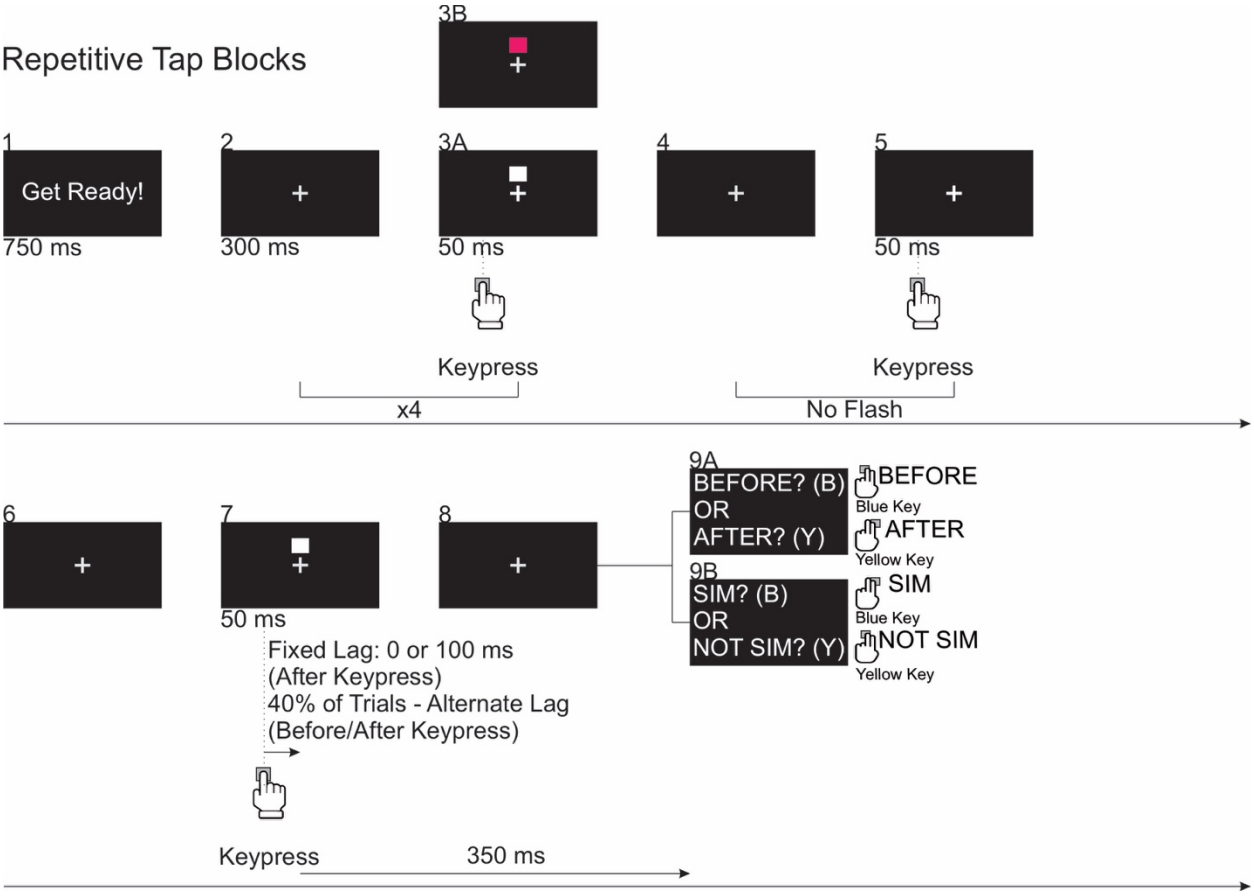


Figure 4. Blocks 1-5: Visual events occurring during the (8) trials in the repetitive tap adaptation block. In the repetitive tap practice and test blocks, participants completed Blocks 1-9. During these trials, the white square flashed at a fixed lag (0 ms or 100 ms) following the 6th keypress on 60% of trials. For the remaining 40% of trials, the white square flashed at one of 10 alternate lags relative to the expected time of the final keypress: ±15, 45, 75, 105, and 135 ms, where '+' corresponds to a lag presentation time following the expected keypress and '-' corresponds to a lag presentation time before the expected keypress.

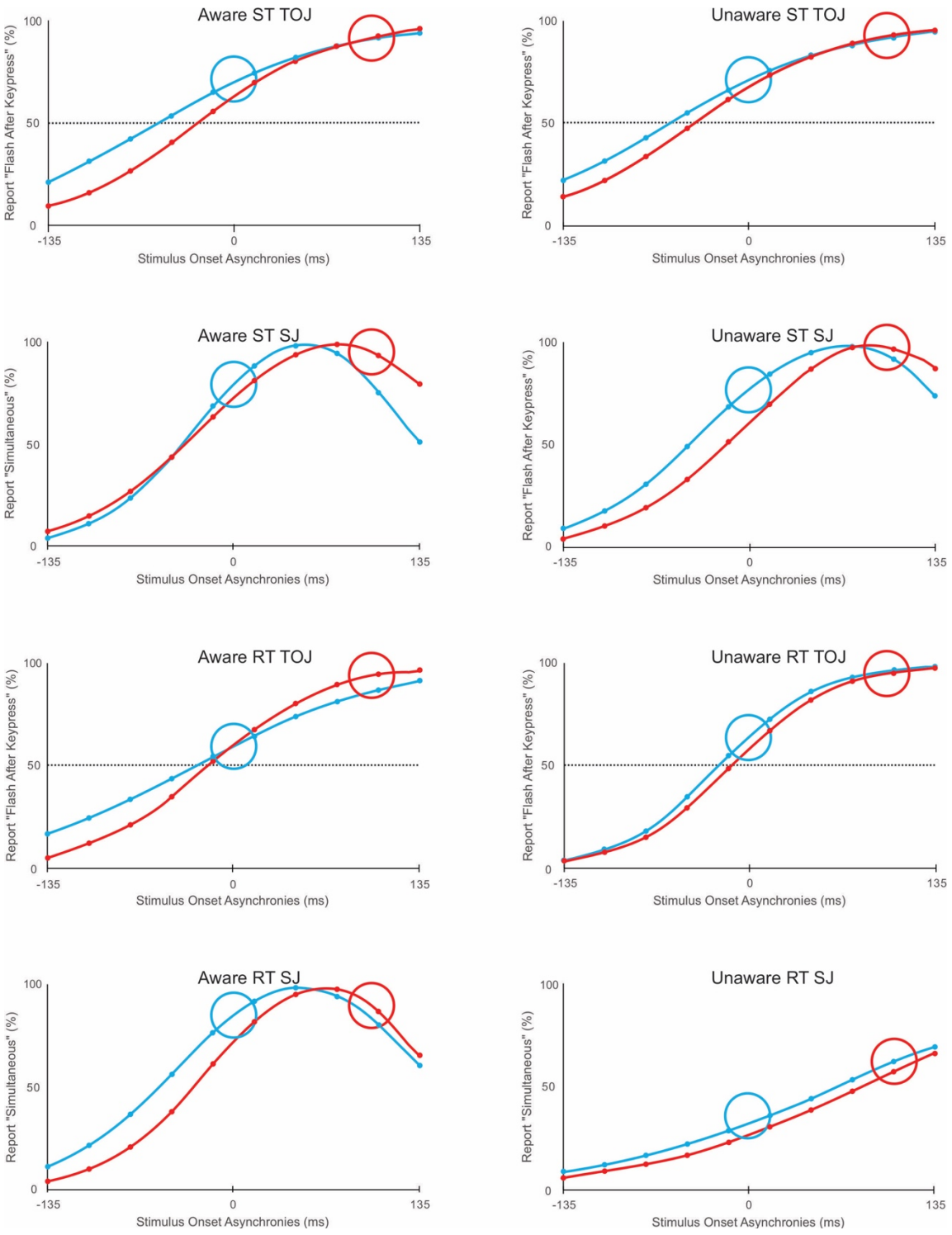
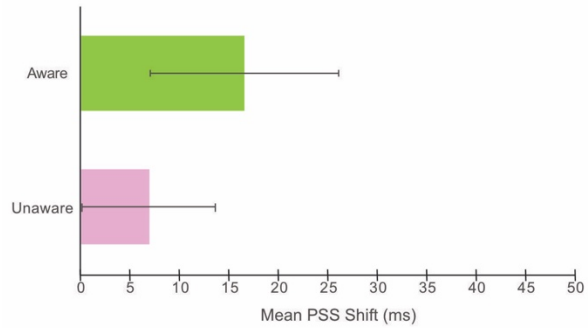


Figure 5. Temporal Order Judgment (TOJ) and Simultaneity Judgment (SJ) responses for participants in the Aware and Unaware groups in the single tap task (top two rows) and repetitive tap task (bottom two rows) in the 0 ms lag (blue) and 100 ms lag (red) blocks. Circle size indicates the number of trials at each stimulus onset asynchrony (SOA) between keypress and

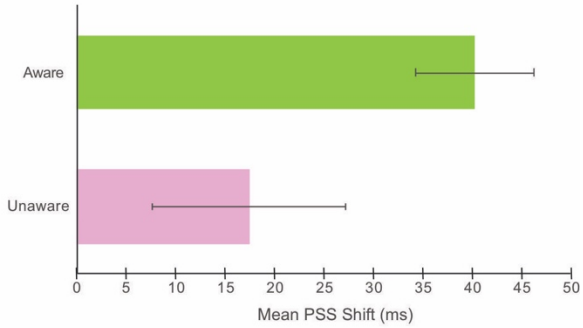
visual flash. Curves reflect sigmoidal functions fit to the mean of participant data in the TOJ task and Gaussian functions fit to the mean of participant data in the SJ task. The dashed lines in the TOJ plots indicate values at which the response “flash after keypress” was 50% (i.e., the PSS).

TEMPORAL RECALIBRATION: DOES AWARENESS INFLUENCE HOW WE PERCIEVE TIME?

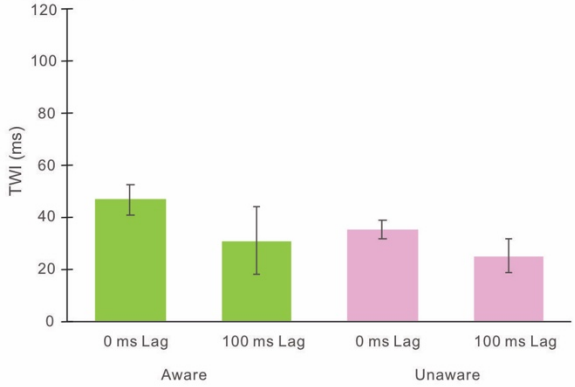
Single Tap TOJ



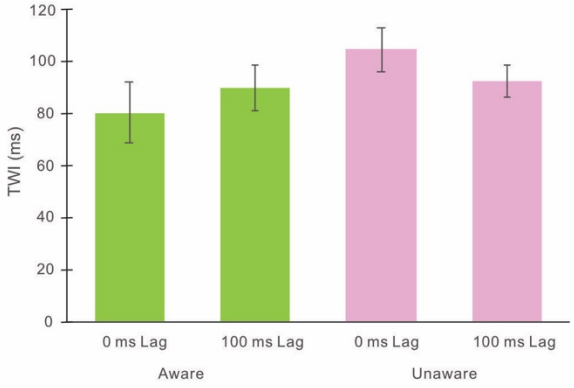
Single Tap SJ



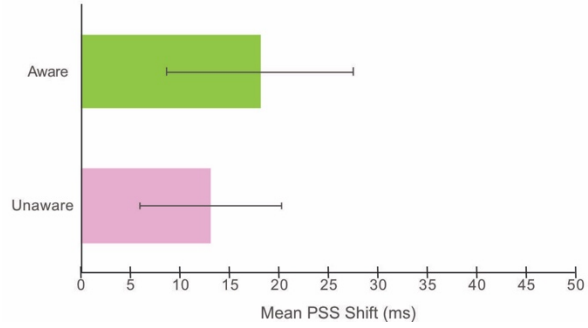
Single Tap TOJ



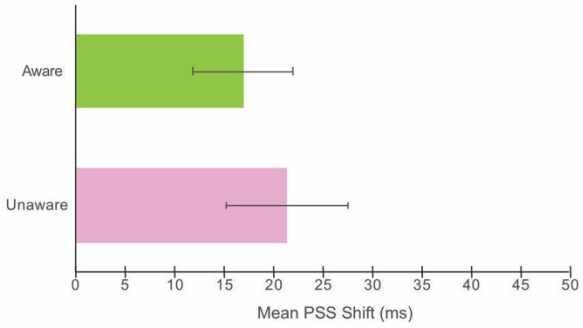
Single Tap SJ



Repetitive Tap TOJ



Repetitive Tap SJ



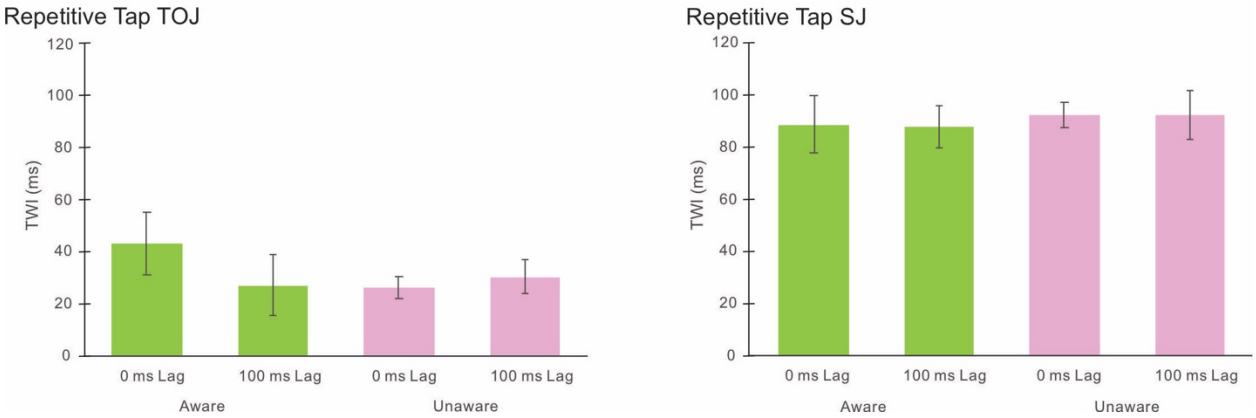


Figure 6. Mean shifts in the points of subjective simultaneity (PSS) (first and third rows), and temporal windows of integration (TWI) (second and fourth rows) are shown for the Aware (green) and Unaware (pink) participants in the single tap task (top two rows) and repetitive tap task (bottom two rows) for temporal order judgments (TOJ; left two columns) and simultaneity judgments (SJ; right two columns). Data related to the TWI are shown for the 0 ms lag and 100 ms lag blocks. Error bars denote standard error of the mean.

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Chapter 4: General Discussion

This thesis sought to examine whether awareness of a temporal lag between a motor action and sensory stimulus is necessary for individuals to recalibrate time. We also investigated whether awareness would change the magnitude of TR observed depending on the different motor and judgment tasks used. Specifically, we examined how awareness influenced the magnitude of TR observed across two different motor tasks (e.g., single versus repetitive tap) and judgments (e.g., TOJ and SJ) typically employed in this literature. We manipulated awareness of the temporal lag between a participant's keypress and visual flash by indicating to some participants (i.e., Aware group) that there was a lag between their keypress and visual flash. Participants in the Unaware group did not receive these instructions regarding the lag, and an end of experiment probe demonstrated that all but one participant (who was removed from our analyses) remained unaware of this lag.

We found TR across both motor and judgment tasks for all participants. Moreover, and more critical to the current research question, we found that awareness of the temporal lag between keypress and visual stimulus did not impact the magnitude of TR observed, nor the consistency of performance as indicated by the TWI values. Furthermore, the type of motor task did not affect the magnitude of TR, or the PSS and TWI values observed. Interestingly, there was a significant difference in the direction and accuracy of perceived simultaneity between the two judgment tasks. Participants had a more difficult time with the SJ task compared to the TOJ task, such that the PSS values were perceived closer to true simultaneity in the TOJ task compared to the SJ task. As well, we found that the TWI was larger in the SJ task compared to the TOJ task. Based on our current data, these results suggest that awareness does not influence the magnitude

of TR, and that the judgment tasks may be subserved by different cognitive processes, as suggested previously (Basharat et al., 2018; Binder, 2015; Love et al., 2013).

4.1 Awareness

Our main goal was to determine the role of awareness in TR, as previously, Tsujita and Ichikawa (2016) have suggested that awareness is critical for TR to arise. In fact, they found that only participants who were aware of a temporal lag between their keypress and visual stimulus significantly recalibrated time (~99 ms), as opposed to unaware participants. While Tsujita and Ichikawa (2016) directly manipulated awareness, it remains unclear whether or not participants in previous paradigms were aware of the temporal lag, as awareness was never directly assessed (e.g., Stetson et al., 2006a). In our experiment, we established that there was no significant difference in the magnitude of TR between our Aware and Unaware groups of participants observed across our different experimental manipulations of motor task (i.e., single tap and repetitive tap task), and judgment task (i.e., TOJ and SJ task).

4.1.1 Experimental Design and Set-Up

As stated above, we found no influence of awareness on TR within our study. Our results may differ from Tsujita and Ichikawa (2016) due to differences in experimental design and set-up. With respect to experimental design, Tsujita and Ichikawa (2016) included only 15 participants within their study, and their results across participants were highly variable as shown by the average PSS 95% confidence intervals for their Aware group (e.g., ~170 ms) and Unaware group (e.g., mean: ~57 ms). In contrast, we included 22 participants, and found that TR

was more similar across participants (e.g., PSS: Aware SEM mean = 7.4 ms and Unaware SEM mean = 7.5 ms).

Our experimental set-up, specifically the temporal delay within our hardware system, may also have led to us observing a smaller magnitude of TR compared to Tsujita and Ichikawa (2016). Within our experiment, we used a sensitive custom-made tactile response pad which produced a system delay of 17-21 ms. With this set-up, our participants demonstrated TR of 6.9 – 40.3 ms across our different blocks. Studies that have found similar, smaller magnitudes of TR (e.g., 10 – 30 ms), as we showed here, also used custom-made tactile response pads with limited delays (~1 ms – 3 ms) (Keetels & Vroomen, 2012; Stekelenburg et al., 2011; Sugano et al., 2010). Notably, the single tap tasks in which a large magnitude of TR has been observed appear to have used set-ups requiring participants to complete keypress responses using buttons or keyboards (e.g., Parsons et al., 2013; Stetson et al., 2006a; Timm et al., 2014; Vercillo et al., 2015). These buttons or keyboard presses add additional delays in the system. As Sugano and colleagues (2010) note, the amount of time for a keypress to be read can be up to ~25 – 35 ms. Thus, participants may expect these delays as computer and laptop use is quite commonplace. As our set-up has minimal delays, this may mitigate the magnitude of TR established, as participants already expect larger delays in computer systems and therefore automatically calibrate to them.

Another issue related to using button or keyboard responses is that it is unclear as to why TR arises. Is it due to participants shifting their response criterion, (e.g., shifting the perceived timing of the motor component or the sensory component, or both)? For example, in the single tap tasks in which participants depress a key, it is unknown what the participant's criteria is for deciding temporal order or simultaneity (i.e., do participants bias their judgment with respect to when they initially press the key or when it is fully depressed and released?). Our tactile pad only

required a light touch, resulting in consistency in the time-course of trial events. Studies requiring participants to press keys may find larger variability and/or greater magnitudes of TR due to participant's equivocal decision-making strategies regarding how they judged the temporal order or simultaneity of their keypress relative to the sensory stimulus. To narrow down the participant's criteria of how they judged event order or simultaneity, future studies should use a tactile pad with limited delays.

4.1.2 Neural Processes Underlying TR

Two models that may explain the neural processes that underlie TR have been put forward by Cai et al. (2012), and Roach et el. (2011). The neural model of Cai et al. (2012) includes three features of neural systems (i.e., 1. information pooling, 2. opponent processing, and 3. synaptic scaling), in which both time and space share a common neural mechanism. Specifically, Cai and colleagues state that specific neurons encode the different lags between one's action and sensory stimuli. These outputs pool into two competing higher-level neural populations to reach a decision (i.e., flash before keypress, or flash after keypress). The neural population that had the most activity can increase or decrease its synaptic input weight (Cai et al., 2012; Ibata et al., 2008), therefore contributing to the feedback system in which the decision adapts based on previous experience (Cai et al., 2012).

Another neural model that has been used to explain the phenomenon of TR is the neural population coding model put forth by Roach et al. (2011). In contrast to Cai et al.'s (2012) model, they propose that TR is subserved by low-level processing. In their study, they used an audio-visual paradigm and had participants quantify the time between an auditory and visual stimulus across a large range of SOAs (Roach et al., 2011). From their results, they simulated

responses to produce a model of the auditory-visual temporal relationships for the different lags and estimated parameters (i.e., the amount of neurons in the population tuned to varying SOAs, their tuning bandwidth and depth, and the gain reduction bandwidth caused through adaptation), to examine patterns of biases within the data. Based on their findings, they suggest that the specific stimulus relationship is represented by neural populations that specialize in different temporal asynchronies (i.e., SOAs), thus, adaptation to temporal lags occurs through reducing the response gain (i.e., suppression) of those specific neurons (Roach et al., 2011). They additionally suggest that this same model can be generalized to understand motor-sensory relationships due to the commonalities in TR between sensory-sensory and motor-sensory paradigms (Roach et al., 2011).

Tsujita and Ichikawa (2016) suggest that participants who are aware of the temporal lag between their keypress and visual flash use this knowledge to make judgments and thus recalibrate time appropriately. Specifically, these researchers argue that because voluntary movements use efferent and afferent signals for feedback, participants are able to use this feedback to decide on the order of events (Tsujita & Ichikawa, 2016). Furthermore, they state that these decisions depend upon high-level processes such as awareness, and hence the neural model of Cai et al. (2012) explains their results.

Cai et al. (2012) do not examine awareness in their paper, nor do they interpret their higher-level neuronal populations as reflecting awareness. To clarify, Cai and colleagues (2012) propose that the decision on event order occurs through competing low-level neural populations that scale up depending on the synaptic strength of activity of either event. This leads to the judgment of what event occurred first, not upon awareness of the temporal lag itself. Therefore, Tsujita and Ichikawa's (2016) argument that awareness engages these higher-levels of neuronal

populations remains weak as Cai et al.'s (2012) model is partially built upon Stetson et al.'s (2006b) study, in which awareness of their temporal lag was not examined. Thus, at this time, our results cannot confirm nor rule out which model correctly lays out the neural processes underlying TR.

4.2 Conclusion

Our study examined whether the influence of awareness of a temporal lag between one's motor action (i.e., keypress) and sensory stimulus (i.e., visual flash) was necessary for TR to occur. In addition, we manipulated the motor (single tap vs. repetitive tap) and judgment (TOJ vs. SJ) tasks commonly used within TR paradigms to determine whether awareness would further change the magnitude of TR observed across tasks. We found that the magnitude of TR was not significantly influenced by participants' awareness of the temporal lag. Based on these results, we can conclude that the magnitude of TR is not tied to the engagement of higher cognitive processes (i.e., awareness) as suggested by Tsujita and Ichikawa (2016), but instead, it is likely that TR uses more low-level processing. Furthermore, we found that the TOJ and SJ tasks resulted in different PSS and TWI values, such that the performance was more accurate within the TOJ task than the SJ task as indicated by a PSS value closer to true simultaneity. Together, these results indicate that, while awareness does not play a role in TR, the two different judgment tasks are likely subserved by two different cognitive processes with respect to TR. To understand the neural processes underlying TR, it is important for future research to test different neural models, such as the ones proposed by Cai et al. (2012) and Roach et al. (2011). These models look to explain the mechanisms underlying TR with the goal of bringing new insights to this temporal illusion and its' real-world applications.

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Appendix A

Example results for the TOJ and SJ tasks

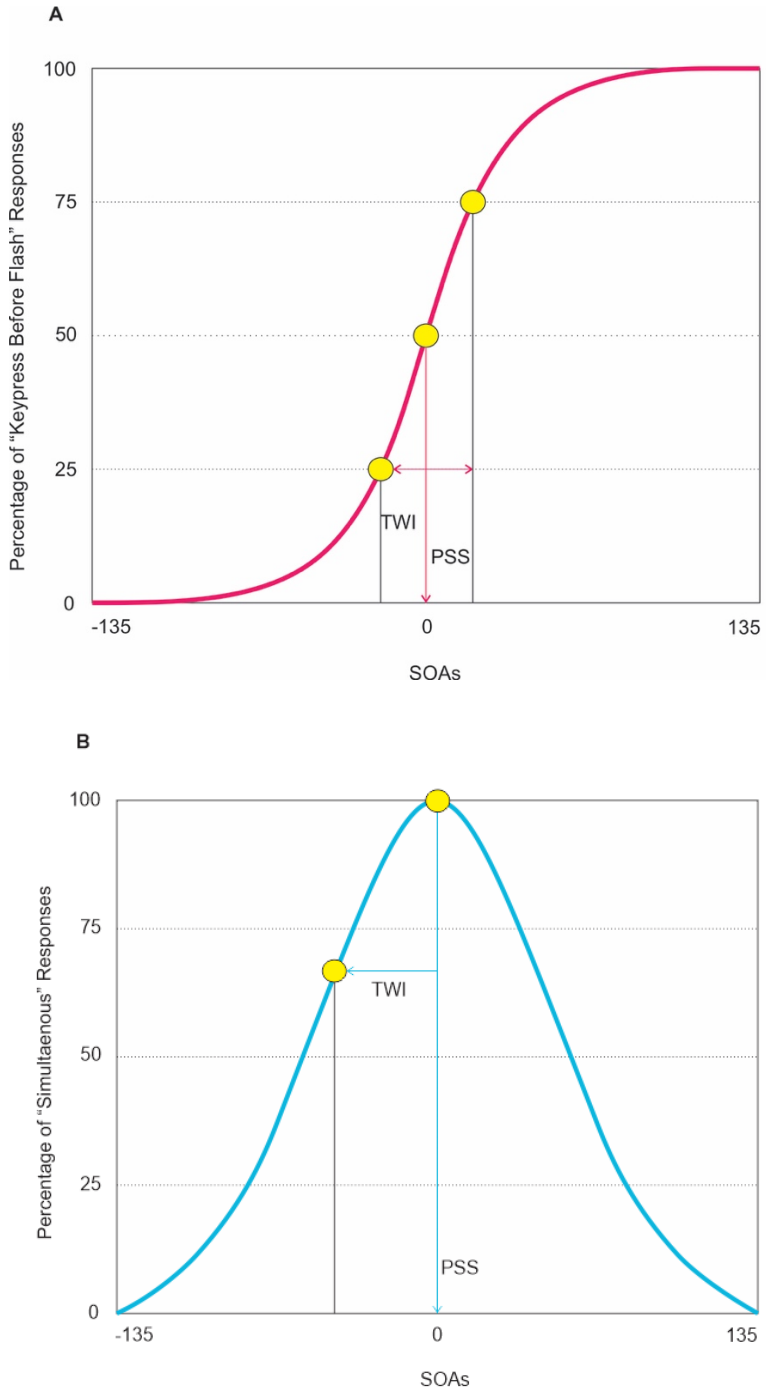


Figure 1. Hypothetical results for the two judgment tasks. **A** In the TOJ task, responses are plotted as a function of SOA and a sigmoid function fit to the data. The PSS corresponds to the SOA at which the participant judged "keypress before flash" 50% of the time (Stetson et al.,

2006). The TWI is represented in the TOJ task by the standard deviation (SD) (Basharat et al., 2018). **B** In the SJ task, responses are plotted as a function of SOA and a Gaussian function fit to the data. The PSS corresponds to the SOA at which participants reported, "simultaneous" most of the time (i.e., the peak of the curve). The TWI is represented by the SD (Vroomen, & Keetels, 2010; Kostaki & Vatakis, 2018; Harris et al., 2010).

Appendix B

Edinburgh Handedness Inventory

Name: Date:

Please **indicate with a number (1 or 2)** your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put the number 2.

Where there is a general preference that you are more likely to use the one hand over the other, put the number 1.

If you are indifferent, put a 1 in each column (1 | 1).

Task/Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a box (lid)		
Total Checks:	LH =	RH =

Modified from: Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97-113.

Participants will not see the below section.

Handedness will be determined using the following equation(s):

Cumulative Total: $CT = LH + RH =$
Difference: $D = RH - LH =$
Result: $R = (D/CT) \times 100 =$

Interpretation:
(Left Handed: $R < -40$)
(Ambidextrous: $-40 \leq R \leq +40$)
(Right Handed: $R > +40$)

Appendix C

Ollen Musical Sophistication Index

1. How old are you today? _____ age in years

2. At what age did you begin sustained musical activity? "Sustained musical activity" might include regular music lessons or daily musical practice that lasted for at least three consecutive years. If you have never been musically active for a sustained time period, answer with zero. _____ age at start of sustained musical activity

3. How many years of private music lessons have you received? ! If you have received lessons on more than one instrument, including voice, give the number of years for the one instrument/voice you've studied longest. If you have never received private lessons, answer with zero. _____ years of private lessons

4. For how many years have you engaged in regular, daily practice of a musical instrument or singing? "Daily" can be defined as 5 to 7 days per week. A "year" can be defined as 10 to 12 months. If you have never practiced regularly, or have practiced regularly for fewer than 10 months, answer with zero. _____ years of regular practice

5. Which category comes nearest to the amount of time you currently spend practicing an instrument (or voice)? Count individual practice time only; not group rehearsals.

- ☐ I rarely or never practice singing or playing an instrument
- ☐ About 1 hour per month (Current practice1)
- ☐ About 1 hour per week (Current practice2)
- ☐ About 15 minutes per day (Current practice3)
- ☐ About 1 hour per day (Current practice4)
- ☐ More than 2 hours per day (Current practice5)

6. Have you ever enrolled in any music courses offered at college (or university)?

☐ No (Skip to #8)

☐ Yes

7. (If Yes) How much college-level coursework in music have you completed? If more than one category applies, select your most recently completed level.

☐ None (College1)

☐ 1 or 2 NON-major courses (e.g., music appreciation, playing or singing in an ensemble) (College2)

☐ 3 or more courses for NON-majors (College3)

☐ An introductory or preparatory music program for Bachelor's level work (College4)

☐ 1 year of full-time coursework in a Bachelor of Music degree program (or equivalent) (College5)

☐ 2 years of full-time coursework in a Bachelor of Music degree program (or equivalent) (College6)

☐ 3 or more years of full-time coursework in a Bachelor of Music degree program (or equivalent) (College7)

☐ Completion of a Bachelor of Music degree program (or equivalent) (College8)

☐ One or more graduate-level music courses or degree (College9)

8. Which option best describes your experience at composing music?

☐ Have never composed any music

☐ Have composed bits and pieces, but have never completed a piece of music (Composition1)

☐ Have composed one or more complete pieces, but none have been performed (Composition2)

☐ Have composed pieces as assignments or projects for one or more music classes; one or more of my pieces have been performed and/or recorded within the context of my educational environment (Composition3)

☐ Have composed pieces that have been performed for a local audience (Composition4)

☐ Have composed pieces that have been performed for a regional or national audience (e.g., nationally known performer or ensemble, major concert venue, broadly distributed recording) (Composition5)

9. To the best of your memory, how many live concerts (of any style, with free or paid admission) have you attended as an audience member in the past 12 months? Please do not include regular religious services in your count, but you may include special musical productions or events.

☐ None

☐ 1 - 4 (Concert1)

☐ 5 - 8 (Concert2)

☐ 9 - 12 (Concert3)

☐ 13 or more (Concert4)

10. Which title best describes you?

☐ Nonmusician

☐ Music-loving nonmusician (Rank1)

☐ Amateur musician (Rank2)

☐ Serious amateur musician (Rank3)

☐ Semiprofessional musician (Rank4)

☐ Professional musician ((Rank5)

Equation to establish musical sophistication index:

Logit = -3.513 + -.423(College1) + .274(College2) + -.616(College3) + .443(College4) + .055(College5) + 2.801(College6) + .387(College7) + 1.390(College8) + 3.050(College9) + .027(Age) + -.026(Age at commencement of musical activity) + -.076(Years private lessons) + .042(Years regular practice) + -.060(Current practice1) + -.098(Current practice2) + -.301(Current practice3) + -1.211(Current practice4) + -1.528(Current practice5) + .516(Composition1) + 1.071(Composition2) + .875(Composition3) + .456(Composition4) + -1.187(Composition5) + 1.839(Concert1) + 1.394(Concert2) + 1.713(Concert3) + 1.610(Concert4) + -.553(Rank1) + .328(Rank2) + 1.589(Rank3) + 1.460(Rank4) + 2.940(Rank5)

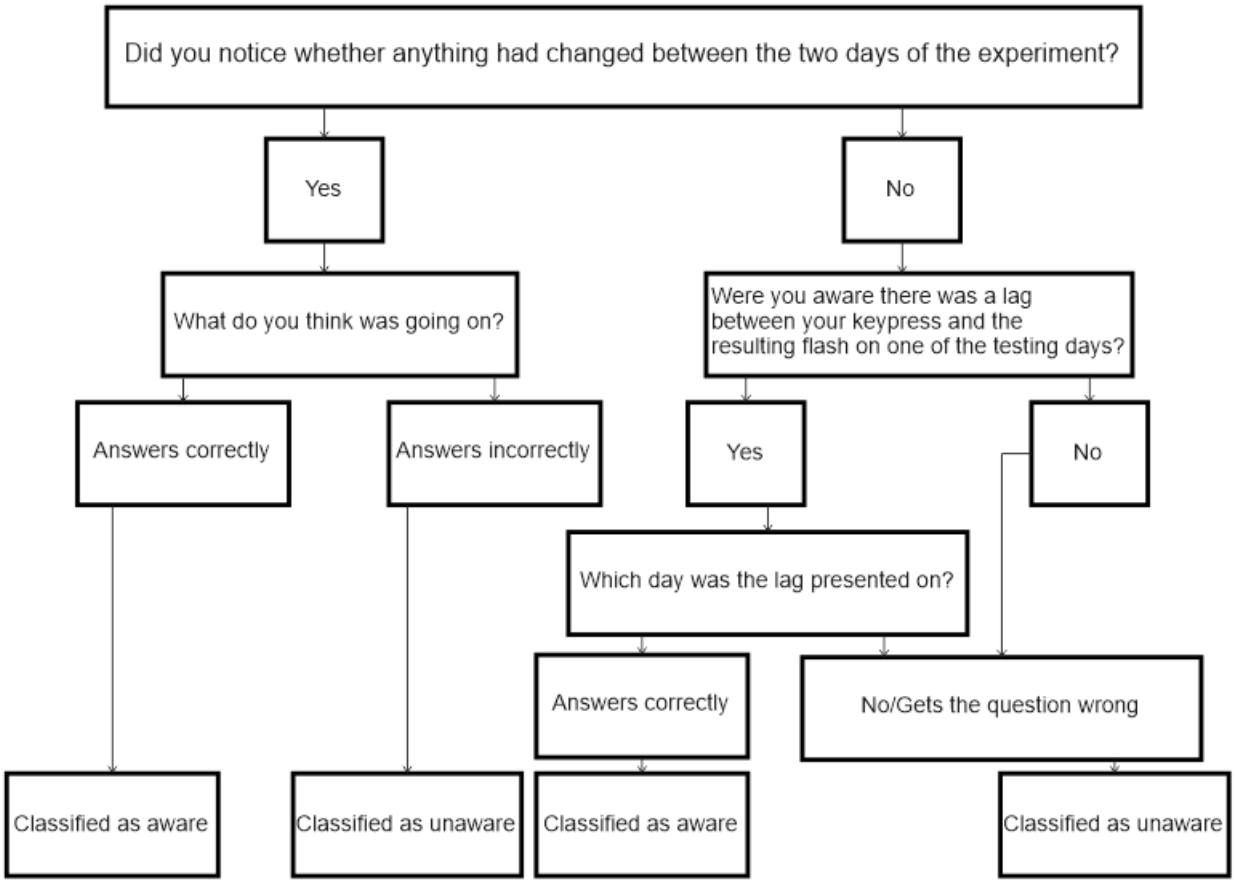
Appendix D

Video Game Questionnaire

1. **How many years have you played video games?** _____ years.
2. **How many hours per week do you play video games on average (in the last 6 months)?** _____ hours.
3. **How many hours per week of first-person shooter video game experience have you had within the past 6 months?** _____ hours.
4. **How many hours per week of real-time strategy video game experience have you had within the past 6 months?**_____ hours.
5. **How many hours per week of sports video game experience have you had within the past 6 months?**_____ hours.
6. **Have you played first-person shooter games for at least 5 hours per week at some point in your life?** Yes/No
7. **Would you rank yourself as an expert, intermediate, or novice player with respect to first-person shooter video games?** Expert/Intermediate/Novice
8. **Would you rank yourself as an expert, intermediate, or novice player with respect to real-time strategy video games?** Expert/Intermediate/Novice
9. **Would you rank yourself as an expert, intermediate, or novice player with respect to sports video games?** Expert/Intermediate/Novice

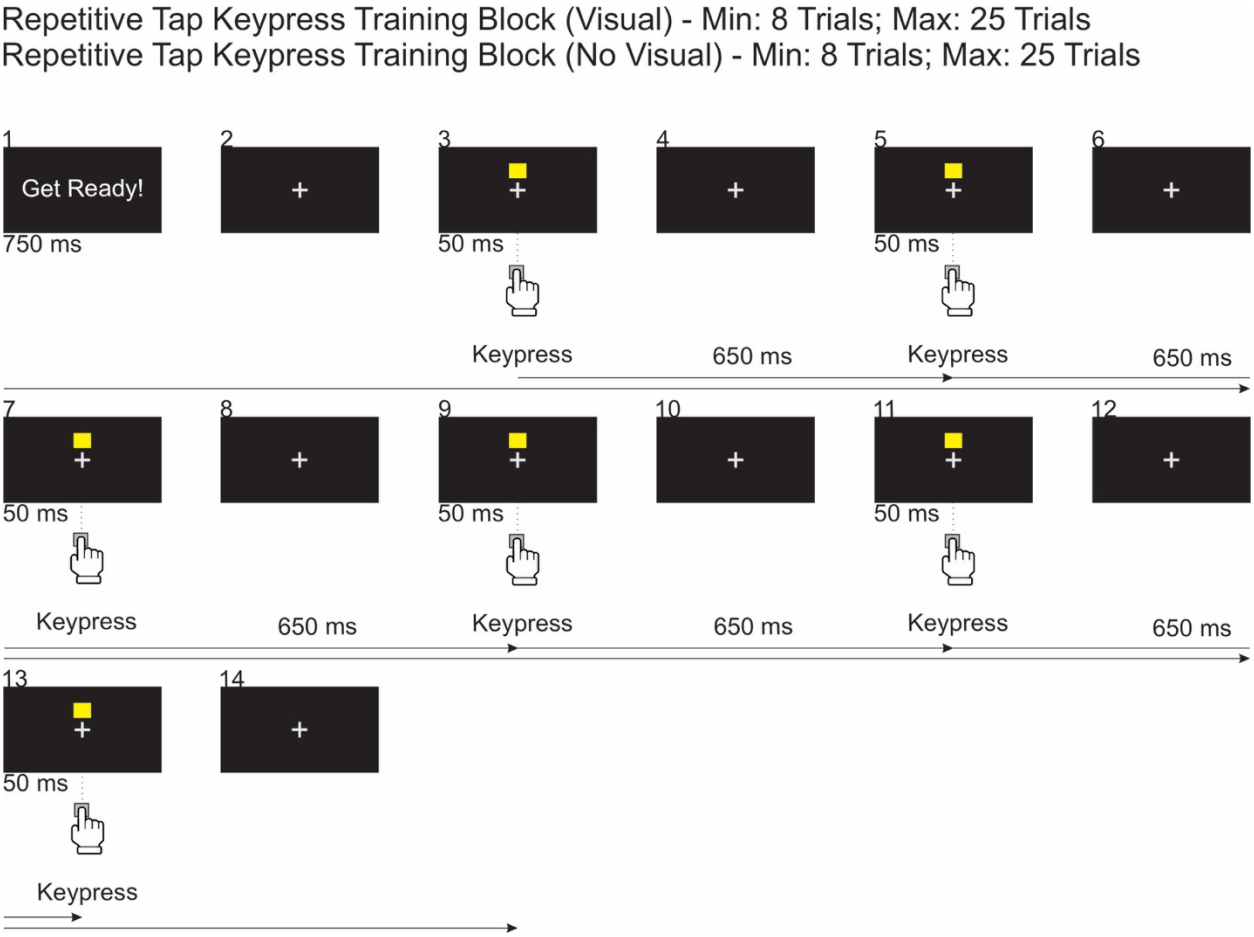
Appendix E

End of Experiment Probe



Appendix F

Keypress Training Block



A1. Visual events occurring in the repetitive tap keypress training block. Within the training block, participants tapped 6 times in pace with a yellow square that appeared at a frequency of ~1.54 Hz. Within the second half of the training block, participants continued to tap with the same frequency, however, the yellow squares were not presented.

Appendix G

Experimental Script

Aware vs Unaware Groups

Instructions regarding the flash delay provided before the adaptation blocks:

Aware Group:

0 ms Fixed lag adaptation block:

In this block of trials, you will see a visual flash on the screen immediately after your keypress. Thus, there will be no lag between pressing the key and the white flash appearing.

100 ms Fixed lag adaptation block:

In this block of trials, you will see a visual flash on the screen that will follow your keypress after a slight delay. In particular, there will be a 100 ms lag between pressing the key and the white flash appearing.

Unaware Group:

No instructions will be given regarding the timing of their keypress and visual flash.

Instructions within Blocks to all Participants

Placement

Hand placement - rest your dominant finger above the tactile pad and your non-dominant hand near the response pad
Head placement - rest your forehead on the pad and your chin on the wood

Single Tap

Block I (Adaptation)

[~2.5m]

This block will start with the screen displaying “Get Ready!”. A white cross will appear in the middle of the screen, which will serve as the go-signal. You must press the tactile pad with your dominant index finger as fast as possible once the cross appears. After your keypress, a flash will occur above the cross. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key - 0 ms Fixed Lag - Aware: The flash will appear

immediately after your keypress with no lag]. Should you press the key too early or too late, the trial will be counted as incorrect and you will have to redo the trial. You must complete 50 correct trials. After each trial, you will tell me what colour the flash was. The flash can be pink or white. This will end one trial. Do you have any questions?

Block II & III (Practice & Test TOJ)

[~7m]

These trials are similar to the ones you just completed. To begin, the screen will display "Get Ready!", and the white cross will appear. That is your go-signal, so you will press the tactile pad with your finger as quickly as possible. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key - 0 ms Fixed Lag - Aware: The flash will appear immediately after your keypress with no lag]. {This time, you won't have to indicate the colour}. There will be 5 trials.

- PAUSE -

We are now going to change the task slightly. Similar to before, the screen will display "Get Ready!", and the white cross will appear. That is your go-signal, so you'll tap as quickly as possible. This time, the flash can occur before or after your keypress. At the end of the trial, you will be asked if the flash came before or after your keypress. If the flash came before your keypress, press the blue button, if the flash came after, press the yellow button. Take as long as you want to consider, there is no rush. I will give you feedback on whether or not your response was accurate at the end of each trial. There will be 5 trials.

- PAUSE -

Now that you have completed the practice trials, we will continue the same task. Once again, your main task is to react as quickly as possible to the cross appearing on screen by pressing the tactile pad. The flash can occur before or after your keypress. If the flash came before your keypress, press the blue button, if the flash came after, press the yellow button. Take as long as you want to consider, there is no rush. There are 100 trials, however, we will pause after 10 to see if you have any questions.

- PAUSE -

Do you have any questions? We shall continue the same task. We have another 90 to go.

Block IV (Adaptation "Top-Up")

[~0:30m]

We just finished one of the four blocks for today. This block will be similar to the first block you completed, in that you just have to react to the go-signal. You do not need to indicate the time that the white flash appeared. The screen will display "Get Ready!", and the white cross will appear. That is your go-signal so you'll tap as quickly as possible. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key - 0 ms Fixed Lag - Aware: The flash will appear immediately after your keypress with no lag]. Should

you press the key too early or too late, the trial will be counted as incorrect and you will have to redo the trial. You will complete 10 trials.

Block V & VI (Practice & Test SJ)

[~7m]

These trials are similar to the ones you just completed. To begin, the screen will display "Get Ready!", and you will press the tactile pad with your finger as soon as you see a white cross displayed. This will be the go-signal. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key - 0 ms Fixed Lag - Aware: The flash will appear immediately after your keypress with no lag]. There will be 5 trials.

- PAUSE -

We are now going to change the task slightly. Similar to before, the screen will display "Get Ready!", and the white cross will appear. That is your go-signal, so you'll tap as quickly as possible. This time, the flash can occur simultaneously or not simultaneously with your keypress. At the end of the trial, you will be asked if the flash was simultaneous or not simultaneous with your keypress. If the flash was simultaneous with your keypress, press the blue button, if the flash was not simultaneous with your keypress, press the yellow button. Take as long as you want to consider, there is no rush. I will give you feedback on whether or not your response was accurate at the end of each trial for the first three trials. There will be 5 trials.

- PAUSE -

Now that you have completed the practice trials, we will continue the same task. Once again, your main task is to react as quickly as possible to the cross appearing on screen by pressing the tactile pad. The flash can occur simultaneously or not simultaneously with your keypress. If the flash was simultaneous with your keypress, press the blue button, if the flash was not simultaneous with your keypress, press the yellow button. Take as long as you want to consider, there is no rush. There are 100 trials, however, we will pause after 10 to see if you have any questions.

- PAUSE -

Do you have any questions? We shall continue the same task. We have another 90 to go.

Repetitive Tap

Block I (Keypress Training)

[~2m]

In this block, you will tap six times for each trial with a specific frequency. On the screen, you will see a yellow flash that will appear every 650 ms above the white cross. Tap in

time with the appearance of the yellow squares. If you tap too slowly or too quickly, you will have to redo the trial. You need to get 8 trials correct to move to the next block.

- PAUSE -

Now that you have learned the timing, the yellow flash will no longer appear, however, I want you to tap with the same frequency. Again, if you tap too slowly or too quickly, you will have to redo the trial. You need to get 8 trials correct to move to the next block.

Block II (Adaptation)

[~1m]

On these trials you will continue to tap with the frequency you have learned. Again, you must tap 6 times in each trial with your finger. After each tap, a white or pink flash will be presented in the middle of the screen. Following each trial, you will indicate how many times a pink flash appeared (once or twice) within the trial of 6 taps. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: The flash will appear immediately after your keypress with no lag]. I will give you feedback regarding your tapping frequency if you tap too slowly or too quickly. There will be 8 trials.

Block III & Block IV (Practice & Test TOJ)

[~12m]

In this block, you will do the same thing as before, in which you will tap 6 times for each trial. These trials will be slightly different such that you will see a flash appear after the first four keypresses. [100 ms Fixed Lag - Aware: For the first four taps, the flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: For the first four taps, the flash will appear immediately after your keypress with no lag]. There will not be a flash after the 5th tap. On the 6th tap, the flash may occur before or after the tap. After the 6th tap, you will be asked if the flash came before or after your keypress. If the flash came before your keypress, press the blue button, if the flash came after, press the yellow button. Take as long as you want to consider, there is no rush. We will start with two practice trials. I will give you feedback on whether or not your response was accurate at the end of each trial.

- PAUSE -

Now that you have completed the practice trials, we will continue the same task. Once again, you will tap 6 times, with the flash appearing from taps one to four. [100 ms Fixed Lag - Aware: For the first four taps, the flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: For the first four taps, the flash will appear immediately after your keypress with no lag]. On the 5th tap, there will be no flash. On the 6th tap, the flash may occur before or after the tap. After the 6th tap, you will be asked if the flash came before or after your keypress. If the flash came before, press the blue button, if the flash came after, press the yellow button. Take as long as you want to consider, there is no rush. We will start with 20 trials.

- PAUSE -

We just completed 20 trials. Now you will complete two training trials to ensure that you are tapping at the required pace. One trial will include the visual flashes as pacing stimuli, the other block will not have the flashes.

Now we will do the same thing 4 more times

Block V (Adaptation "Top Up")

[~0:15m]

In this block, you will continue to tap with the frequency you have learned. Again, you will tap 6 times in each trial with your finger. Following each tap, a white flash will be presented in the middle of the screen. [100 ms Fixed Lag - Aware: The flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: The flash will appear immediately after your keypress with no lag]. I will give you feedback regarding your tapping frequency. You will complete 2 trials.

Block VI & Block VII (Practice & Test SJ)

[~12m]

In this block, you will do the same thing as before, in which you will tap 6 times for each trial. These trials will be slightly different such that you will see a flash appear after the first four keypresses. [100 ms Fixed Lag - Aware: For the first four taps, the flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: For the first four taps, the flash will appear immediately after your keypress with no lag]. There will not be a flash after the 5th tap. On the 6th tap, the flash can occur simultaneously or not simultaneously with your keypress. After the 6th tap, you will be asked if your keypress was simultaneous or not with the flash. If your keypress was simultaneous with the flash, press the blue button, if it was not, press the yellow button. Take as long as you want to consider, there is no rush. We will start with two practice trials. I will give you feedback on whether or not your response was accurate at the end of each trial.

- PAUSE -

Now that you have completed the practice trials, we will continue the same task. Once again, you will tap 6 times, with the flash appearing from taps one to four. [100 ms Fixed Lag - Aware: For the first four taps, the flash will appear at a slight lag, specifically 100 ms after you press the key, 0 ms Fixed Lag - Aware: For the first four taps, the flash will appear immediately after your keypress with no lag]. There will be no flash after the 5th tap. On the 6th tap, the flash may appear simultaneously with your keypress. After the 6th tap, you will be asked if the flash was simultaneous or not with your keypress. If the flash was simultaneous with your keypress, press the blue button, if it was not, press the yellow button. Take as long as you want to consider, there is no rush. We will start with 20 trials.

- PAUSE -

We just completed 20 trials. Now you will complete two training trials to ensure that you are tapping at the required pace. One trial will include the visual flashes as pacing stimuli, the other block will not have the flashes.