ABSTRACT

Title of Thesis: FORCE AND TEMPORAL CONTROL IN CONTINUOUS AND SYNCHRONIZATION UNIMANUAL FINGER TAPPING

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Temporal control is essential to human movement both in the activities of daily living and the skilled actions of the athlete, dancer, or musician. Although the temporal control ability has been widely and well-studied for over a hundred years, little attention has been paid to the other movement parameters such as space and force that might influence temporal control. To probe the relationship between force and temporal control, 17 right-handed participants were required to perform a continuous (without metronome) and synchronization (with metronome) tapping task with temporal constraints (1500, 1000, or 500 ms tapping interval) and with no force constraint. The results reveal that the contact time for a tap (initial time when finger touches the surface) was less controlled than the time of the tap's peak force. In addition, in the synchronization task, tapping error at the time of peak force was closer to zero. The force production pattern as reflected in peak force, impulse, and the time to peak force varied across tapping modes and intervals. Taken together, these results suggest that force and temporal control are systematically related to each other in finger tapping and that different force production strategies may be used to optimize the temporal control.

FORCE AND TEMPORAL CONTROL IN CONTINUOUS AND SYNCHRONIZATION UNIMANUAL FINGER TAPPING

By

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Chapter 1 Introduction

The precision of temporal control is important to human motor behavior because action takes place in time. Temporal control is both a perception and an action ability that estimates and produces movement in time intervals. Action takes place over different timescales: from the circadian 24-hour cycle to, the minutes, seconds or milliseconds of some behaviors. For example, temporal control at the millisecond level is crucial to playing music or performing with other musicians (Buhusi & Meck, 2005). Pianists estimate the time interval between successive notes to play wonderful music and dancers estimate the right moment when they should pace their movements to specific musical tempos. Interestingly, temporal perception and action ability are not unique to humans. Animals such as the cockatoo, for example, can spontaneously adjust the tempo of their movements to synchronize with rate changes in an external stimulus (Patel, Iversen, Bregman, & Schuiz, 2009). However, even well-trained musicians and dancers exhibit variability and inaccuracy in their time estimation and synchronization.

Many models have been proposed to explain temporal control, especially temporal variability and inaccuracy. Movement parameters such as force, however, have been ignored in these models. In this thesis, it is this variability and inaccuracy of movement temporal control that is the central focus. In particular, this research examines force production during uni-manual finger tapping, a paradigm that has been widely used to study temporal control's variability and inaccuracy.

Two different perspectives on temporal control are found in the literature. Traditionally, an internal timer has been considered to be the central mechanism of time estimation; although there are many views on the nature of this timer and whether it has a physical instantiation. Several models from this perspective, such as the pacemaker-accumulator model (Ivry & Richardson, 2002), have been proposed to explain how time perception and estimation work and to explain the variability and inaccuracy of temporal control. Alternatively, others have argued that there is no central timer in the brain. Here temporal perception is conceptualized as a cognitive mechanism rather than an internal timer (Grondin, 2010). Or as suggested in a recent neuroimaging study, a distributed brain network, rather than an internal timer located in a specific region of brain, is responsible for temporal control (Buhusi & Meck, 2005).

For the most part, the central timer models of temporal control have seen the issue as one predominantly concerned with the central nervous system. It could be argued that without the peripheral system that executes the movement, the explanation is incomplete or incorrect. One particular model that took the motor component into consideration serves as an exemplar for understanding how motor timing is conceptualized. In this model, timing is viewed as a two-level process. The two-process model was originally proposed by Wing and Kristofferson (1973) and later developed by Vorberg and Wing (1996), and Vorberg and Schulze (2002). It was developed to explain perception-action coupling variability that had been an almost universal finding in previous research. In this model, variability of temporal control is attributed to two independent sources: 1) a central timer; and, 2) motor delay. The central timer estimates the time interval and provides a stochastic timekeeping signal. The motor delay component indicates the neural transmission delays between the central timer triggering and the overt movement execution. This model provides an estimate of the variability of the central timer and the motor delay.

In the laboratory, two major experimental paradigms have been widely used to study the precision of temporal control: synchronization-continuous tapping (see Wing, 2002, for a review) and synchronization tapping (see Repp, 2005, for a review). The synchronization-continuous finger tapping paradigm, introduced by Stevens (1886) focuses on the variability of inter-response interval production. In this paradigm, participants start tapping their finger to an external cue (paced phase). After about 10-15 taps, the external cue is turned off and participants are asked to continue tapping at the same rate given by the external cue (unpaced phase). The interval between the two successive external cues is defined as the inter-stimulus interval. During the unpaced phase, the longer-than-average inter-response interval (IRI) alternate with the shorter-than-average IRI, thus creating a "zig-zag interval" (Stevens, 1886) or negative lag-one auto-correlation (Semjen, Schulze, & Vorberg, 2000; Vorberg & Wing, 1996; Wing & Kristofferson, 1973). Wing (1980) found that for typical adults, only the internal timekeeper variance increased with increasing external cue rate, while the motor variance remained relatively constant. These results suggested that the central timer is the major source contributing to temporal variability.

In contrast to the continuous tapping paradigm in which the inter-response interval is the datum of interest, the synchronization paradigm focuses on the error correction mechanism where the synchronization error (SE) is defined as the time difference between the taps and the corresponding external cues. Synchronization tapping is a task paced with external cues (auditory, visual, tactile etc.) extensively used to test sensorimotor synchronization (Repp, 2005). It has been argued that synchronization tapping is more complex than continuous tapping because, in addition to the IRI production, subjects must correct the SE (Hary & Moore, 1987). The error correction ability is very important to sensorimotor synchronization because without it, the accumulated error will increase without bound causing an incorrect timing output. Since 1967 (reported by Repp, 2005), the error correction mechanism has been studied using the paced finger tapping task. Phase and period error correction models have been established (Hary & Moore, 1987; Pressing, 1998; Semjen, Vorberg, & Schulze, 1998). However, these studies ignored the notion that there was a central timer. Taking the two-level process framework into consideration, Vorberg and Wing (1996) extended the original two-level process model to the synchronization paradigm and the validity of the extended model was examined by simulation studies (Semjen, et al., 1998). Using this extended model, Semjen and his colleagues (Semjen, et al., 2000) compared the temporal variability between synchronization-continuous and synchronization finger tapping movements. They found the timekeeper variance increased with increasing external cue rate for both paradigms, but more steeply during continuous compared to synchronization tapping. This result suggested that, during synchronization tapping, the central variance was counteracted by the variance contributed by the corrective mechanism.

The other focus of sensorimotor synchronization studies is the negative SE which refers to the taps always preceding the external cues in adults. A review of the extant studies demonstrated that the negative SE was found in almost all the sensorimotor synchronization studies (Aschersleben, 2002; Repp, 2005) . In Aschersleben's learning study (2003) of finger tapping in typical adults, the participants were provided with the visual feedback of the SE after each tap. However, they still tapped their fingers preceding the external metronome although their error decreased. Compared to non-musicians, musicians showed smaller (Aschersleben, 2002) or sometimes no negative SE (Repp & Doggett, 2007). Aschersleben and colleagues showed that sensory information plays an important role in negative SE (Aschersleben, Gehrke, & Prinz, 2001; Aschersleben & Prinz, 1995, 1997; Drewing, Hennings, & Aschersleben, 2002; Stenneken, Prinz, Cole, Paillard, & Aschersleben, 2006). However, the reasons for negative SE are still unclear. One hypothesis forwarded to explain the negative SE is the sensory accumulation model (Aschersleben, 2002). This model assumes that the synchronization occurs at the central representation level rather than at the motor response level and the sensory information is represented at the central level after the threshold for this sensory information is reached. The different processing speeds for tactile (tap) and auditory (metronome) information cause the SE in the representation at the central level. Therefore, to compensate for this discrepancy at the central level, one of these two sources of information (i.e., tactile information) should start processing earlier than the other, resulting in the tap preceding the metronome. Other hypotheses, such as the neural-conduction hypothesis (reviewed by Aschersleben, 2002) and the virtual amplitude hypothesis (Vaughan, Rosenbaum, Diedrich, & Moore, 1996) have also been used to explain the negativity of SE.

All of these above-mentioned studies have ignored another important movement parameter: force. Implicitly, these studies assume that temporal control is independent of other factors in motor coordination. However, examination of our daily activities, such as writing, dancing, and playing piano, reveals that all require simultaneous force production as well as temporal control. Indeed, some studies have shown that we cannot separate force control from temporal control: The impulse-timing hypothesis, for example, assumed that the amount, duration and temporal onset of force are determined by the duration of the neurological activity and the time of its occurrence (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Stein (1982) suggested that force is a muscle variable that the nervous system controls in producing limb movements. Moreover, motor behaviors are represented by kinematic parameters such as acceleration and velocity, both of which are highly related to time and force. Even in an isometric force production study, the results suggested that the time for reaching the target force level is highly correlated with the peak force variability (Newell & Carlton, 1985).

Although there is a paucity of studies focusing on force and temporal control simultaneously, a few studies have suggested that the relationship between force and temporal control exists. Keele and his colleagues (Keele, Ivry, & Pokorny, 1987) used the synchronization-continuous tapping paradigm to test the correlation between peak force variability and IRI variability. Their results suggested that peak force variation was significantly correlated to IRI variation. The positive and negative lag-one cross-correlations were found between the tap-to-tap force variation and IRI variation in their study. The relationship between peak force variability and IRI variability has also been found for synchronization tapping with high tapping frequencies (Sternad, Dean, & Newell, 2000). This study also suggested that when force control is required, the temporal property is stable across force conditions. In a notable study about the force-timing relationship (Billon, Semjen, & Stelmach, 1996), participants were required to accentuate one tap in a periodic tapping movements of five taps. It was found that the IRI of movement onset preceding the accentuated tap was shortened, while the IRI of movement onset following the specific tap was lengthened. These results suggested that force production and temporal control are coupled to each other.

In the Billon et al.(1995) study, the authors suggested that the timing goal was the time of contact between finger and surface so that tapping onset can be flexibly changed to coordinate when a more forceful tap is required. Alternatively, the virtual amplitude hypothesis suggests that the endpoint of tapping is a virtual point beyond the tapping surface (Vaughan, et al., 1996). Is the time of peak force or is the time of contact, the goal of temporal control in both continuous and synchronization tapping? In all the studies that found the negative synchronization, the time of contact was used as the endpoint of the tapping movement. Is the synchronization error at the time of peak force zero or positive?

In addition, in the previous studies, participants were required to tap their fingers with a given force target or use a relatively constant force implying that both force and time needed to be controlled simultaneously. Would force and time be related if the participants were only required to control their tapping speed and no force constraints were specified? In addition, what is the role of the external stimulus (i.e., the metronome) in regulating the force-time relationship? Previous studies found a force-time relationship in both continuous and synchronization paradigms (i.e., metronome unpaced or paced). When no force constraints are specified, is the time-force relationship different between continuous (without metronome) and synchronization tapping (with metronome) since they are proposed to use different temporal mechanisms?

Therefore, the purpose of this thesis is to determine if the temporal parameter that needs to be precisely controlled is a force parameter time - namely, the time of peak force. It is hypothesized that the IRI and SE of the time of peak force will have a higher accuracy magnitude and smaller variations than the IRI and SE for contact time, respectively, indicating that the temporal control target of finger tapping is the time of peak force and not the tap's contact time. It is also expected that different force production strategies are used in the two tapping paradigms, one with an external pacing cue (i.e., synchronous tapping) and one without an external cue (i.e., continuous tapping) as tapping intervals or speeds are varied. Specifically, we hypothesize that the time-related variables (dwell time, time-to-peak force, etc.); force-related (peak force, variability of peak force, variability of force deviation); and, force-time related variables (impulse, and force increasing rate) will differ between continuous and synchronization tapping as tapping interval changes.

In addition to this first introductory chapter (Chapter 1), three additional chapters are included in this thesis. The second chapter contains a review of the relevant literature. The third chapter describes the methodology of the proposed studies and presents the results and discusses the findings. The last chapter discusses the study's limitations and offers possible directions for future research.

Chapter 2 Review of Literature

Temporal or timing control plays an essential role in human movements. Timing control is involved in self-paced rhythmic movements such as locomotion, writing, and speech production; referential movement (Pressing, 1999) such as movements that are temporally coordinated with external events, such as dancing, singing, and playing musical instruments; and, in discrete actions, such as catching and reaching. Since 1886 (Stevens), research has been conducted to explore the temporal control mechanism of human movement. These research efforts have included mathematical modeling (Pressing, 1998; Schulze & Vorberg, 2002; Vorberg & Wing, 1996); development of the internal timer model (Helmuth & Ivry, 1996; Ivry & Richardson, 2002; Zelaznik, Spencer, & Ivry, 2002); exploration of the role of sensory information (Aschersleben, et al., 2001; Aschersleben & Prinz, 1995, 1997; Drewing, et al., 2002; Stenneken, et al., 2006) and the role of brain function (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Ivry & Spencer, 2004; Spencer, Ivry, & Zelaznik, 2005; Thaut, 2003); studies of a timing correction mechanism (Delignieres, Torre, & Lemoine, 2009; Hary & Moore, 1987; Semjen, et al., 1998); examination of the nonlinear properties of temporal variability (Delignieres et al., 2006; Delignieres, Torre, & Lemoine, 2008; Lemoine, Torre, & Delignieres, 2006; Roberts, Eykholt, & Thaut, 2000) ; and, research on timing ability across the lifespan (Bo, Bastian, Contreras-Vidal, Kagerer, & Clark, 2008; Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Drewing, Aschersleben, & Li, 2006; Greene & Williams, 1993; Piek & Skinner, 1999).

While timing is an essential element of movement, it is not the only factor involved in motor control and coordination. Indeed, movement involves three elements:

time, space, and force. Interestingly, limited attention has been paid to the interrelationship of these factors and in particular, the timing-force relationship (Billon, Semjen, et al., 1996; Sternad, et al., 2000; Therrien & Balasubramaniam, 2010). It is this latter relationship that is the focus of the present thesis.

In the first section of the thesis' review of literature, the conceptual model of timing and the different definitions of the internal timer are discussed. Two classic experimental paradigms with mathematical models are described in the subsequent two sections. The variability and synchronization error of temporal control are discussed in the later sections. The sixth section introduces a hypothesis explaining the negativity of synchronization error of sensorimotor synchronization. Lastly, the review discusses the timing-force relationship and the effect of other force-related factors (trajectory etc.) on temporal control. Because the temporal control mechanism has been widely studied for over a hundred years, the literature is immense. Therefore for the purposes of this thesis, the review of literature has been limited to the scientific work that focuses on the 1:1 in-phase discrete finger tapping experiments.

Conceptual Model and Central Timer

The first study on human movement timing was conducted in by L.T. Stevens in 1886 (Stevens, 1886). He asked participants to tap a lever repetitively matching an external metronome beats at rates from 360 ms to 1500 ms. The results revealed a pattern of temporal variability, which Stevens called "constant zig-zag." (1886). He also found that even with the short-term fluctuations, participants maintained the response intervals within 5% percent of the target mean intervals. Almost a century later, Wing and colleagues proposed a model to explain the variability in the findings of Stevens and others. Wing and Kristofferson (1973) proposed a two-level process model, in which there is a central timer in the central nervous system that controls movement timing. In this model, in addition to the central timer, the motor delay is another component that contributes to the temporal variability. The latter is the neural transmission delays between the central timer trigger and the overt movement execution. The prediction of the mathematical model of the two-level process has been supported by a number of studies (see Wing, 2002, for a review). The mathematical model is discussed in section 3 of this review.

Although the two-level process model is well-supported by the research literature, there has been a debate about the definition of the central timer. Schöner (2001), for example, has argued that the central timer is actually a pacemaker, which is a basic time measurement method in physics. In Schöner's conceptualization, the central timer measures time by counting the number of oscillation cycles of the pacemaker. In other words, one cycle of the pacemaker oscillator is a unit of time. The pacemaker's frequency could be adjusted based on the task demands. The other conceptualization of the central timer is the hourglass model or interval timer. The only difference between the hourglass model and the pacemaker oscillator is that the interval of one cycle is preset. Therefore, the model requires a set of hourglasses with different durations to produce different intervals (Ivry & Richardson, 2002).

Ivry and colleagues conducted a set of studies on the internal timer mechanism. They (Ivry, Keele, & Diener, 1988) found that patients with unilateral cerebellum lesions showed higher timing variability when they tapped their ipsi-lateral effectors (foot and finger) than the variability produced by the contra-lateral effectors. Indeed, it was interesting that this higher variability was attributed to the central timer component based on the two-level process model. These results implicitly indicated that the ipsi-lateral and contra-lateral effectors of cerebellum-lesion patients use different internal timers. In one of their later studies (Franz, Ivry, & Helmuth, 1996) involving both uni-manual and bimanual finger tapping movement in uni-lateral cerebellum lesions patients, timing variability of the ipsi-lateral finger tapping was dramatically reduced when participants tapped their ipsi- and contra-lateral fingers in-phase. According to the two-level process model, this reduced response variability was associated with reduced central component variability. A consistent result was also found in typical young adults (Helmuth & Ivry, 1996). Ivry (1996), based on these results, proposed that there were a set of internal timers used by different perceptual (afferent modalities) and motor systems (effectors), which he referred to as the "multiple timer" model.

Experimental Paradigms for The Study of Temporal Control

Finger tapping has been widely used as a task to study the temporal control of human movement. Two of the most common research paradigms to study tapping are the synchronization-continuous and synchronization tapping. These two paradigms are described below.

Synchronization-continuous paradigm.

The synchronization-continuous paradigm was first developed by Stevens (1886) to study the timing of the inter-response interval. This paradigm requires participants to match their finger taps to external cues with a fixed rate (synchronization phase). After participants match the rate, the external cues are turned off. Participants are asked to keep tapping with the same rate for some fixed interval to follow (continuous phase). The inter-response intervals during the continuous phase are the data of interest.

Synchronization paradigm.

During synchronization finger tapping, participants are instructed to tap their finger(s) to match external cues with a fixed rate. The sensorimotor synchronization is the focus of this paradigm and the synchronization errors (SE) between response and external cues are the data of interest. Different effectors (finger, wrist, and foot etc.), different external cues (visual and auditory), and different coordination patterns between external cues and response (in-phase and anti-phase; 1:1 or 2:1) have been used in this experimental paradigm.

Modeling Human Temporal Control

Wing and Kristofferson (1973) developed the two-level process model for the synchronization-continuous paradigm. As stated earlier, two components contribute to the overt temporal variability (Figure 2.1):

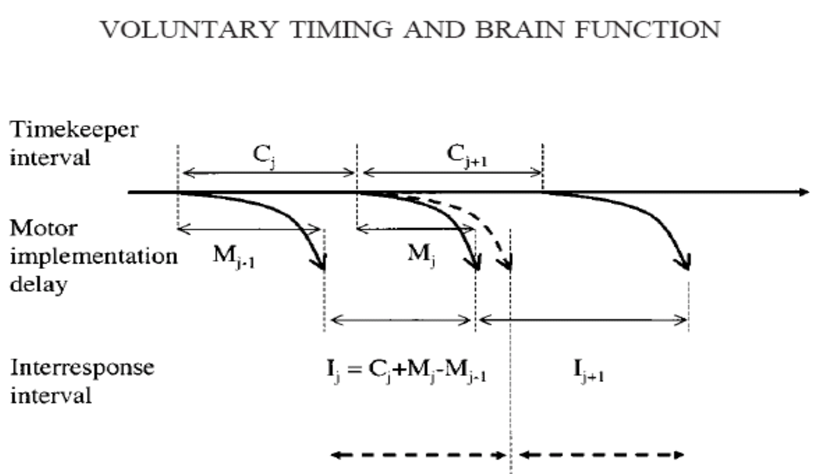

Figure 2. 1: The two-level process model for continuous tapping (Vorberg & Schulze, 2002)

In this model, the jth inter-response interval I_j is related to the timekeeper of current tap C_j and is bounded by the current motor delay M_j and the preceding motor delay component M_{j-1}:

$$I_j = C_j + M_j - M_{j-1} \tag{2.1}$$

To check the "zig-zag interval" found by Stevens (1886) , the auto-covariance coefficient can be calculated:

$$\begin{aligned}
&\mathrm{cov}(I_n, I_{n+j}) = \mathrm{cov}(C_n + M_n - M_{n-1}, C_{n+j} + M_{n+j} - M_{n+j-1}) \\
&= \mathrm{cov}(C_j, C_{n+j}) + \mathrm{cov}(C_n, M_{n+j}) - \mathrm{cov}(C_n, M_{n+j-1}) + \mathrm{cov}(M_n, M_{n+j}) \\
&- \mathrm{cov}(M_n, M_{n+j-1}) - \mathrm{cov}(M_{n-1}, C_{n+j}) - \mathrm{cov}(M_{n-1}, M_{n+j}) + \mathrm{cov}(M_{n-1}, M_{n+j-1})
\end{aligned} \tag{2.2}$$

With the assumptions 1). $\forall m,n,\ \mathrm{cov}(C_n, M_m) = 0$ that means the central timer and motor delay component are independent. 2). $\forall m,n,\ \mathrm{cov}(C_n, C_m) = 0$ and $\mathrm{cov}(M_n, M_m) = 0$ that means the independence within component, we can simplify equation (2.2) to:

$$\mathrm{cov}(I_n, I_{n+j}) = \gamma_I^j = \begin{cases} \delta_C^2 + 2\delta_M^2 & j = 0 \\ -\delta_M^2 & j = 1 \\ 0 & j > 1 \end{cases} \tag{2.3}$$

Then, it is obvious that

$$\rho_I(0) = \frac{\gamma_I(0)}{\gamma_I(0)} = 1 \qquad \textit{when} \quad j = 0 \tag{2.4a}$$

$$\rho_I(1) = \frac{\gamma_I(1)}{\gamma_I(0)} = -\frac{\delta_M^2}{\delta_C^2 + 2\delta_M^2} \qquad \textit{when} \quad j = 1 \tag{2.4b}$$

$$\rho_I(K) = 0 \qquad \textit{when} \quad j = K > 1 \tag{2.4c}$$

where the ρ and γ are the auto-correlation and auto-covariance function of the inter-response interval, respectively. The δ_M^2 is the variance of the motor delay component, and the δ_C^2 is the variance of the central timer. The model indicates that the lag one auto-correlation of the inter-response interval is bounded between 0 ($\delta_M^2 = 0$) and -1/2 ($\delta_M^2 >> \delta_C^2$), which is consistent with Stevens' "zig-zag fluctuations" and has also been supported by a number of studies about temporal control (Wing, 2002). Equation (2.4) has been used to calculate the variability of the motor delay and central timer (Greene & Williams, 1993; Helmuth & Ivry, 1996), which cannot be observed by the overt temporal response.

In contrast to the modeling of continuous finger tapping, early models of sensorimotor synchronization focused on the error correction and they did not distinguish between the central and peripheral components proposed in the two-level process model of Wing and Kristofferson (1973). The first model of synchronization timing was proposed by Michon (reported by Repp, 2005) who suggested a linear correction mechanism in which each inter-response interval is based on the two preceding inter-onset intervals which is the interval between two successive external cues. Hary and Moore (1987) formulated a mixed phase resetting model which suggested the current tap is based on the previous cue or preceding tap. These two sources are randomly chosen by the person tapping. Another type of model, referred to as the period correction model, was proposed by Mates (Mates, 1994a, 1994b). In his model, the central timer corrected the timing based on the difference between the preceding inter-response interval and inter-onset interval. The choice of which one of these two correction mechanisms is used depends on the different task parameters, such as the amount of perturbation of the external cues (Semjen, et al., 1998; Thaut, Miller, & Schauer, 1998).

In 1996, Wing and a colleague (Vorberg & Wing, 1996) extended the two-level process model for continuous tapping to the sensorimotor synchronization task. In this phase correction model, the basic assumption is that participants correct the synchronization error by adjusting the timekeeper based on the previous synchronization error (Figure 2.2).

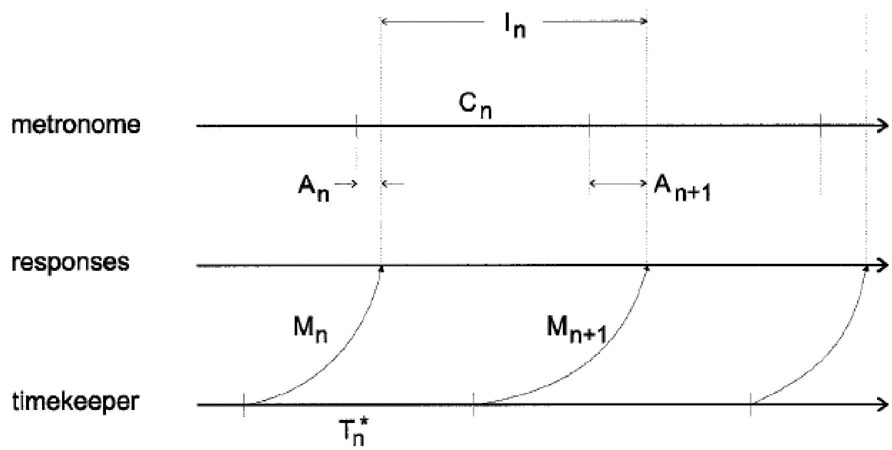

Figure 2. 2: The two-level process model for synchronization tapping (Vorberg & Schulze, 2002)

In figure 2.2, the definitions of capital letters are the same as in Figure 2.1. In addition, C_j and A_j are the external cues' j[th] interval and the j[th] synchronization error, respectively. It is clear that the synchronization is the time discrepancy between the external cue and corresponding response, but formally, it is defined as the difference between cumulated inter-response intervals and cumulated inter-onset intervals (Vorberg & Schulze, 2002):

$$A_{n+1} = A_1 + \sum_{j-1}^{n} I_j - \sum_{j-1}^{n} C_j \qquad (2.5)$$

It is obvious in Figure 2.2 that the inter-response interval can be stated as a function of synchronization error and the inter-onset interval:

$$I_n = C_n + A_{n+1} - A_n \tag{2.6}$$

The same as for the model for continuous tapping, the inter-response interval is a linear combination of motor delay and central timer:

$$I_j = T_j^* + M_{j+1} - M_j \tag{2.7}$$

However, the difference here is the adjustable central timer T_j^*. According to the assumption of phase correction mechanism, this adjustable central timer can be described as:

$$T_j^* = T_j - \alpha A_j \tag{2.8}$$

Using these basic equations, we can calculate the auto-correlation function of inter-response intervals (same as equation (2.2)):

$$\rho_I(0) = \frac{\gamma_I(0)}{\gamma_I(0)} = 1 \qquad when \quad j = 0 \tag{2.9a}$$

$$\rho_I(1) = \frac{\gamma_I(1)}{\gamma_I(0)} = -\frac{\delta_M^2}{\delta_T^2 + 2\delta_M^2 + \delta_C^2} \qquad when \quad j = 1 \tag{2.9b}$$

$$\rho_I(K) = 0 \qquad when \quad j = K > 1 \tag{2.9c}$$

Equation (2.9) can be used to calculate the time dependence of temporal control as well as the variance of the central timer and the motor delay.

Temporal Variability

Wing and Kristofferson (1973) examined the mathematical model by experimental data. Their experimental results showed that the auto-correlation is always negative and bounded between -0.43 to -0.1 for finger tapping when the rate is between 180 to 400 ms. The same negative lag-one auto-correlation was also found by Semjen and colleagues using 200 to 640 ms interval (Semjen, et al., 2000). In Greene and William's developmental study (1993), 98% trial of all participants showed a negative lag-one auto-correlation. Moreover, they used this model to calculate the variability of the motor delay and the central timer. They found children, older adults, and females showed higher variability of the central timer, but no differences in variability of the motor component, which suggested that the differences observed in temporal variability across the lifespan are explained by age-related difference in the central timer. The same method for estimating the variability of the two components was also used by other studies (Franz, et al., 1996; Helmuth & Ivry, 1996; Ivry, et al., 1988). All of these studies found that the central timer rather than the motor component contributed more to the observed temporal variability.

Besides the variability of the inter-response intervals, the synchronization error also provides information about a person's sensorimotor synchronization ability. The same as for the inter-response interval during continuous tapping, the variability of the inter-response interval and the synchronization error during synchronization tapping decreases as the rate of the external metronome increases (Semjen, et al., 2000). As described above, the variability of temporal control during sensorimotor synchronization is also explained by the central and peripheral source (Vorberg & Wing, 1996). However, few studies have applied this model to experimental data to calculate the central timer and motor delay variability during synchronization tapping.

In addition to short duration variability, temporal variability has been studied during a long sequence of finger tapping (up to thousands of taps). In an experiment involving long sequence finger tapping task (Ding, Chen, & Kelso, 2002), Ding and his colleagues asked participants to perform 1200 taps with the right index finger. They found that a long memory process of type $1/f^{\alpha}$ exists for sensorimotor synchronization mechanism. The existence of this power law relationship has also been found in continuous tapping (Lemoine, et al., 2006). The slope of the power-law relation has been suggested as a criterion to distinguish healthy and handicapped persons (Yoshinaga, Miyazima, & Mitake, 2000). Using a non-linear time series method and fractal analysis, several studies have also found a long correlation and a chaotic property for temporal control variability (Delignieres, Lemoine, & Torre, 2004; Delignieres, et al., 2008; Roberts, et al., 2000; Torre, Delignieres, & Lemoine, 2007). This would suggest that the variability of the inter-response interval and SE are not random, but chaotic.

Negative Synchronization Error

One of the question of interest for synchronization tapping is how precise is the timing of the response to the external cue. For one hundred years, it has been known that the mean synchronization error, also referred to as asynchrony, is always negative, suggesting that the tapping response tends to precede the external cue (Dunlap, 1910; Hary & Moore, 1987; Johnson, 1899; Mates, Muller, Radil, & Poppel, 1994; Peters, 1989; Stenneken, et al., 2006). Interestingly, even when subjects were trained on sensorimotor synchronization for 10 sessions for five consecutive days, Aschersleben (2003) found that without synchronization error feedback or with non-informative feedback, participants consistently showed negative synchronization error and no change occurred across sessions; however, the errors decreased across sessions when the direction and magnitude of the synchronization errors were provided after each tap. Interestingly, even though the timing error of the 10^{th} session was close to 0, it was still negative. The participants reported that they had to delay their tapping to achieve the synchronization. Two months later when subjects were re-tested, the synchronization errors went back to the same magnitude as seen before the extended practice.

Besides the negativity, two other characteristics of the SE have been reported in several studies. The magnitude of SE was found to be positively correlated to the length of the inter-onset interval (Mates, et al., 1994; Peters, 1989). The other characteristic of SE that is of interest was the individual differences that have been reported. In particular, trained musicians have been shown to have much smaller SEs than those not trained in music (Inui & Ichihara, 2001; Repp & Doggett, 2007).

Effect of Sensory Information

The negative synchronization error (SE) phenomenon, which many consider to be an anticipation behavior, is still not well explained or understood. Aschersleben (2002) proposed the sensory accumulator model which assumed that synchrony is formed at the level of central representation, not at the level of the overt movement response. In this model, it is assumed there are thresholds for the sensory information representation from different modalities. Perfect synchronization occurs when the auditory information from the external metronome and the tactile-proprioceptive information from finger reach their own thresholds simultaneously. Consequently, if the accumulation functions of afferent information for different sensory modalities are different, the synchronization error of central representations would occur. In a synchronization finger tapping task, Aschersleben (2002) suggested that the accumulation process is faster for auditory information than tactile-proprioceptive information. In order to precisely synchronize these two events at the central representation level, the tap response has to precede the external metronome to start accumulating information earlier. This idea was initiated and supported by a series of studies about sensory information effects on sensorimotor synchronization conducted by the same research group (Aschersleben, et al., 2001; Drewing & Aschersleben, 2003; Mates & Aschersleben, 2000; Stenneken, et al., 2006). By manipulating auditory feedback, Aschersleben & Prinz (1997) and Mates & Aschersleben (2000) found the synchronization error varied with different auditory feedback, even though the rate of the external metronome was kept the same across all auditory feedback conditions, indicating that the central representation for finger tapping with and without auditory feedback is different. The auditory feedback effect was supported by a bimanual tapping task (Drewing & Aschersleben, 2003). Although this experiment used a bimanual continuous tapping task, the authors focused on the intra-hand temporal variability. On the other hand, Aschersleben et al. (2001) studied how tactile feedback influenced the sensorimotor synchronization. In this experiment, three finger tapping tasks: 1) standard tapping; 2) isometric tapping in which the finger was not allowed to leave the tapping surface; and, 3) contact-free tapping were used. The effect of tactile information for those participants with a peripheral nerve block showed larger synchronization error than the control group in the standard and isometric tapping, while no differences in synchronization error were shown during the contact-free tapping. In Drewing & Aschersleben's study (2003), they replicated Helmuth & Ivry's (1996) experiment, and suggested that less temporal variability in bimanual finger tapping was not only due to the multiple timer mechanism, but also may be attributed to the additional tactile information provided by two hands rather than one hand. The effect of tactile and auditory feedback was also found in deaffereent patients (Stenneken, et al., 2006) and musicians (Goebl & Palmer, 2008; Krause, Pollok, & Schnitzler, 2010; Loehr & Palmer, 2009). However, one recent study found inconsistent evidence for the sensory accumulation model (Białuńska, Bella, & Jaśkowski, 2011). In this current study, manipulating the intensity of external auditory signal did not affect the size of the synchronization error.

Effect of Effectors

The neural-conduction hypothesis has also been proposed to explain the negativity of the synchronization error. This hypothesis, with the same central representation as the sensory accumulation model, was proposed by Fraisse in 1980 (reviewed by Repp, 2005). It is based on the assumption that the afferent information transmission speed depends on the distance of the effectors to the brain. For example, auditory information transmission is faster owing to its distance from the brain compared to tactile-proprioceptive information transmission that comes from the finger. Therefore, tapping movement is conducted preceding the auditory cue to obtain the tactile-proprioceptive information earlier. This differential transmission is thus the source of the asynchrony during synchronization tapping. Support for this hypothesis comes from studies about simultaneous tapping with two effectors that are different distances to the brain, such as the foot and finger. The results demonstrate that the foot always leads the finger in tapping for both the synchronization (Aschersleben & Prinz, 1995; Billon, Bard, Fleury, Blouin, & Teasdale, 1996) and continuous tapping tasks (Bard et al., 1992; Billon, Bard, et al., 1996; Stenneken, Aschersleben, Cole, & Prinz, 2002). However, the kinematic properties of these effectors might be the cause of these temporal differences. Vaughan et.al. (1996) used a tapping task without constraining the wrist, elbow and shoulder in their study. By manipulating the tapping rate and force level, they found the contributions of the finger, elbow, wrist and shoulder amplitudes varied. They hypothesized that different effectors have different implicit preferred frequencies, so when the tapping rate is close to the frequency of one joint, this joint would play a more dominant role in the tapping performance than would the others. In the same study, Vaughan and his colleagues also proposed the virtual amplitude hypothesis. Although their study was not about the negativity of synchronization error, this hypothesis could be used to explain the negativity of the synchronization error. In this hypothesis, the virtual target of tapping is considered to be beyond the contacting surface. Indeed, it is assumed that the target is the point when the velocity of the finger reaches zero if the finger tapping is unimpeded. If the target of the finger tapping is to be synchronized to the virtual target rather than the external cues, the finger might contact the tapping surface earlier than the external cue to achieve the "virtual" target, thus causing the negative synchronization error. However, Repp (2005) has argued that this hypothesis cannot explain the effect of sensory feedback on the negative synchronization error. More details on this debate are presented in the knowledge gap section at the end of this chapter.

Timing and Force

Force is an essential factor in causing an object to accelerate or change its movement status. Without force, a stationary object cannot move or moving object stop or change its direction. The motions involved in finger tapping involve forces created by muscles. However, all of studies described in this literature review so far have ignored the role of force. Either implicitly or explicitly, these conceptualizations of temporal control have assumed that timing is an independent factor in motor coordination. But theoretically and perhaps practically, force and temporal control interact with each other.

At the muscle structure level, muscle contractions are caused by the cross-bridge whose movement is triggered by the nerve impulse sent from the central nervous system. The whole process of the nerve impulse transmission is a dynamical process implicitly involving the time. In Huxley's cross bridge theory (Huxley, 1957), it was assumed that the force generated by the muscle is proportional to the number of cross-bridge linkages formed at that time and that the probability of formation of a cross-bridge is proportional to the speed of shortening, which also depends on time. On the neuromusculoskeletal level, the impulse-timing hypothesis (Schmidt, et al., 1979) assumes that the amount, duration and temporal onset of force are determined by the duration of the neurological activity and the time of its occurrence. This means that force production is interrelated with the time factor.

Although there is a paucity of studies focusing on force and temporal control simultaneously, a few studies have suggested that the relationship between force control and timing control exists. Keele and his colleagues (Keele, et al., 1987) suggested that time variation was related to force variation. In their study, participants tapped their index finger with a specific force and rate in both the continuous and synchronization paradigms. A high correlation was found between the variation of the inter-response interval and force magnitude. Moreover, the significant positive lag-one cross-correlation between force magnitude and inter-response interval showed a larger force was followed by a longer inter-response interval and preceded by a shorter one. The authors suggested that force production influenced the central timer. Using a continuous finger tapping task with preferred, half and double preferred force and tapping speed, Inui and his colleagues also found a positive correlation between force and the inter-response interval variation (Inui, Ichihara, Minami, & Matsui, 1998). Later (Inui & Ichihara, 2001), they used specific tapping rates (180, 200, 400, or 800 ms) and force levels (50, 100, 200, or 400g) instead of the preferred tapping speed and force level to test this relationship. The results were consistent with their previous study (Inui, et al., 1998). They also found that the inter-response interval was less variable when higher force was used. This result was supported by Sternad and Newell (2000).

In a notable study about the force-timing relationship (Billon, Semjen, et al., 1996), participants were required to accentuate one tap in a periodic tapping movements of five taps. It was found that the IRI preceding the accentuated tap was shortened, while the IRI following the specific tap was lengthened, suggesting that the central timer could be adjusted at the point at which force was adjusted. The relationship between force and time was also supported by the study about whole body rhythmic movement (Rousanoglou & Boudolos, 2006). Recently, Therrien and Balasubramaniam (2010) also found that the force magnitude variability depended on the inter-response interval length, but in their study, a dependence of inter-response interval variability on force level was not found. They concluded that the central timing mechanism is robust under different force level production.

Movement Trajectory on Temporal Control

Movement trajectory also appears to be a factor influencing the temporal control of movements such as tapping. In their study, Balasubramaniam et al. (2004) instructed participants to oscillate their index finger in either a flexion or extension direction with the beat from an external metronome. This task was considered to be a continuous movement which had a different timing mechanism from the discrete finger tapping movements (such as used in a synchronization tapping task on a surface). The results revealed that the finger trajectory was symmetrical during unpaced tapping task, and asymmetrical during paced tapping (synchronization tapping), which contributed to the accuracy of the synchronization. The more asymmetry that occurred, the closer to zero the synchronization was. Moreover, the velocity of the return phase was also small if the preceding SE was larger. The authors suggested that changing the velocity of the moving finger could be a strategy to compensate for the synchronization error.

Knowledge Gap

From the preceding survey of the literature on temporal control, several knowledge gaps have been identified. These gaps are described here and form the basis for the experiments proposed for this thesis.

Force strategies differ between continuous and synchronization tapping.

Continuous and synchronization tapping have different targets and degrees of freedom, so they are always studied separately. It has been suggested that force and timing variability are correlated during both of these two tapping tasks, but the relationship is still not clear. Indeed, we also do not know why this relationship exists or the nature of the relationship. Perhaps studying both tasks together may reveal more about the relationship between timing and force control.

Negativity of the synchronization error.

It is commonly shown that the tap contact tends to precede the external metronome beat (defined as a negative SE). This phenomenon is often referred to as anticipation. Some hypotheses have been proposed to explain this negativity of the synchronization error (Repp, 2005). However, these explanations have difficulties in explaining the following properties about the synchronization error: 1) negativity of that the taps always precede the external cues; 2) the positive correlation with a decreasing tapping interval; and, 3) individual differences – in particular, those seen with experts on timing task (i.e., musicians). For example, the neural-conduction hypothesis (Aschersleben, 2002) cannot explain the individual differences and the tapping interval dependence. However, the virtual amplitude hypothesis proposed by Vaughan et al. (1996) can explain why the synchronization error would be negative. In this hypothesis, finger tapping is considered as an oscillation interrupted by the contact surface. After the finger contacts the surface, the movement trajectory stops but the force production does not, so this movement has a virtual target that is beyond the contact surface. If the synchronization occurs at the virtual target, the negativity of the synchronization error can be explained well. Moreover, if the interval of the external metronome decreases, the virtual amplitude decreases so the time needed to reach the target is reduced. The individual differences in timing precision could be explained by the individual differences in force production. The fact that the musician has much smaller synchronization errors could be attributed to their better force control ability. However, Repp (2005) has argued that this hypothesis could not explain the decreasing error when auditory feedback is provided. One could claim, however, that the synchronization tapping with and without auditory feedback is a totally different task and therefore synchronization would be predicted to occur at different events. The virtual amplitude hypothesis assumes that the tapping and metronome synchronize at the virtual target, while the tapping task with the auditory feedback changes the synchronization point to the sounds of two auditory inputs (i.e., the metronome and feedback). Clearly, the movement does not stop at the point that the auditory feedback is triggered.

According to the experimental definition of synchronization error and the discussion concerning the virtual amplitude hypothesis, it is logical to conjecture that the implicit goal of synchronization finger tapping is the accuracy of the time at which the peak force occurs. Changing the peak force or the force production speed would be one strategy for the timing correction.

Definition of inter-response interval and synchronization error.

If the plan is to study the force-timing relationship, it is important to know where on the force curve the time target is defined. Most studies have used an electrical switch as the tapping surface (Aschersleben, 2003). The timing of a tap in these studies is defined at the initial time of contact, which ignores the entire process of force production. The contact time when the finger contacts the surface was also used to define the two temporal parameters (Inui & Ichihara, 2001; Inui, et al., 1998). One study (Białuńska, et al., 2011) used the force to calculate the timing, but in this study, the timing of finger tapping was defined when the force exceeded 1.5 N when calculating the inter-response interval, Sternad et al. (2000) used the time of peak force. Surprisingly, few studies defined synchronization error using the time of peak force. Using this method to calculate the synchronization error, a positive result regarding to the hypotheses of this thesis should be expected.

Summary

Based on the review of literature and the identified knowledge gaps, an experiment is proposed to study the temporal-force relationship and to examine if the temporal control properties defined at different points such as the time of contact and the time of peak force differ from each other. The experiment and its results are discussed in the next chapter.

Chapter 3 Experiment

Introduction

Temporal control is essential to human movement both in the activities of daily living and the skilled actions of the athlete, dancer, or musician. Timing is critical in self-paced rhythmic movements such as locomotion and the externally modulated actions such as intercepting balls or playing in an orchestra. Although temporal control has been widely and well-studied for over a hundred years (Stevens, 1886), little attention has been paid to the other movement parameters such as space and force that might influence temporal control. Indeed most of the extant models of timing control (e.g., Wing & Kristofferson, 1973) assume that it is independent of the other movement dimensions. But time, space, and force are all important parameters of human movement, so it might be predicted that the three parameters would be interrelated. Indeed in 1954, Fitts (1954) proposed a logarithmic relationship between spatial amplitude and time duration; a relationship that has been well studied over the ensuing years. Although several experiments suggest that there may be a relationship between time and force control, this relationship has been understudied. In the experiment described here, it is this time-force relationship that is the focus.

Keele and his colleagues (Keele, et al., 1987) using a synchronization-continuous tapping paradigm (i.e., tapping first with a metronome and then without) tested whether there was a correlation between the variability of a tap's peak force and timing variability as measured by the variability of the inter-response interval (IRI). Their results suggested that peak force variation was significantly correlated to IRI variation. Similar findings were reported for synchronization tapping with high tapping frequencies

(Sternad, et al., 2000). The correlation between force magnitude and tapping frequencies was also found in a continuous tapping task (Inui & Ichihara, 2001; Inui, et al., 1998). In an interesting study by Stelmach and his colleagues (Billon & Semjen, 1995; Billon, Semjen, et al., 1996), participants were required to accentuate one tap out of five in a periodic tapping task. They found that the IRI of movement onset, in both continuous and synchronization tapping, preceding the accentuated tap was shortened, while the one following the specified tap was lengthened. Taken together the results from these studies suggest that force production and temporal control are coupled to each other.

In the Billon et al.(1995) study, the authors suggested that the timing goal was the time of contact between finger and surface so that tapping onset can be flexibly changed to coordinate when a more forceful tap was required. Alternatively, the virtual amplitude hypothesis suggests that the endpoint of tapping is virtual point beyond the tapping surface (Vaughan, et al., 1996). Is the time of peak force or the time of contact, the goal of temporal control in both continuous and synchronization tapping? All the studies that found a negative synchronization used the time of contact as the endpoint of the tapping movement. Is the synchronization error at the time of peak force zero or positive?

In addition, in the previous studies, participants were required to tap their fingers with a given force target or use a relatively constant force implying that both force and time needed to be controlled simultaneously. Would force and time be related if the participants were only required to control their tapping speed and no force constraints were specified? In addition, what is the role of the external stimulus (i.e., the metronome) in regulating the force-time relationship? Previous studies found a force-time relationship in both continuous and synchronization paradigms (i.e., metronome unpaced or paced). When no force constraints are specified, is the time-force relationship different between continuous (without metronome) and synchronization tapping (with metronome) since they are proposed to use different temporal mechanisms?

The purpose of this thesis is to explore this temporal-force relationship. Specifically, we seek to determine if the time of peak force is the temporal parameter that is the target in tapping. It is hypothesized that the IRI and SE of the time of peak force will be more accurate and have smaller variations than IRI and SE of contact time, respectively indicating that the temporal control target of finger tapping is the time of peak force and not the tap's contact time. It is also expected that different force production strategies are used in the two tapping paradigms, one with an external pacing cue (i.e., synchronous tapping) and one without an external cue (i.e., continuous tapping) as tapping intervals or speeds are varied. Specifically, we hypothesize that time-related variables (dwell time, time-to-peak force, etc.), force-related (peak force, variability of peak force, variability of force deviation) and force-time related variables (impulse, and force increasing rate) will differ between continuous and synchronization tapping as the tapping interval changes.

Methods

Participants.

Seventeen right-handed young adults (20.8 ± 1.5 yrs) from the University of Maryland, College Park were recruited as subjects for this study. Only right-handed participants were included in this study. Hand dominance was determined by a self-report questionnaire (Oldfield, 1971) administered to the participants before the study began (Appendix A). A neurological health questionnaire was also given to each participant

(Appendix B). All participants with neurological impairments or medical conditions that may affect motor performance were excluded. All participants signed the informed consent (Appendix D) based on the procedures approved by the University of Maryland's Institutional Review Board (IRB) before starting the experiment). Upon completion of the testing session, participants received $ 10 monetary compensation.

Apparatus.

The force data produced by the index, middle, ring, and little finger were collected by four six-component (three force and three moment components) force transducers (ATI Industrial Automation, Garner, NC, USA), and the force signals were routed to the two synchronized 12-bit analog-digital converters (PCI-6031, National Instrument, Austin, TX, USA). The sensors were mounted on a flat wooden board with a Velcro strap. This set-up was fixed on a table. A custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.) produced rhythmic beeps (frequency 440 Hz, duration 30 ms) transmitted to the participants through a headphone. All force data were sampled at 200 Hz.

Procedure.

Subjects were seated comfortably in a chair facing a 19'' computer screen (Figure 3.1). The height of the chair was adjustable so that subjects could reach the force sensor with the entire arm comfortably positioned and relaxed. The forearm rested on a wooden panel and was fixed by the velcro straps to avoid forearm and wrist movements. Each of the four fingers including the index, middle, ring and little finger rested on individual force transducer before the experiment started. Three practice trials were provided before the experimental trials. During the experimental trials, subjects were asked to only tap their right index finger on the force sensor to match the external metronome in either the continuous paradigm in which subjects tapped 10 times before the external metronome was turned off and were instructed to continue tapping at the same rate given by the metronome or the synchronization tapping paradigm in which participants tapped their index finger in synchrony with the external metronome throughout the entire trial. The metronome rates used in this experiment were 500 ms, 1000 ms, and 1500 ms. Each condition included two trials and each trial lasted for 60 taps. All the conditions were randomly arranged within subjects. Throughout the experiment, no visual feedback was provided.

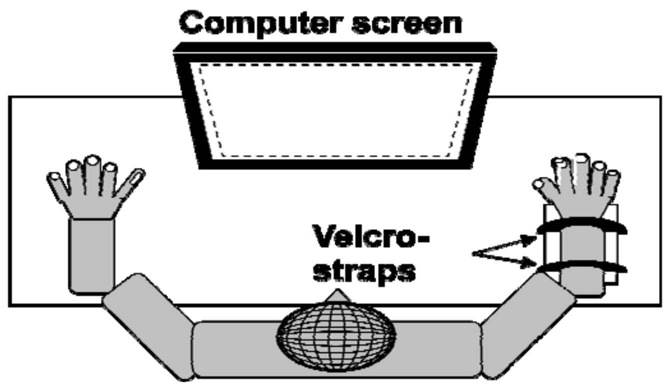

Figure 3. 1: The experimental setup. The wrist and forearm are fixed by velcro straps. Subjects were required to tap their index finger.

Data reduction and measures.

All data were filtered by low-pass filter (4th order Butterworth with cut off frequency 20Hz). Custom-designed MATLAB programs derived the following time and force variables using the last 50 taps in each trial. Both the magnitude and variability of these variables were the data of interest in this study. The variability of each variable was calculated as the standard deviation of the magnitude of each variable within a subject's trial. The mean of the magnitude/variability of each variable across trials within subject was used to determine the ISI and tapping mode effect and the potential interaction effect on these variables. The time series of the variables' magnitudes were used to calculate the auto-correlation for each subject.

Time variable.

Inter-response interval at the time of initial contact (IRIC) & peak force (IRIP).

IRIC was defined as the time interval between two successive times of force onset when the finger initially touches the force sensor. The initial touching time was extracted when force reached 0.05% of the peak force in each tap. This calculation method for determining contact onset time was selected to exclude the influence of white noise on this onset time. IRIP was the time interval between two successive times of peak force. The magnitude and variability of these two variables were used to determine the temporal control accuracy and variability across tapping mode and ISI length. The difference between the IRIC and IRIP was used to examine if the temporal property of the initial contact time of tapping was different from that of the time of peak force.

Synchronization error at the time of initial contact (SEC) & peak force (SEP).

The SEC was defined as the time difference between the time of tapping force onset and the time of the external metronome. The difference between the time of peak force and the time of the external metronome was the SEP. A negative value of SE meant tapping precedes the external metronome. As for IRI, the magnitude and variability of these two variables were used to determine the temporal control accuracy and variability of synchronization tapping (with metronome) across ISI lengths. The difference between the SEC and SEP was also used to examine if the temporal property of the initial contact time of tapping was different from that of the time of peak force.

Force variables.

Three types of force variables were used in this study: time-related, force-related and the time-force related. Each of these characterizes different aspects of force production:

Time-related variable: dwell time & time-to-peak (end) force.

Dwell time is the time duration when the finger is in contact with the force sensor. The time-to-peak force was defined as the time that was needed to reach the tap's peak force. The onset of the time-to-peak force was also set as the time when force reached 0.05% of the peak force. Corresponding to the time-to-peak force, the time needed to release the finger from the force sensor after reaching the peak force was defined as time-to-end force.

Force-related variable: peak force.

Peak force was defined as the peak point of the force curve in each tap. For most taps, especially in synchronization tapping, there were two peaks of the force curve at each tap. The time duration from the initial contact t to the first peak was always 1.25 to 2.5 ms (one or two sampling point with the 200Hz sampling frequency), which might be caused by the internal impact of the sensor rather than the physical tapping. Therefore, the time of the second peak was used to define the time to peak force. For a few taps in which the two peaks had same shapes, the first peak was used because some subjects might try to tap again to correct the temporal error.

Time-force related variable: Force increasing (decreasing) rate & impulse.

These two variables characterize both the time and force information of the tap.

Force increasing (decreasing) rate was the ratio between the peak force and the time-to-peak and time-to-end force, which indicates how fast the force was produced and released. Impulse is the accumulated force effect during each tap. It was calculated as the area under the force curve of each tap. The impulse is related to dwell time. Figure 3.2 graphically illustrates the definition of all the dependent variables.

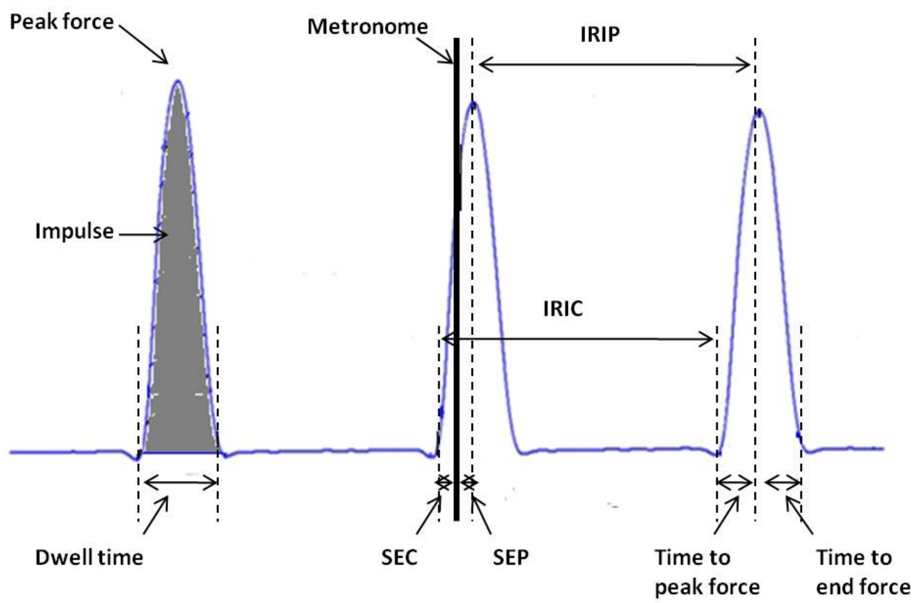

Figure 3. 2: The definition of each dependent variable. The figure shows three taps in an experiment trial.

Statistical analysis.

Linear mixed model (Proc Mixed, SAS, version 8.2) 3 x 2 repeated measures ANOVA was used to determine the main and interaction effect of (3) ISI length and (2) tapping mode on each variable except SEO and SEP. In this model, the correlated measure within subject and the subject heterogeneity was controlled. Unstructured covariance structure determined by the Akaike's Information Criterion was used in this model. Post hoc analyses (adjusted by Bonferroni procedures) were applied when any main or interaction was found. Using the same random terms, the linear mixed model for

SEO and SEP only considered the main effect of ISI length since this analysis was used only for the synchronization tapping task. Model diagnosis was conducted to check if the assumptions of ANOVA were satisfied. Logarithm transformation was used if the assumptions were violated. The paired t-test was used to test the difference between temporal properties defined at the time of force onset and the time of peak force, such as IRIC and IRIP. Auto-correlation of the time series for each variable was tested by R. The significant level $p=0.05$ was used for all effects.

Results

Temporal Property and Tapping End Time.

Difference between IRIC & IRIP.

To determine whether the temporal accuracy as defined by the time of force onset (i.e., contact time) and the time of peak force were influenced by the ISI length and tapping mode (with or without metronome), the magnitude of the absolute errors of IRIC and IRIP were analyzed by a 3 (ISI length) × 2 (tapping mode: 'with/without metronome') repeated measures ANOVA. Figure 3.3 shows the absolute temporal error between IRI and ISI. The main effect of tapping mode (IRIC: $F(1,48)=110.69$, $p<0.0001$; IRIP: $F(1,48)=109045$, $p <0.0001$) and ISI length (IRIC: $F(2,32)=23.02$, $p<0.0001$; IRIP: $F(2,32)=23.49$, $p <0.0001$) and the interaction effect (IRIC: $F(2,48)=33.16$, $p<0.0001$; IRIP: $F(2,48)=32.19$, $p <0.0001$) for both IRIC and IRIP were significant. As revealed in the interaction (Fig 3.3), temporal accuracy decreased as ISI increased when the external cue was not present (i.e., continuous tapping); whereas there was no effect of ISI on tapping with an external cue (i.e., synchronization paradigm). No previous studies have reported differences in temporal control accuracy between continuous and synchronization tapping, but it was not surprising that higher errors were seen in the former mode, since the synchronization condition offered additional auditory information that was not available during continuous tapping.

In order to examine whether the absolute error of IRIC is less controlled than that of IRIP, a paired t test between these two dependent variables was conducted for each ISI level. No difference for absolute error between IRIC and IRIP was found at each ISI level ($p>0.05$).

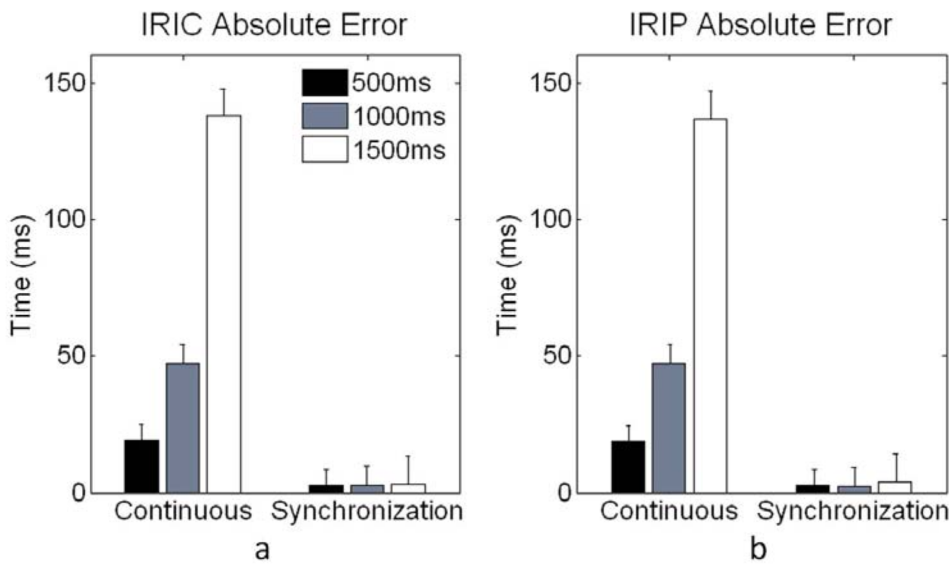

Figure 3. 3: The mean and standard error (SE) for the magnitude of IRIC and IRIP absolute error across tapping modes and ISIs.

Another major property of temporal control that has been widely studied is the variability of IRI. In figure 3.4 and 3.5, this variability is shown for both IRIC and IRIP. A 3 (tapping speed) x 2 (tapping condition) repeated measures ANOVA revealed that there were main effects for tapping condition (IRIC: $F(1,48)=5.69$, $p<0.05$; IRIP: $F(1,48)=14.24$, $p<0.001$) and tapping interval (IRIC: $F(2,32)=214.26$), $p<0.0001$; IRIP: $F(2,32)=149.27$, $p<0.0001$) (Figure A.1 in Appendix E shows IRIC and IRIP at each tapping condition and interval combination). Consistent with previous studies, we found that as ISI changes from shorter to longer, the variability increased, suggesting it was more difficult to maintain the target interval for slower tapping. The continuous tapping showed higher variability for IRI than the synchronization tapping.

In order to examine whether the IRIC is less controlled than that of IRIP, a paired t test of the variability between these two dependent variables was conducted for each ISI level. No difference in variability between IRIC and IRIP was found at each ISI level (p>0.05).

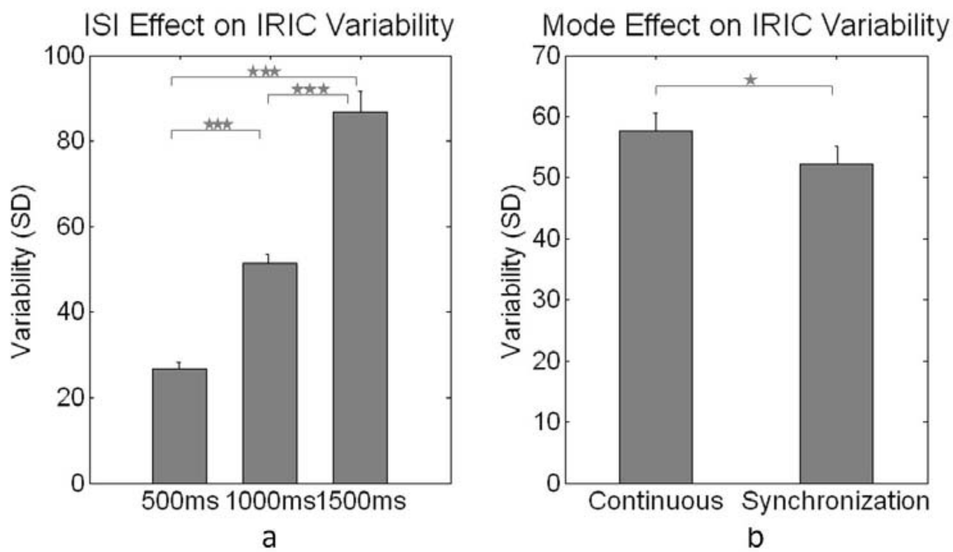

Figure 3. 4: The mean and standard error (SE) for the variability of IRIC across tapping modes and ISIs. See figure A.1a in Appendix E for IRIC for each tapping condition.

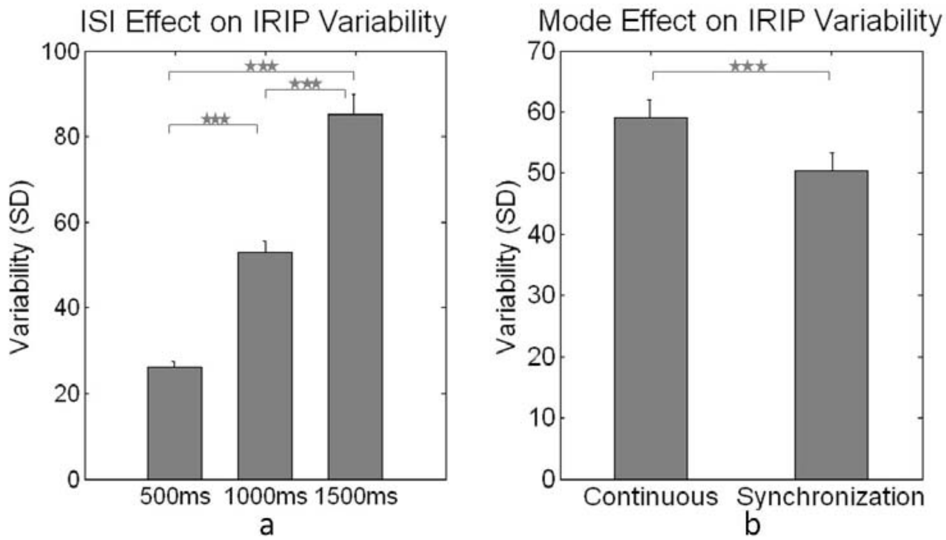

Figure 3. 5: The mean and standard error (SE) for the variability of IRIP across tapping modes and ISIs. See figure A.1b in Appendix E for IRIP for each tapping condition.

Difference between SEC & SEP and the negative SE.

Two main properties of the synchronization error during synchronization tapping have been considered as the mean negative of synchronization error and the increasing variability of SE with ISI (Repp, 2005). Both SECs and SEPs at all ISI levels were negative and different from 0 as tested by a simple t-test ($p<0.001$ for SEC; $p<0.05$ for SEP) except for SEP at the 500 ms interval. To illustrate the individual differences observed in SE, figure 3.6 shows the density of the SEP across each tapping interval. The peak of the density distribution was around -4ms and about half of subjects produced positive SE that was outside the range reported in the literature (as denoted by the two vertical lines on the x-axis).

As illustrated in Figure 3.7(a), the SE magnitude for both contact and peak force showed an increasing trend from 500 ms to 1500 ms, but this was not statistically significant effect for ISI.

As shown in the literature, the longer the ISI used, the larger the variability of SE produced (SEC: $F(2,32)=73.17$, $p<0.0001$; SEP: $F(2,32)=31.16$, $p<0.0001$). The highest variability was produced during tapping with 1500 ms interval, followed by 1000 ms, and then 500 ms (all $p<0.001$) for both tapping modes (Figure 3.7(b)).

To determine if the SEC is less controlled than SEP, the difference between the variability of SEC and SEP at each interval level was tested by paired-t test. Subjects showed more stability to control the SEP than SEC regardless of the length of tapping interval ($p<0.05$ for each ISI). Figure 3.8 shows the difference between the variability of SEC and SEP. These findings indicated that subjects changed the time of contact more than the time of peak force in the synchronization task, suggesting that the temporal control target is to synchronize the time of peak force with the external metronome.

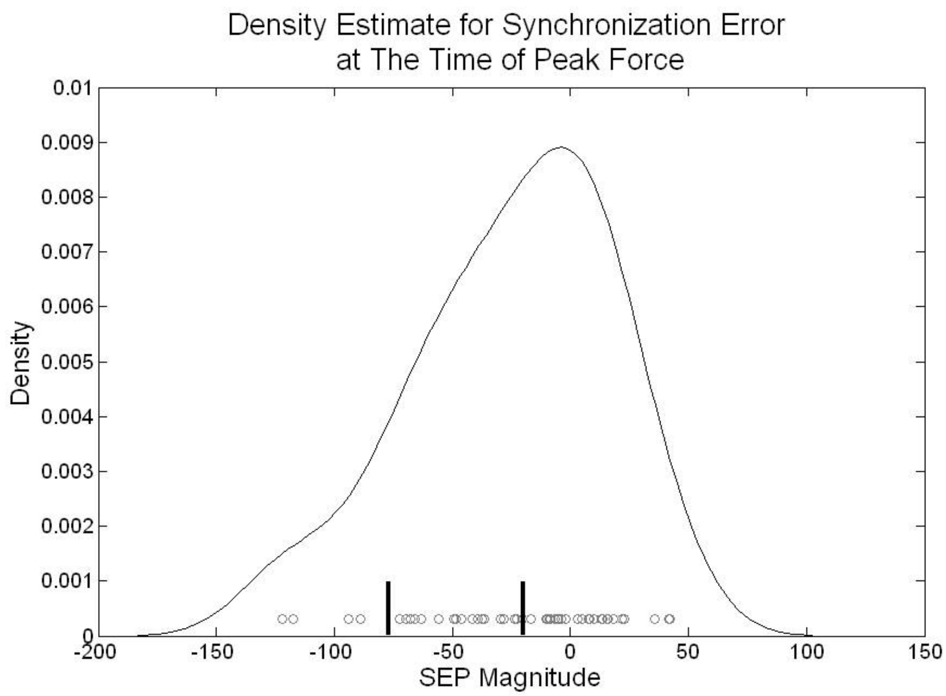

Figure 3. 6: The density distribution of SEP. The two vertical lines are the range of SEC (-20ms to 80ms) reported in the literature.

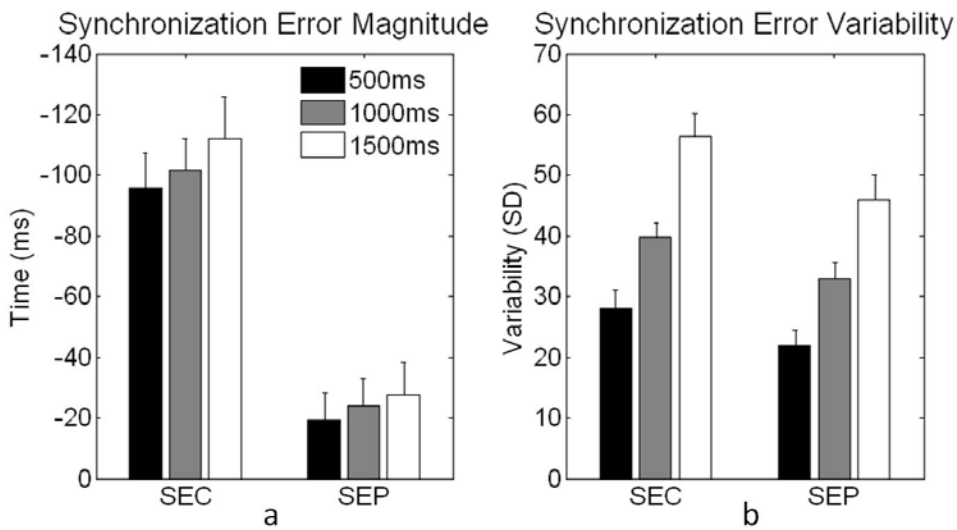

Figure 3. 7: The mean and standard error (SE) for the magnitude and variability of SEC and SEP.

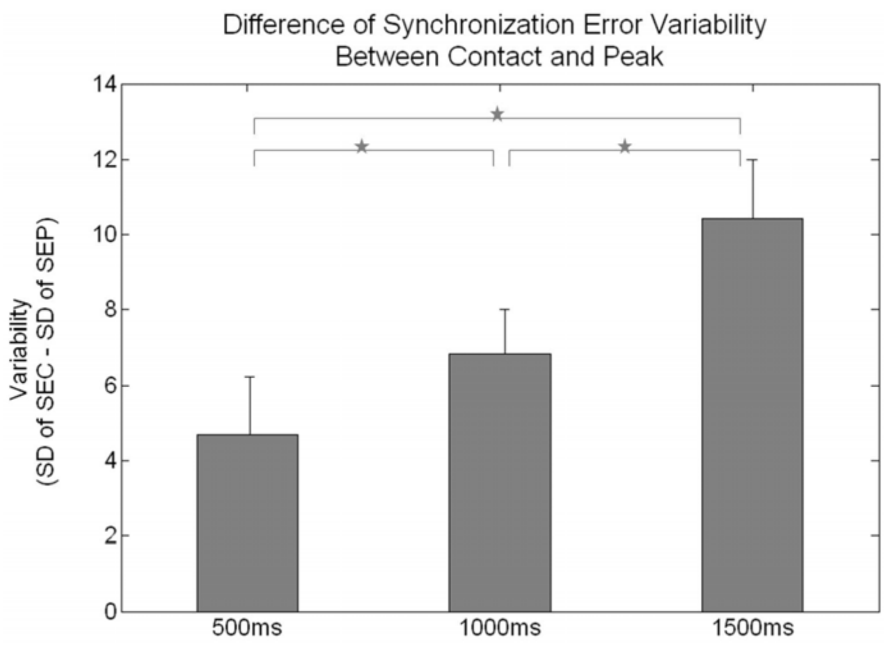

Figure 3. 8: The mean and standard error (SE) for the difference of variability between SEC and SEP for each ISI.

Different force strategies during finger tapping.

***Time-to-peak (end force) & dwell time*.**

Figure 3.9 shows the time-to-peak force magnitude for each tapping condition at each tapping interval. Tapping mode ($F(1,48)=0.72$, $p=0.4$) and ISI length ($F(2,32)=2.13$, $p=0.14$) did not show a main effect for the time to peak force. A significant interaction ($F(2,48)=4.01$, $p=0.0245$) was found. Post hoc analysis revealed the time-to-peak force differed between the 500ms and 1000ms ($p<0.01$), and 500ms and 1500ms ($p<0.05$) in tapping task without metronome (continuous paradigm). Only the main effect for tapping speed was revealed for the time-to-end force ($F(2,32)=0.0013$) (Fig. 3.10a) and this effect mainly occurred between 500ms and the other two longer interval ($p<0.05$ for 1000ms; $p<0.01$ for 1500ms).

For the variability of time-to-peak force, no any significant effect was found for ISI and tapping mode, while the significant effect of ISI on the variability of time-to-end force was found ($F(2,32)=5.92$, $p=0.0065$). This difference was shown between 500ms and 1000ms ($p<0.05$) and between 500ms and 1500ms ($p<0.01$) (Figure 3.10b). No main effect of tapping mode was found for the variability of time-to-end force.

The dwell time was found to change across tapping intervals ($F(2,32)=5.15$, $p<0.05$). The effect mainly occurred between 500ms and 1000ms ($p<0.05$) and between 500ms and 1500ms ($p<0.01$). The difference in dwell time variability also depended on the ISI intervals ($F(2,32)=4.52$, $p<0.05$) and this difference mainly occurred between the 500ms and 1500ms interval ($p<0.05$) (Figure 3.11). No main effect for mode nor interaction effect were found for these two variables.

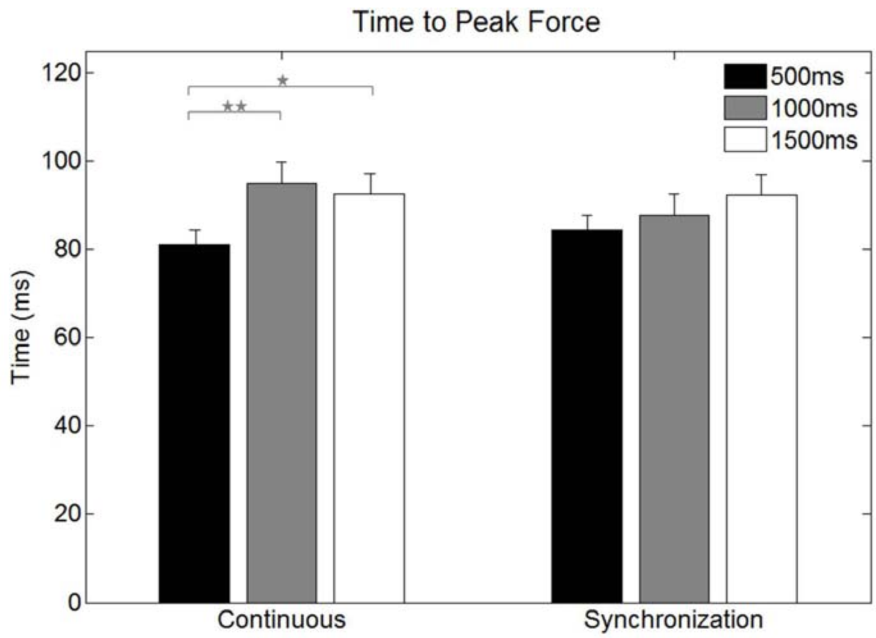

Figure 3. 9: The mean and the standard error for the magnitude of time to peak force across tapping modes and ISI.

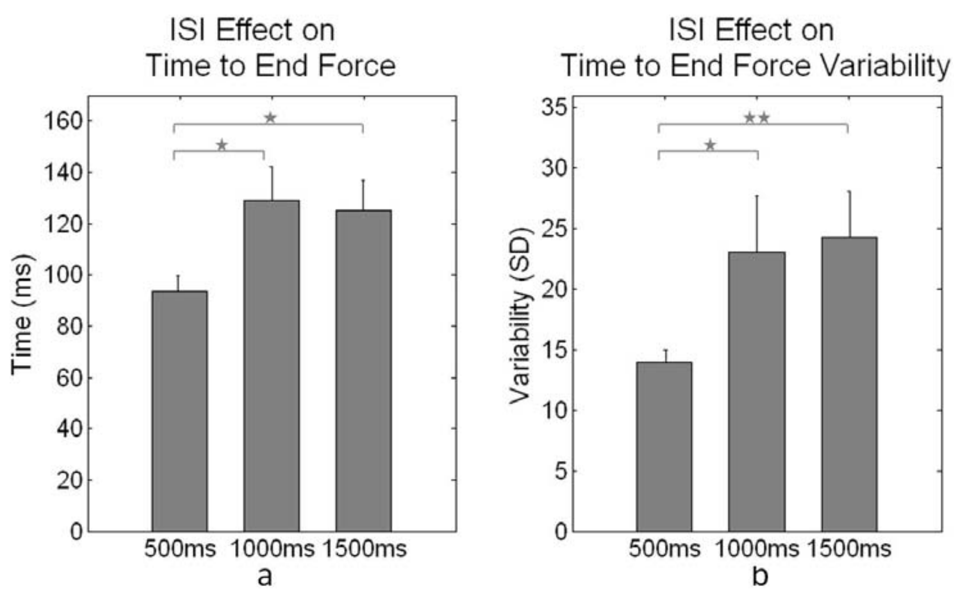

Figure 3. 10: The mean and the standard error for the magnitude and variability of time to end force across ISIs. See figure A.2 in Appendix E for time to end force for each tapping condition.

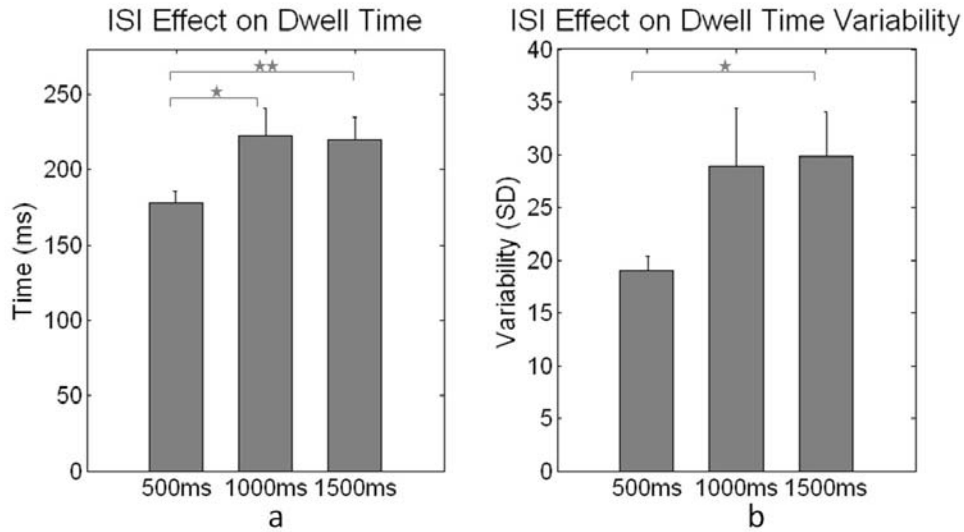

Figure 3. 11: The mean and the standard error for the magnitude and variability of dwell time across ISIs. See figure A.3 in Appendix E for dwell time for each tapping condition.

Peak force.

This variable, peak force, was analyzed after a logarithm transformation because the peak force variable in the original scale violated the ANOVA assumption that $\varepsilon_i \overset{iid}{\sim} N(0,\sigma^2)$ where ε_i was the residual and $N(0,\sigma^2)$ was the normal distribution with mean of zero and variance of σ^2. Due to the monotonicity of the logarithm function, the magnitude relationship shown in figure 3.11 is consistent with the data in the original scale.

In this finger tapping experiment participants were not required to meet a specified force level. To determine if the ISI length and/or the tapping mode affected the force strategies, peak force magnitude and variability were analyzed. Both the main effect for tapping mode ($F(1,48)=11.68$), $p<0.01$) and ISI ($F(2,32)=8.94$, $p<0.001$) and the interaction effect between those two factors were found ($F(2,48)=3.26$, $p<0.05$) for peak force magnitude. Post hoc analysis revealed that continuous tapping showed smaller peak force at 500ms interval length than 1000ms ($p<0.01$) and 1500ms ($p<0.01$). Larger peak force was found at 1000ms ($p<0.05$) and 1500ms ($p<0.05$) for continuous tapping compared to synchronization tapping task (Figure 2.12a).

For peak force variability, an effect for the tapping interval length was found ($F(2,32)=7.41$, $p=0.0023$) while no main effect of tapping mode and the interaction between mode and ISI were revealed. The significant ISI effects on variability of peak force was shown between 500ms and 1000ms ($p<0.01$) and between 500ms and 1500ms ($p<0.05$). Figure 3.12b graphically illustrates these relationships.

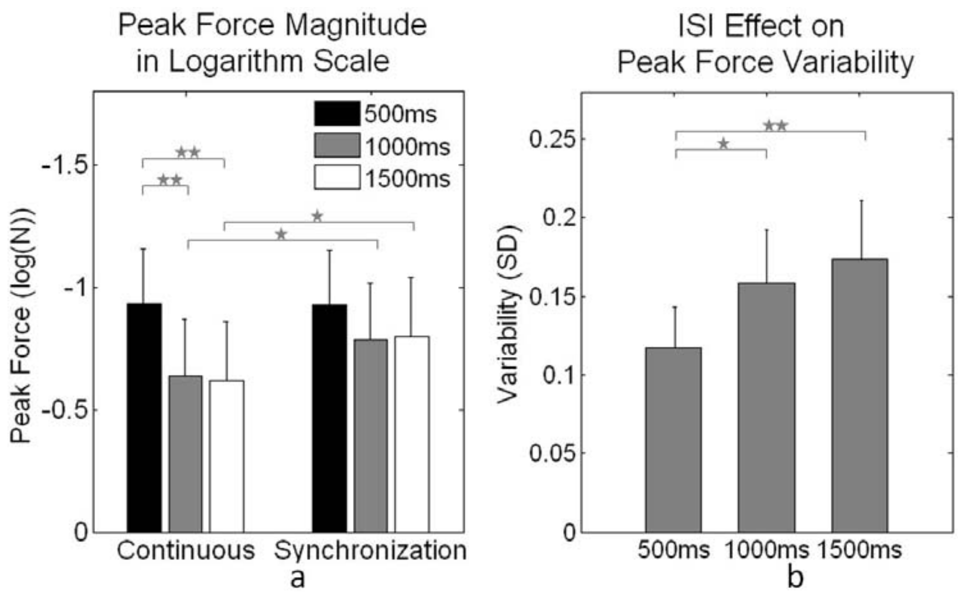

Figure 3. 12: The mean and the standard error for the magnitude and variability of peak force across tapping modes and ISIs. The peak force magnitude is in logarithm scale. See figure A.4 in Appendix E for peak force magnitude and variability for each tapping condition.

Force increasing (decreasing) rate & impulse.

These three variables (force increasing, decreasing rate and impulse) were analyzed after logarithm transformations. Two-way ANOVA revealed the main effect of tapping mode but not ISI on the force increasing rate ($F(1,48)=8.31$, $p<0.01$). As Figure

3.13a illustrates, subjects used larger force increasing rate in continuous tapping. In contrast with the force increasing rate, no effects were found for the force decreasing rate. The main effect of tapping interval was found ($F(2,32)=12.4$, $p<0.0001$) for the variability of force increasing rate. In figure 3.13b, it can be seen that the force increasing rate was less variable at the 500ms level than the 1000ms and 1500ms and less variability at 1000ms than 1500ms (all $p<0.01$).

For impulse, the repeated measure ANOVA demonstrated a main effect for both tapping mode ($F(1,48)=13.56, p=0.0006$) and tapping interval length ($F(2,32)=6.44, p=0.0044$) and a significant interaction between these two factors ($F(2,48)=5.21$, $p=0.009$) (Figure 3.14). The tapping interval length effect occurred in continuous tapping only. Subjects produced higher impulse at 1500ms ($p<0.001$) and 1000ms ($p<0.05$) compared to 500ms during continuous tapping. The tapping mode effect was significant at the 1000ms ($p<0.01$) tapping length interval. The main effect of tapping interval was found on the variability of impulse ($F(2,32)=12.9$, $p<0.0001$). At the same time, the variability of impulse also differed between the two tapping modes ($F(1,48)=5.02$, $p<0.05$). In figure 3.15, the findings for impulse variability are illustrated. Higher variability was produced during continuous tapping, and the tapping interval effect existed between 500ms ($p<0.0001$) and 1000ms and between 500ms and 1500ms ($p<0.0001$).

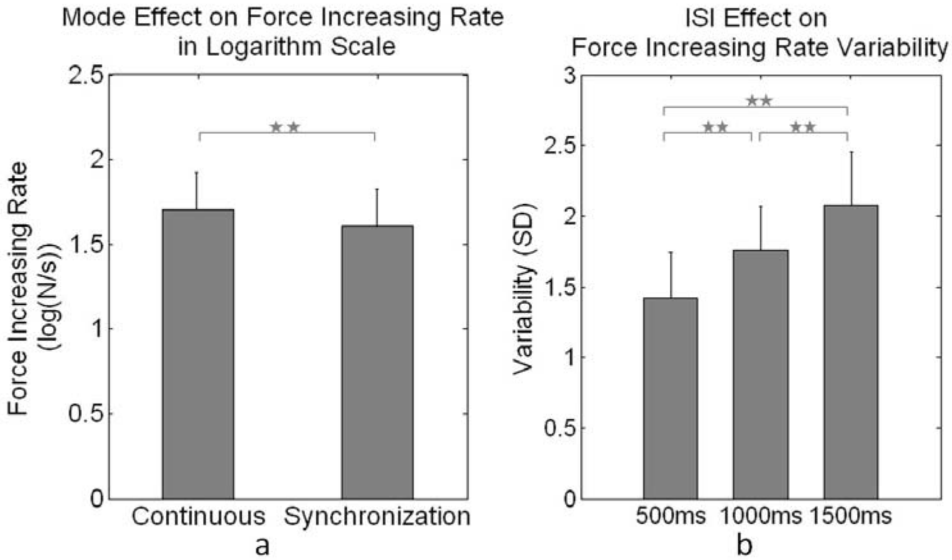

Figure 3. 13: The mean and the standard error for the magnitude and variability of force increasing rate across tapping modes and ISIs. The magnitude of the force increasing rate is in logarithm scales. See figure A.5 in Appendix E for the magnitude and variability of force increasing rate for each tapping condition.

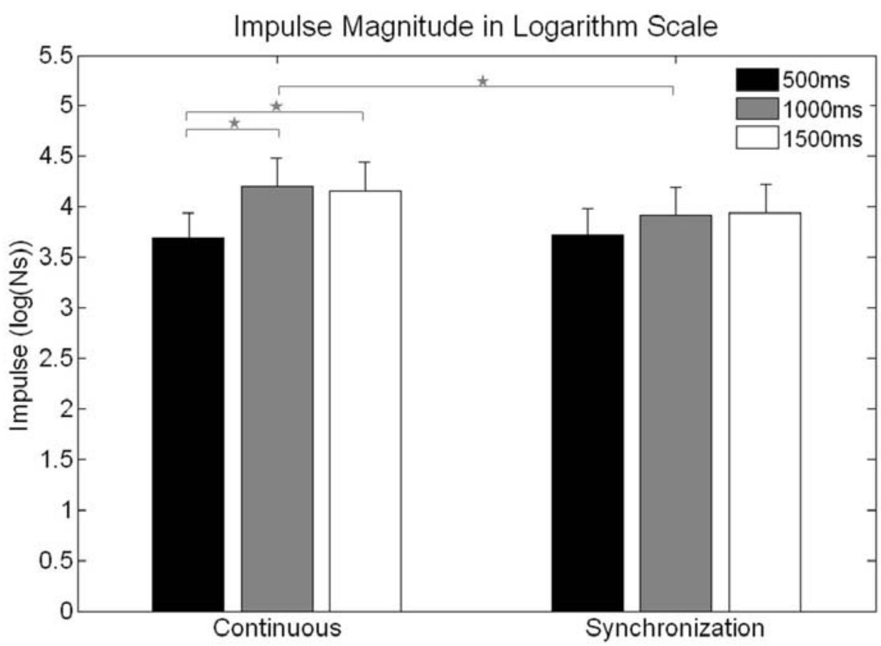

Figure 3. 14: The mean and the standard error for the magnitude of impulse across tapping modes and ISIs. The impulse is in logarithm scale.

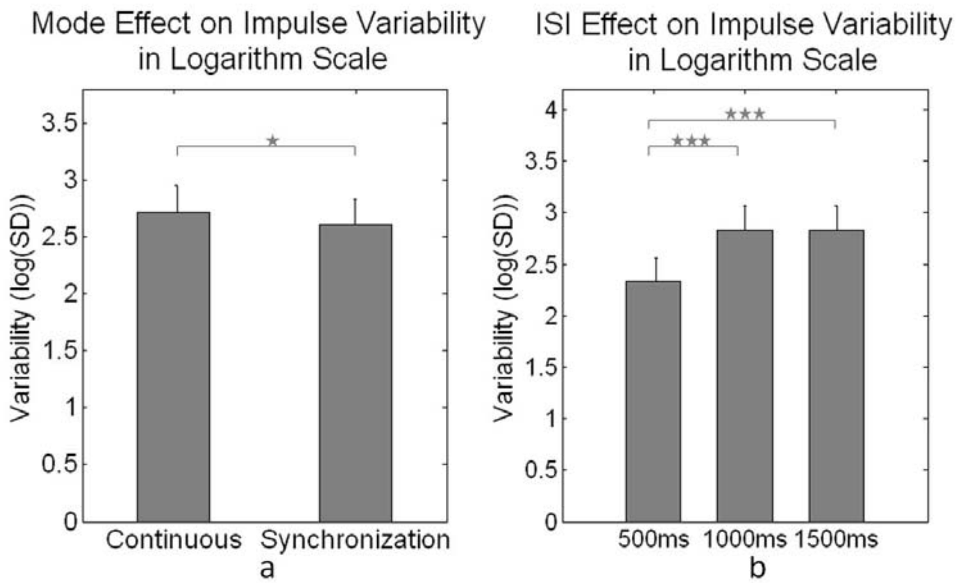

Figure 3. 15: The mean and the standard error for the variability of impulse across tapping modes and ISIs. The variability of impulse is in logarithm scale. See figure A.6 in Appendix E for the variability of impulse for each tapping condition.

Time series structure of the temporal and force variables.

A negative lag one auto-correlation has been found theoretically (Wing & Kristofferson, 1973) and practically (Wing, 1980) for IRI during continuous tapping (without metronome). The lag one auto-correlation coefficients for both IRIC and IRIP are shown in Figure 3.16 (top row). Most coefficients were out of the range (-0.5 to 0) given by the two-level processing model (Wing & Kristofferson, 1973). When tapping with 1000ms and 1500ms intervals, the lag one auto-correlations were shown to have positive values. Figure 3.16 (bottom row) also illustrates the positive lag-one auto-correlation for SE during synchronization tapping. This result was consistent with literature.

The lag one auto-correlation was also tested for all dependent variables discussed above. The only dependent variable that had a significant lag one coefficient for some subjects was impulse (Figure 3.17). It was shown that the impulse production for some subjects was positive correlated at each ISI level. A significant negative lag one auto-correlation of impulse rarely appeared.

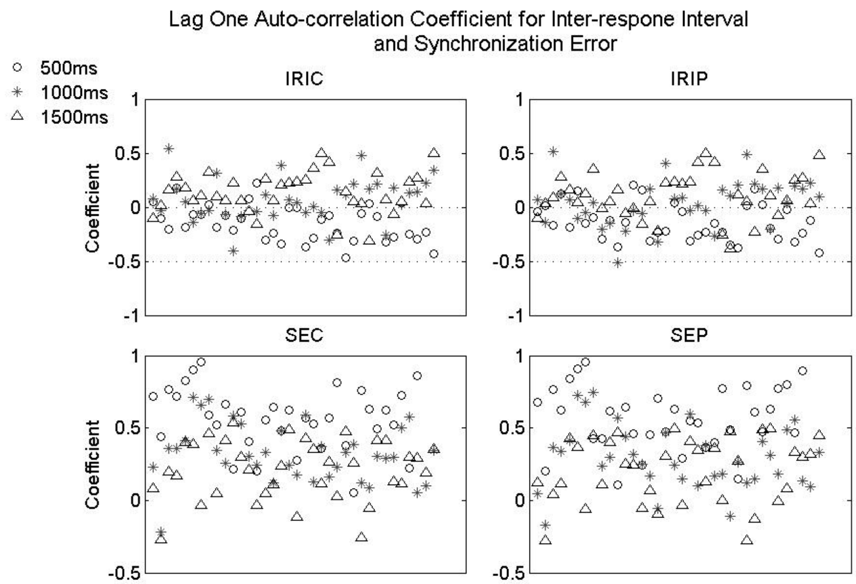

Figure 3. 16: The lag one auto-correlation coefficient for IRI (top) and SE (bottom) across ISI. The two horizontal dashed lines are the theoretical bounds for the lag one auto-correlation coefficient of IRIC. Each point is the coefficient for one trial of one subject.

Discussion

Movements are assembled in time and space, and with force. In this experiment, we examined the relationship between time and force. We used a finger tapping task to probe if temporal control (as defined by variables such as inter-response interval (IRI) and synchronization error (SE)) is coupled to a force parameter— namely, the peak force magnitude. We proposed that the timing end point for finger tapping is the time of peak force rather than the time of contact – the usual tapping endpoint. In other words, in tapping the time of peak force would be precisely controlled while the time of the tap's

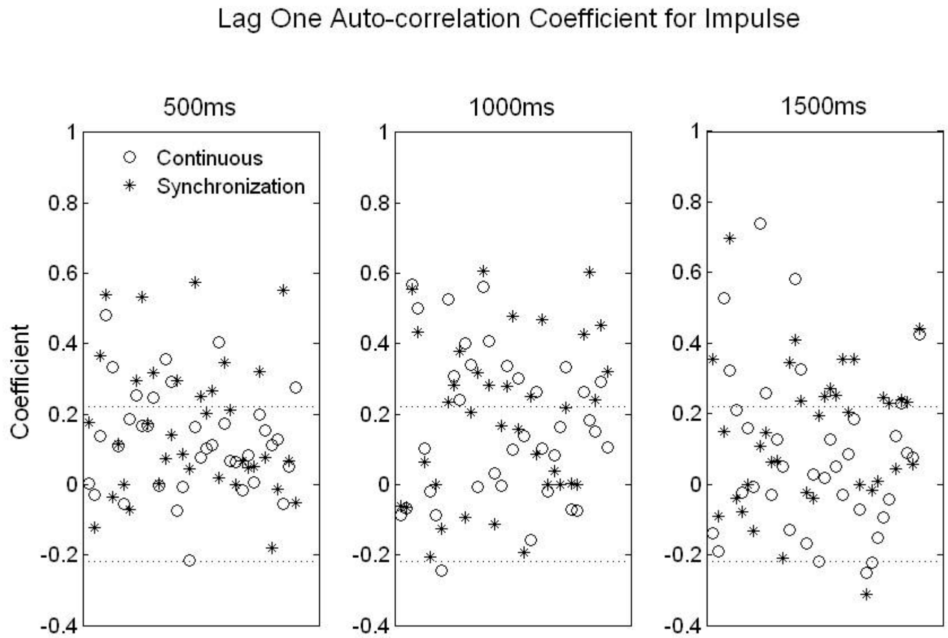

Figure 3. 17: Lag one auto-correlation for the impulse across tapping mode and ISI. The two horizontal dashed lines are the 95% confidence interval for the lag one auto-correlation coefficient. Each point is the coefficient for one trial of one subject.

contact is less controlled. This would result in the IRI and SE at the time of contact (IRIC/SEC) being less controlled than the IRI and SE defined at the time of peak force (IRIP/SEP). In general, the results of our experiment support this hypothesis. In addition, the synchronization error for the time of peak force (SEP) was shown to be smaller and more stable than the synchronization error for the contact time (SEC).

If the tapping temporal control variable is the time of peak force, the time of contact would be less well controlled. This variable time of contact and the more stable time of peak force would cause different times to peak force (time duration between the contact and peak force) at each tap. To precisely control the time of peak force, different force production strategies would have to be used to compensate for the variable time to peak force. For example, if the time of contact is earlier, then a larger time to peak force is needed to make the time of peak force longer, which can be reached by producing larger force or produce force slowly. Therefore, we examined the force production patterns during different finger tapping tasks. As our results reveal, the force production strategies differed across the tapping mode (with/without metronome) and the tapping interval (ISI).

The temporal control variable is the time of peak force.

In our study, participants performed finger tapping with an external cue (i.e., synchronization to a metronome) and without an external cue (i.e., a continuation paradigm) and with no force constraint at tapping intervals of 500, 1000 and 1500ms. We chose these three tapping speed intervals because they have been shown to result in different temporal control properties. For example, the variability of fast (e.g. 500ms) and slow (e.g. larger than 1000ms) tapping is attributed to different sources, which might indicate different temporal control mechanisms during tapping with these intervals (Madison, 2001). The choice of two different tapping paradigms, continuous and synchronization, was made as they have been hypothesized to utilize different temporal control mechanisms (Repp, 2005). It was expected that, if temporal and force control are coupled to each other, tapping tasks using different temporal control mechanisms would result in a change in the force control when no constraint force control is imposed.

To repeat the previous results of temporal control found in the literature, this study firstly tested the variability of IRI, during both continuous (without metronome) and synchronization tapping (with metronome) and the variability of SE during synchronization tapping. The commonly acknowledged positive relationship between variability of IRI/SE and the length of ISI was found in the present study. Our results also revealed the SE increases with the ISI. As we expected, the higher variability of IRI in continuous tapping with the longer ISI than that in synchronization tapping was found in this study. The auto-correlation structures of IRI and SE also are consistent with the literature (Wing, 2002). The negative lag-one auto-correlation (coefficient range -0.5 to 0) of IRI was found for tapping with 500ms interval and positive lag-one auto-correlation was found for tapping with 1000 and 1500ms interval. The former has been theoretically suggested by the two level-process model (Wing & Kristofferson, 1973) and practically suggested by experimental studies (Wing, 2002) for tapping with intervals from 200 to 800ms and the latter phenomenon has been found for tapping with longer intervals.

As shown in our results, both IRI at tap contact (IRIC) and at the time of peak force (IRIP) had the same properties across tapping mode and intervals. The difference in the variability between the IRIC and IRIP did not emerge as we expected. One reason for this result could be due to the experimental task we used. No force constraints or temporal perturbations were used in our study, so subjects did not need to change their force production. For example, they could use a relative stable time to peak force to (the time duration between contact and peak force) produce force so that the time difference between IRIC and IRIP would be very stable. This should not be a problem for synchronization tapping where there are external cues. In tapping with the external metronome, subjects correct their taps when they are not perfectly synchronizing the external cue. If the time of peak force is the temporal control target, the variability of SEC (SE between the time of contact and the metronome) must be larger than the variability of SEP (SE between the moment of peak force and the metronome). Indeed our results were as expected. The SEC at each tap interval was more variable than the

SEP. The larger variability of SEC indicated the dynamics of the time at contact: the time of contact was flexibly changed to minimize the SEP.

The magnitudes of SEP in our study offers further support for the hypothesis that the time of peak force is the temporal control target during finger tapping. The SEP was negative, but statistically, the SEP of the tapping with 500 ms interval was not significantly different from 0. This result is contradictory to negative mean synchronization error in literature. The range of negative SE in typical young adults without musical training has been reported to be from -20 ms to -80 ms with individual differences and musicians have been found to always have smaller or even no SE (reviewed by Aschersleben, 2002). Although The SEP at 1000 ms and 1500 ms interval conditions were not 0 statistically, when we checked the density distribution, most of taps were close to 0 and below the 20ms suggested by previous studies. The non-significant t test results might be due to the large standard deviation caused by large individual differences within our sample. The difference of the SE range we found was caused by the temporal variables we used that were defined at the time of peak force. SE has been studied based on the moment of initiation in the literature (Hary & Moore, 1987; Keele, et al., 1987; Semjen, et al., 2000; Semjen, et al., 1998; Thaut, et al., 1998; Wing, 1980), while we used the SE at the time of peak force. In our study, we asked subjects after the experiment if they tried to synchronize the time of the peak force or the time of the tap's contact to the external metronome. Some participants reported their temporal goal was the time of the peak force, while a few participants were unable to report what their goal was. Future studies should test the SEP of tapping within the 200 to 800ms interval to check if SEPs are still 0 for these ISIs.

Different tapping force patterns across tapping mode and intervals

If the time of peak force is the variable that is controlled during finger tapping, temporal and force control would be related to each other. Indeed, during finger tapping with temporal requirements but without force constraints, the force production changed when the temporal requirement changed (i.e. tapping interval).

In our experiment, we found that the variability of most force variables including impulse, peak force, dwell time and the force increasing rate were larger at 1000ms and 1500ms than those at 500ms. As seen as well for the temporal control variability (previous section), 1000ms seems to be the critical tapping interval for the variability of force control, suggesting that the variability of the temporal and force variables might be related. Other force parameters also depended on the tapping mode or ISI, but it was difficult to tell which variable was influenced by the temporal property directly because these force variables are correlated to each other. For example, force increasing rate is the ratio between peak force and time-to-peak force. The change of force increasing rate could be caused by the change of peak force, time-to-peak force or both.

It has been claimed that when a subject taps with a specific force magnitude and preferred frequency, the IRIs are the same across force target including preferred force (Sternad, et al., 2000). In combination with our results, this may indicate that temporal control is more stable than force control. Therefore, those force parameters in our study that changed would reflect the strategies used to optimize the temporal target. For example, when the previous tap has a large SEP, to minimize the error in the following tap, one could tap later so that the time of the peak force would be closer to the external cue. Alternatively, slowly producing the same force for the previous tap or producing larger force using the same speed for force production as the previous tap also could correct the SEP.

Summary

The results from the present study indicate that the time of a tap's peak force is more precisely controlled than the time of the tap's contact. The variability and magnitude of the synchronization error are smaller at the former time than the latter. The latter has been normally used to characterize the temporal control (as defined as inter-response interval and synchronization error). Different force production strategies were found across tapping tasks with different modes (with/without metronome) and different tapping intervals. These results suggest that the tapping temporal control variable is the time of peak force indicating that the temporal and force control are coupled to each other. Furthermore, the force control strategies are flexibly adjusted to reach different temporal targets during finger tapping task.

Chapter 4 Limitations And Future Direction

In this study, we examined the temporal-force control relationship in finger tapping. Our results provide support for two conclusions. The first finding is that in tapping the temporal control variable is the time of a force parameter – namely, the tap's peak force. The other is that force production strategies vary as the temporal targets vary. In this last chapter, we discuss the limitations and possible future studies on the temporal-force control relationship suggested by our findings and the limitations of the current experiment.

Limitations

In the process of conducting the experiment, certain decisions were made that may influence the results of the present study. First, compared to the literature that uses the onset of external metronome as the referential time during synchronization tapping, the entire 30ms duration of metronome was considered in the present study. For example, if the time of a tap falls within the 30ms duration then the SE is calculated as zero. It is difficult to determine at which time point the auditory signal (i.e., metronome) is perceived by the subject and this perception might be different across subjects. Choosing the entire duration of the metronome controls for the individual differences in perceptual ability. Secondly, the time point when the force reaches 0.05% of peak force at each tap was considered as the initial time of contact. The bias estimation of this time point would be caused by the individual difference of the peak force production, because this time point changed as the peak force changed, which was not stable across subjects. Finally, the standard deviation was used to describe the variability of each variable in order to be consistent with the extant literature. However, the data show large individual differences on some variables' magnitudes such as peak force and SE so the standard deviation might not provide as much information as might be found if we had used coefficient of variation.

Future Direction

Temporal Control Parameter Is the time of Peak Force

Three possible experiments are suggested based on our finding that the variable of temporal control is the time of peak force. These include looking at musicians (those with timing expertise), varying the force constraints within the tapping task (accentuation), and using different effectors to test the generalizibility of the study.

Time of peak force in musicians.

In this study, we found the synchronization error at the time of peak force (SEP) rather than the synchronization error at the time of contact (SEC) was closer to the external metronome during synchronization tapping (with metronome). More than half the subjects showed negative SE closer to zero than the range (-20ms to -80ms) reported in the literature.(Aschersleben, 2002), even though tapping at 1500ms interval is closer to the upper limit of sensorimotor synchronization(see Repp, 2005, for a review). Some subjects also showed a positive SE which is rarely observed in the literature.

Based on our finding, we cannot say definitively that the time of peak force is the variable of temporal control because our subjects were non-musicians and as such would not have developed their temporal control abilities for synchronizing movement with external events. It has been reported that musically training people show less SE than non-musicians(Aschersleben, 2002), where the SE is defined by the contact time (SEC). We might assume that a musician would have better sensorimotor synchronization ability than a non-musician, so it is important to know how large the SEP is for musicians. We would expect the musicians would show an SEP that would be much closer to zero. The hypothesized result would indicate a strong temporal-force control coupling and this coupling could be used to explain the negativity of the mean SE reported by the literature.

Time of peak force in continuous tapping (without metronome).

During synchronization tapping task, we found a difference in variability between the SEC and SEP. This indicates that the SEP is precisely controlled while SEC is not. The same result was expected for the difference between the variability of inter-response interval at the time of peak force (IRIP) and the variability of inter-response interval at the time of contact (IRIC) during continuous tapping. However, they were the same at each tapping interval. One potential limitation for this finding might be that the tapping pattern is stable when no force constraints are imposed on the tapping performance. To determine if the time of peak force is also more precisely controlled than the time of contact during continuous tapping, force perturbations are needed in a future study by adding several accentuated taps in the tapping sequence. It is expected that the time of contact changes while time of peak force would not. It is hypothesized that right before the accentuate taps, subject might contact the tapping surface earlier to have a longer time to produce larger force. This will extend our conclusion that the temporal control parameter is the time of peak force we made for synchronization tapping to the continuous tapping paradigm.

Time of peak force for different effectors.

Previous studies demonstrated that the foot always leads the finger in tapping for both the synchronization (Aschersleben & Prinz, 1995; Billon, Bard, et al., 1996) and continuous tapping tasks (Bard, et al., 1992; Billon, Bard, et al., 1996; Stenneken, et al., 2002) and moreover, the synchronization error for these two effectors are both negative. The neural-conduction hypothesis was used to explain this phenomenon (Repp, 2005). As previously mentioned, the time of foot and finger tapping were defined for the time of contact in these studies. Based on our findings in this study, we would expect that the tapping of foot and finger would coincide with each other if we consider the time of peak force as the temporal control variable. This hypothesized result would support our finding and extent it to generalized tapping movements.

Force Strategies Used in Finger Tapping Task.

Temporal perturbation for error correction.

In the present study, different force patterns were shown during the different finger tapping tasks. It is suggested that the central timer mechanism is robust for different force constraints (Sternad, et al., 2000; Therrien & Balasubramaniam, 2010). Based upon the preceding result that force production varies with different temporal constraints and the findings in the extant literature, force control is expected to be flexible so that force production can be adjusted to optimize the temporal control; for example, for error correction during synchronization tapping. The error correction mechanism for central timers has been studied for more than 50 years (Repp, 2005). According to the literature, the central timer estimates the temporal error and adjusts the new tapping interval in each tap. Rather than adjusting the temporal estimation in the central timer, our hypothesis would predict that the error correction is made by adjusting the force rather than to re-estimate the temporal interval in the central timer. By adding temporal perturbations to the tapping sequence, we expect force production changes to be shown after the perturbation. These hypothesized results would inform our understanding of the temporal error correction mechanism in the force dimension.

Summary

The first goal for future study is to support the finding that temporal control variable is the time of peak force and extend it to general tapping movement (such as using other effectors). If the musician who has much better temporal control ability than non-musician shows the zero synchronization error at the time of peak force, we would find additional support for the findings in our study. Moreover, this finding can also be used to explain why taps that are characterized by the time of contact in literature always precedes the external events. Furthermore, the properties of the underlying mechanism of this coupling are not so well understood. Thus, the other aspect for future study should explore the relationship between time and force control. Based on the current study, we would propose these experimental goals to extend our knowledge of temporal-force control and eventually to the temporal-space-force control.

Appendices

Appendix A

Edinburgh Handedness Inventory[1]

Your Initials:__________________

Please indicate with a check (✓) 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 two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

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

Appendix B

Adult Neurological Health Questionnaire

Have you ever…(Please circle yes or no)

1) been seen by a neurologist or neurosurgeon? Yes No
   if yes, please explain____________________________________

2) had a head injury involving unconsciousness? Yes No
   if yes, how long?_______________________________________

3) required overnight hospitalization for a head injury? Yes No
   if yes, please explain?_______________________________________

4) had any illness that caused a permanent decrease in memory or cognition? Yes No
   if yes, please explain____________________________________

5) had a seizure? Yes No
   if yes, please explain____________________________________

6) had any illness that caused a permanent decrease in motor ability (including speech)? Yes No
   if yes, please explain____________________________________

7) had difficulty using your hands? Yes No
   if yes, please explain____________________________________

Appendix C

Principal Investigator: Dr. Jae Kun Shim

Appendix II: Form A

INFORMED CONSENT FORM (ADULTS)

Project Title	*Pressing and prehension synergies*
Statement of Age	*I state that I am at least 18 years of age and wish to participate in a program of research being conducted by Jae Kun Shim, PhD in the Department of Kinesiology at the University of Maryland, College Park.*
Purpose of Study	*The purpose of this research is to examine the force patterns generated at the fingers when a certain total force is specified to be produced.*
Procedures	*I will be asked to produce forces of varying intensity with fingers by pressing on force sensors located on a table while watching a computer screen. Electric signals produced by forearm muscles will be recorded from electrodes placed on the forearm skin. The task will require one lab visit which will take approximately 60 minutes. I will be rewarded with $10 for participating in this study.*
Confidentiality	*All information collected in this study is confidential to the extent permitted by law. I understand that the data I provide will be grouped with data others provide for reporting and presentation and that my name will not be used. All data will be stored in a lockable file cabinet and only the principal investigator and his collaborators will have access to the cabinet.*
Risks	*I understand that I may experience the discomfort of muscle soreness following testing.*
Benefits, freedom to withdraw, & Ability to Ask Questions	*The experiment is not designed to help me personally, but to help the investigator learn more about finger coordination in human. I am free to ask questions or withdraw from participation at any time and without penalty.*
Contact Information of Investigator	*Marcio A. Oliveira. PhD (email: marcio@umd.edu) Jae Kun Shim, PhD (e-mail: jkshim@umd.edu) 2136 HHP Bldg., The Department of Kinesiology University of Maryland, College Park, MD 20742*
Contact Information of Institutional Review Board	*If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; e-mail: irb@deans.umd.edu; telephone: 301-405-4212*

NAME OF SUBJECT:
BIRTHDATE OF SUBJECT: (dd/mm/yy)

SIGNATURE OF SUBJECT ______________________

IRB APPROVED
EXPIRES ON

JUN 08 2010

UNIVERSITY OF MARYLAND
COLLEGE PARK

Appendix D

Principal Investigator: Dr. Jae Kun Shim

Appendix II: Form A

INFORMED CONSENT FORM (ADULTS)

Project Title	*Pressing and prehension synergies*
Statement of Age	*I state that I am at least 18 years of age and wish to participate in a program of research being conducted by Jae Kun Shim, PhD in the Department of Kinesiology at the University of Maryland, College Park.*
Purpose of Study	*The purpose of this research is to examine the force patterns generated at the fingers when a certain total force is specified to be produced.*
Procedures	*I will be asked to produce forces of varying intensity with fingers by pressing on force sensors located on a table while watching a computer screen. Electric signals produced by forearm muscles will be recorded from electrodes placed on the forearm skin. Participation in this experiment may require up to six visits. These visits may be scheduled over the course of 1 week or up to two months following the first session, depending upon random group assignment. Each data collection session will take approximately 45 minutes – 1 hour. I will be compensated $10 dollars upon completion of the first session. I will receive an additional $5 dollars following completion of each subsequent session.*
Confidentiality	*All information collected in this study is confidential to the extent permitted by law. I understand that the data I provide will be grouped with data others provide for reporting and presentation and that my name will not be used. All data will be stored in a lockable file cabinet and only the principal investigator and his collaborators will have access to the cabinet.*
Risks	*I understand that I may experience the discomfort of muscle soreness following testing.*
Benefits, freedom to withdraw, & Ability to Ask Questions	*The experiment is not designed to help me personally, but to help the investigator learn more about finger coordination in human. I am free to ask questions or withdraw from participation at any time and without penalty.*
Contact Information of Investigator	*Marcio A. Oliveira, PhD (email: marcio@umd.edu)* *Jae Kun Shim, PhD (e-mail: jkshim@umd.edu)* *2136 HHP Bldg., The Department of Kinesiology* *University of Maryland, College Park, MD 20742*
Contact Information of Institutional Review Board	*If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; e-mail: irb@deans.umd.edu; telephone: 301-405-4212*

NAME OF SUBJECT:
BIRTHDATE OF SUBJECT: (dd/mm/yy)

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Appendix E

Figures:

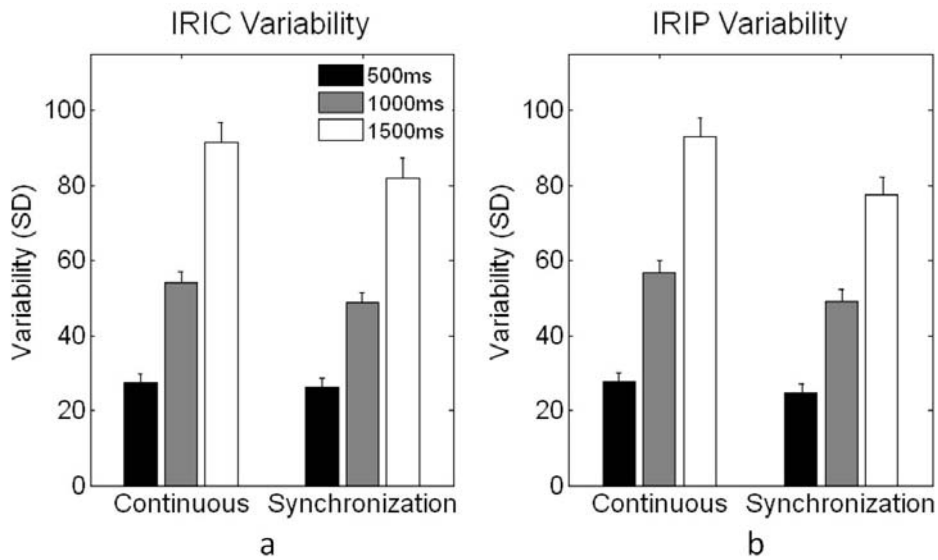

Figure A. 1: The mean and standard error (SE) for variability of IRIC and IRIP for each tapping condition.

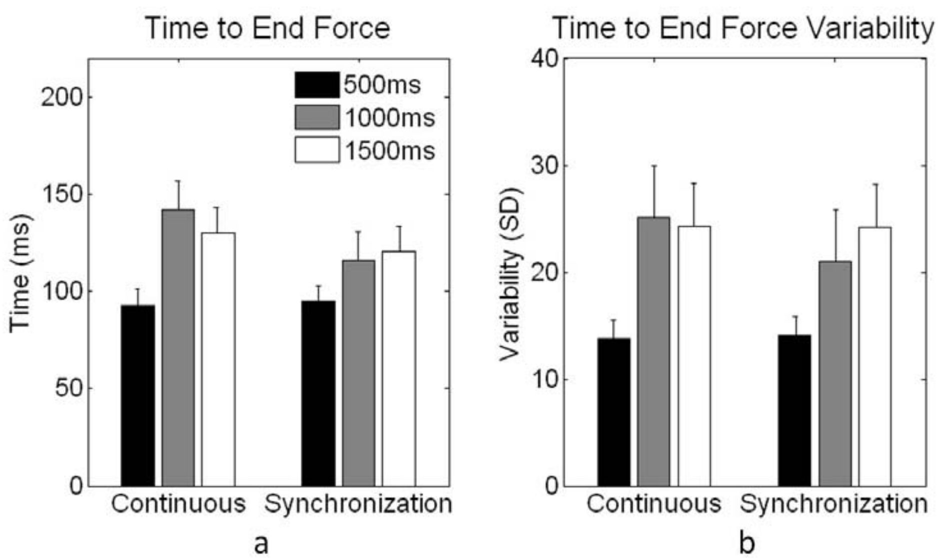

Figure A. 2: The mean and the standard error for the magnitude and variability of time to end force for each tapping condition.

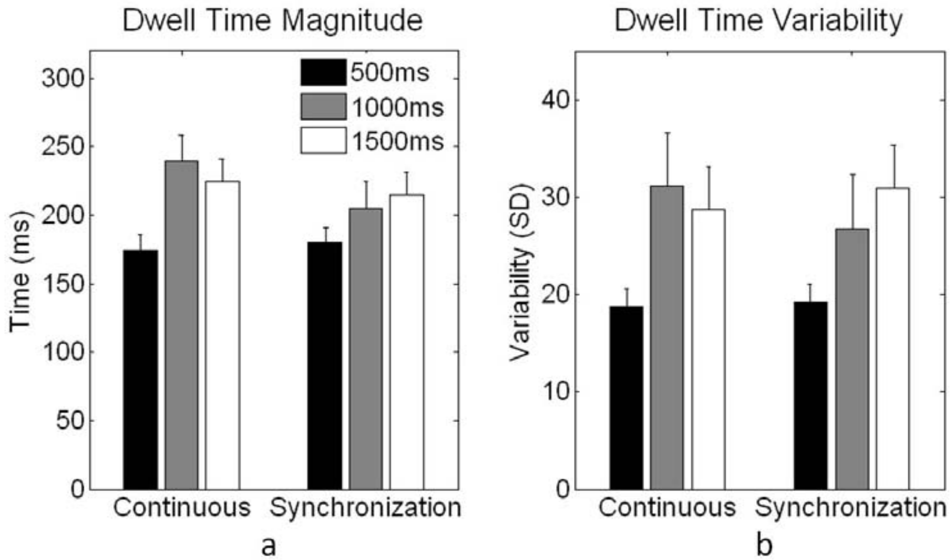

Figure A. 3: The mean and the standard error for the magnitude and variability of dwell time for each tapping condition.

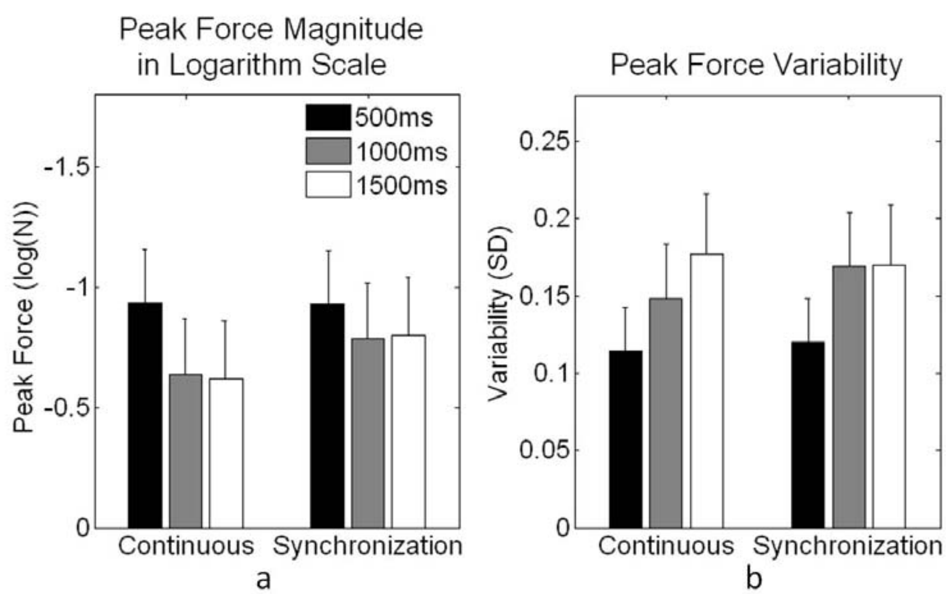

Figure A. 4: The mean and the standard error for the magnitude and variability of peak force for each tapping condition. The peak force magnitude is in logarithm scale.

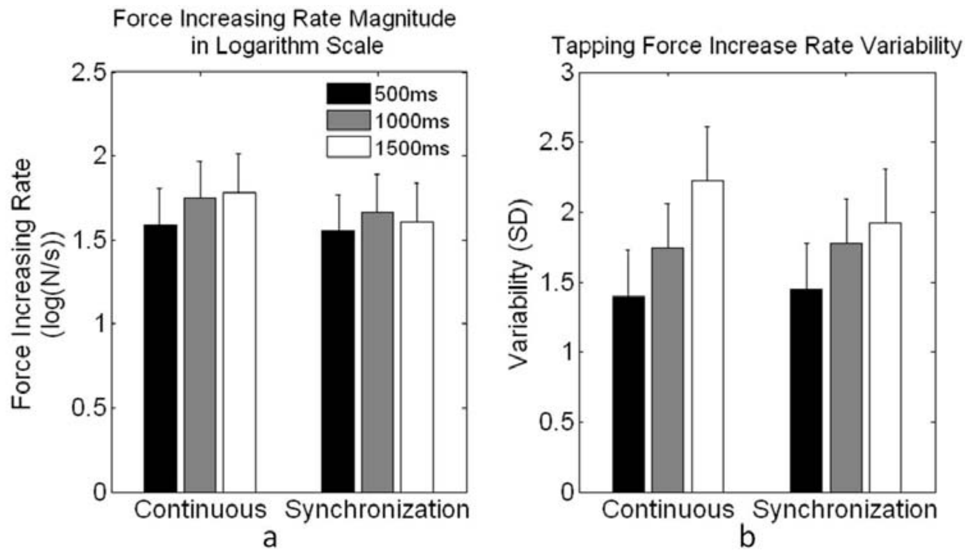

Figure A. 5: The mean and the standard error for the magnitude and variability of force increasing rate for each tapping condition. The force increasing rate magnitude is in logarithm scale.

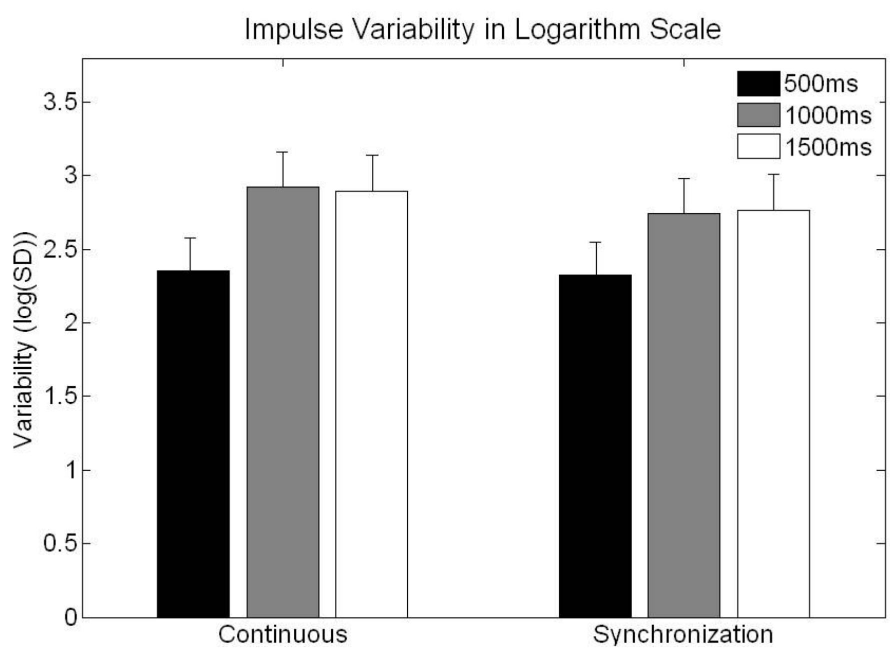

Figure A. 6: The mean and the standard error for the variability of impulse for each tapping condition. The variability of impulse is in logarithm scale.

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