INTERACTIONS BETWEEN FORCE AND TIMING CONTROL OF REPEATED ACTIONS

By

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ABSTRACT

Variability is an inherent component in movement and provides an insight into control processes involved in producing motor responses. This thesis investigates the interactions between force and timing processes in the production of repetitive actions from an information processing perspective. Force-time interactions are examined in steady state sequences, sequences with step changes, and steady state sequences with a secondary visual search task as an attentional load. The account of control in normal healthy participants is then applied to describe behaviour of patients with cerebrovascular accidents (CVAs) in two case studies. Interaction was found to be present in variability measures and was quantified using cross-correlation analysis. Overall, results demonstrated that one locus of force-time interaction is at a cognitive level where motor responses are organised for execution. Corresponding changes in magnitude of dependence according to availability of attentional resources and task prioritisation supported this observation. Dependence patterns in patients with CVAs reflected loss of control when task difficulty increased. Finally, based on the findings, a conceptual model describing the interaction is proposed towards the development of a formal model for simulation studies.

DEDICATION

For the One who called me on this journey and brought it to fruition

– from You all things come, and to You they are returned.

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31st March 2015.

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ABBREVIATIONS

BCoS	Birmingham Cognitive Screen
CNS	Central nervous system
CV	Coefficient of variation
CVA	Cerebrovascular accident
IRI	Interresponse interval
M	Mean
PF	Peak force
SD	Standard deviation
SE	Standard error
W-K model	Wing-Kristofferson model

CHAPTER 1

INTRODUCTION

Voluntary movement is the primary way we interact with our surroundings. We have developed different forms of behaviour to navigate the environment to achieve goals. Some of these actions have a simple repetitive nature which is spontaneous, for example, clapping, knocking, or banging to attract attention. Others may require skill acquisition, such as drumming or playing the piano. Each individual action consists of a timing component (when to respond) and a force component (how much effort to respond with). When the same actions are repeated over a certain period of time, maintaining the accuracy of both force and timing components is necessary to continuously produce correct responses. The requirement of sustaining reasonable accuracy is one of the things that make repetitive actions interesting. Although relatively high accuracy of an action can be achieved over repeated responses, for example, keeping a consistent tempo during continuous drumming, it is impossible to produce two (or more) identical responses over a period of time. Moment-to-moment fluctuations, or variability, are inherent in voluntary movement and present in both timing and force control processes. Therefore, control behaviour in voluntary movement presents a unique challenge to the motor system as it attempts to preserve accuracy in the presence of the uncertainty posed by variability. The nature of this control behaviour is the focus of this thesis. The investigations are directed at elucidating the relationship between the force and timing processes and the nature of their co-variation. A discussion of where to go ultimately begins with where we are now, and where we are is surely a result of where others have been previously.

Therefore, it is imperative that this thesis acknowledges the milestones which have been achieved in this area of interest from its early beginnings to the current state of knowledge.

The discussion of timing control is well developed in the literature. Observations of timing behaviour in experimental settings can be traced back to work by Stevens (1886), conducted more than a century ago. Using a kymograph in a unique setup with two electrical circuits, Stevens made recordings of time intervals from tapping on a compound lever, initially a Morse key. To begin with, tapping was accompanied by beats of a metronome which provided a steady pace. The metronome was then stopped while tapping was continued unpaced at the same rate. This simple yet effective way of investigating timing behaviour is now known as the synchronisation-continuation paradigm and is used in most timing research. Many subsequent timing studies investigating two-level timing processes could be retrospectively related to Stevens' (1886) observations of the distinct variability patterns of a "standard the mind carries" and one which "the hand" cannot keep true (p. 401). Identifying a "timekeeper" which keeps track of temporal events has led to many accounts of an internal clock mechanism.

Subsequently, in a seminal publication, Treisman (1963) proposed a model of an internal clock, which included detailed workings of a mechanism which keeps track of time and how it can be influenced by physiological changes. Treisman's (1963) timekeeping system consisted of an arousal-sensitive pacemaker which continuously sends periodic pulses to a counter. A store kept reference durations and a decision-making comparator determined behavioural output by comparing counter and store values. Treisman (1963) proposed that the operation of the pacemaker was influenced by arousal, introducing the idea that variability is present in the workings of the clock.

The following landmark development in timing models incorporated both the idea of the internal clock mechanism and presence of variability. The Wing-Kristofferson (W-K) model (Wing & Kristofferson, 1973a, 1973b) not only provided an account of moment-to-moment fluctuations in unpaced responding, but also the means to quantify and estimate the amount of variability contributed by each of the two-level processes (central and motor implementation). Initially proposed as an open-looped model, the W-K model has since been extended to include a third process introducing feedback correction with an error-correction parameter describing strength of correction to asynchronies between pacing stimulus and own responses (Vorberg & Wing, 1996).

The search for the internal clock has since taken a neural focus, tracing the neural pathways of timing perception and production. Neuroimaging methodologies are now being used to localise activity in timing tasks. This approach has advanced the understanding of timing control, especially by studying the behaviour of both healthy individuals and neurological patients. The comparison allows the possibility of inferring neural structures involved in time perception and production by correlating deficits in timing behaviour with lesion locations (Coull, Cheng, & Meck, 2011). Experimental findings have implicated the cerebral cortex and cerebellum, as well as subcortical structures, especially the basal ganglia. However, there is converging evidence that the workings of the clock are more similar to a distributed network rather than confined to a core locus (Allman, Teki, Griffiths, & Meck, 2014).

A neglected observation until recently is the study of force control and its effect on timing. In sequential action, force control processes are triggered by motor programs which are stored in the central nervous system (CNS) and are implemented by effectors (Schmidt & Lee, 2011). However, there are fewer formal developments of models describing the process of force implementation. One exception is the Parallel Force Unit Model proposed by Ulrich and Wing (1991). This model provided a theoretical account of how the recruitment of force units has consequences on temporal parameters.

The summary above motivates the two key themes running throughout this thesis. Firstly, that both force and timing control are processes which have a central origin and are integrated to be implemented by the peripheral motor system. This perspective, which is supported by previous literature, draws the distinction between at least two stages of control and thus raises questions about where force-time interactions might occur. The second key idea in the thesis is that patterns of variability, and not just the magnitude, are important in understanding timing and force control, as well as their interactions. Variability is inherent within movement, both in timing and force production. They have been shown to co-vary and this co-variation is of interest as an indication of possible interaction between force and timing processes.

1.1 Thesis Overview

Despite the importance of both force and timing control in generating a motor response, the study of interactions between these two processes has received comparatively little attention. There is a need for the relationship between force and timing to be described with an integrated view. This has been attempted in the literature when complex movements are involved, particularly in musical performance. The dependence between force and timing has been investigated in the context of expressive timing and dynamics. Notes placed at strong metric locations (for example at the beginning of a bar) are often played more loudly (higher force) and with a longer duration (Sloboda, 1983, 1985). The coupling of force and timing in this way is used by the performer to communicate and reinforce the metrical structure of the piece. In addition, the coupling can also be used to influence emotional expression. Pieces with happy or angry emotions are often played louder and faster, whereas sad emotions are played more softly and slowly (Gabrielsson, 1999). Force-time coupling has also been incorporated into a model of musical expression with the assumption of, the faster the louder, the slower the softer (Todd, 1992). In summary, force-time coupling is characteristic of highly-skilled movements required in musical performance. Therefore, considering force-time interactions in a simpler repetitive task, for example in finger tapping, would provide the opportunity of further understanding the mechanisms underlying the coupling which contribute towards more complex movements. Thus, there is a potential for the development of a basic yet testable timing and force control model to illustrate how these two processes interact in time. In order to develop an integrated account of repetitive behaviour, it is necessary to understand force and timing through time series analysis of both processes. For that reason, in this thesis, the relationship between force and timing control is considered by asking the following questions: Firstly, how can the force-time relationship be empirically quantified? Secondly, what are the factors which influence the presence of the force-time relationship and modulate its strength? Thirdly, do different cognitive strategies change force-time control behaviour? Finally, we ask whether the account of control behaviour in healthy participants is applicable to understand force-time relations in patients with a form of cognitive impairment affecting the sequencing of action.

There are seven chapters contained in this thesis; the area of interest is introduced in the first (this chapter); the body of literature is reviewed in the second; the subsequent four describe experiments conducted; and points of interest from the whole thesis are discussed in the seventh. A proposal of a theoretical account of force-time interactions is proposed at the end. An overview of the contents of the chapters are summarised below.

In Chapter 2, a literature review is presented, summarising the research on force and timing control in voluntary repetitive actions. Several models describing both processes have been proposed in the literature, providing accounts from the information processing as well as dynamical systems perspectives. A pertinent theme throughout the literature is the importance of considering variability patterns of these processes, in addition to magnitude related measures. This is because moment-to-moment fluctuations are inevitable in repetitive movements, and variability patterns provide an insight into the nature of the processes involved. Key papers investigating interactions between force and timing parameters are reviewed in more depth, and a number of core themes are drawn, which guide the work in the subsequent chapters. The role of motor programmes in sequential action are considered as the possible link where force and timing information are integrated for executing repetitive responses. The time-varying characteristic of repetitive responses necessitates the use of time series analysis in the literature to describe force-time dependence.

Chapter 3 investigated force-time interactions in steady-state pulse production. It was hypothesised that the interactions would be present in variability measures of both force and timing. A novel method was used to present force levels and time intervals. Both force and timing information were simultaneously delivered via the haptic modality (tactile and proprioceptive) as a way of standardising input, delivered by a robotic haptic device. Cross-correlation analysis was applied as previously described in the literature, but with an additional detrending process to establish statistical stationarity in time series of peak forces and time intervals. Data were collected over a range of force levels and time intervals. Although the primary focus was on steady state pulse production sequences, accented sequences were also included for exploratory purposes. In steady state sequences, interactions between force and timing were found to be present only in force variability measures, whereas in accented sequences, timing was affected when preceded by an accented force pulse. The matched force and timing input provided via the haptic modality during the paced phase was achieved but practical challenges with handling the robotic haptic device required a revision of data recording methodology.

Following on from the force-time interactions found during trials with a change in force levels, Chapter 4 described force-time dependence in a pulse production task where force levels and time interval lengths were manipulated separately as step increases or decreases in force and time, in contrast with the steady state approach used in Chapter 3. The visual modality was used to provide simultaneous force and timing performance feedback. Data were collected using 1D load cells instead of a robotic haptic device. An examination of mean and variability measures of the unmanipulated parameter indicated that the dependence between force and timing was transient at the vicinity of the change, and resulted in changes of both force and timing control behaviour. The corresponding changes in both parameters during a change in force level or time interval reflected the presence of a dependency or a co-variation. Analysis was done using the coefficient of variation (CV; ratio of standard deviation to the mean) as a measure as it is unitless, and allowed a standardised comparison between force and timing. These results, taken together with findings from the previous chapter, suggested that force and timing control are autonomous processes but interact when cognitive resources are recruited to adjust to a new state. To analyse the cognitive involvement, a dual task approach was suggested.

The use of the step change (transition) in Chapter 4 made it challenging for cross-correlation analysis to be applied due to the resulting change in mean and variance within a trial. In Chapter 5, a dual-tasking paradigm was used without transition. The engagement of additional cognitive resources during a secondary task was expected to reveal a consistent dependence in comparison with the transient occurrence observed in Chapter 4. A numerical visual search task was selected as a secondary task because it presented a consistent load throughout a trial by requiring a continuous updating of working memory and has been shown to interfere with timing control (Brown, 1997). The secondary task varied in difficulty and task priority was manipulated. Cross-correlations departed from zero in the dual-task, suggesting that the dependence could be a control strategy to free cognitive resources to engage in another task. The control was handled differently when priority was given to the pulse production task. Surprisingly, the expected larger correlations with increase in difficulty of the secondary task were absent, raising the possibility that the correlations could indicate loss of control.

The account of normal behaviour was then applied to atypical behaviour to explore whether it can be used for understanding force-time relations in neurological patients with cognitive difficulties in the praxis domain. Praxic deficits have been shown to relate to functional deficits for detecting apraxia (Bickerton et al., 2012). Patients with apraxia are prone to difficulties in performing sequential actions which might affect control behaviour of force-time processes in repetitive pulse production. The study in Chapter 6 involved the participation of two CVA patients in the cerebral regions who underperformed in praxis-related items of the Birmingham Cognitive Screen (BCoS). They engaged in a dual-task similar to that used in Chapter 5. Cross-correlation analysis revealed stronger force-time dependence in comparison with healthy participants when only doing pulse production. More crucially, their handling of the dual-task suggested that the force-time dependence was more indicative of a loss in control as the dependence was noticeably absent. There was a corresponding large increase in variability measures of the primary pulse production task. A further investigation of the patient datasets revealed individual differences in handling the dual-task.

Returning to the overarching objective of the thesis to investigate the relationship between force and timing control, Chapter 7 summarises the empirical findings of the four experimental chapters and discusses how they relate to the current body of literature. Finally, opportunities for future research using these current studies as a foundation are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Voluntary action

Movement is a displacement of an object over time as a result of being acted upon by forces. In humans, movement is brought about from force generated by innervations and contraction of muscles. These movements may occur over different timescales within tens of milliseconds (e.g. piano playing), seconds to minutes (e.g. foraging) or circadian (sleeping and waking) ranges. Most voluntary movements fall within the range of tens to hundreds of milliseconds. Within this time range, these actions demonstrate planned control of time and force parameters in producing movements, for example, keeping a regular rhythm (fast or slow) when striking the keys of the piano while maintaining the amount of force used to express the dynamics (loud or soft) of a piece of music. Anecdotally, it is possible to manipulate rhythm and dynamics in piano playing, choosing one over the other or changing both at the same time. Thus, it is interesting to ask about the mechanisms in the central nervous system (CNS) which allow these parameters to be controlled and changed. Moreover, since movement is a result of both variables, there is a possibility of interactions between force and time control as it is initiated and executed by the motor system. How do force and time production co-vary with each other? What are the links between rhythmic timing production and force generation?

Two different perspectives have emerged in the literature for both force and time control in voluntary action: the information processing view and the dynamical systems perspective. The emphasis in this thesis is on the information processing view since the exploration is focused on components of variance and their summation, which is part of information processing. However, the dynamical systems approach will still be discussed, albeit more briefly. The information processing view describes the control systems as being directed by a central processor. The processor receives input from the environment through the senses and applies algorithms to produce an output which is manifested as overt behaviour. Studies which adopt this approach investigate consistency of behaviour by recording discrete motor events over many repetitions to determine average performance and variability around the mean. Computational models propose how variables interact through parameters which researchers endeavour to estimate.

Conversely, the dynamical systems approach views behaviour as an emergent property of couplings between an individual and their environment, determined by laws of physics but without a central controller or processor. An individual is considered as a device with many continuously evolving internal states that can be described by oscillations. This approach focuses on the coupling of oscillation signals within a given state. Behaviours are usually described in terms of order variables that summarise higher order properties of the system as a whole. Predictions of the order variables are simulated using differential equations and qualitatively matched to behavioural data. Points where the rate of change of the order variable yields a value of zero are called fixed points and the system is said to be stable (Schöner, 2002). Thus, dynamical models focus on the likelihood of a system with multiple oscillators settling in a steady state and how it behaves when perturbed.

The two views above represent the ideas of explicit and emergent control in the literature. Explicit control has clearly defined goals or endpoints to achieve, such as tapping to the beat of a metronome. Emergent control is a result of the operation of continuous non-temporal processes, for example in repetitive circle drawing. These processes have been hypothesised to involve different mechanisms (Zelaznik, Spencer, & Ivry, 2002) which may engage different parts of the brain (Spencer & Ivry, 2005). Such a contrast between explicit and emergent control has not yet been developed for the control of force, and would be interesting to investigate using methods similar to timing studies to draw parallels, especially in paradigms which incorporate the use of force sensors to capture timing parameters.

This literature review is structured according to the two key themes running throughout this thesis. Both timing and force production are firstly described as individual processes with a central origin and peripheral implementation process. Then, accounts of variability within the processes are presented. This is followed by a discussion of studies investigating interactions between force and timing processes. Both force and timing processes are then considered in the context of motor programmes which are components of sequential actions. Finally, methodological considerations are presented, demonstrating the need for a method (cross-correlation analysis) of characterising force-time dependence as it occurs through time.

2.2 Timing

This section provides an overview of key ideas in the study of timing, focusing specifically on the idea that the production of time intervals is a two-stage process which consists of a central origin component and a peripheral implementation process. Different models which have been proposed based on this premise are then reviewed.

2.2.1 Internal clock

The formal representation of an internal clock was proposed by Treisman (1963) although research on time estimation can be traced back to Stevens (1886), François (1927), and Hoagland (1933). Treisman (1963) described a timekeeping system (see Figure 1) which consists of an arousal-sensitive pacemaker that continuously sends periodic pulses to a counter. A store keeps reference durations and a decision-making comparator determines behavioural output by comparing counter and store values.

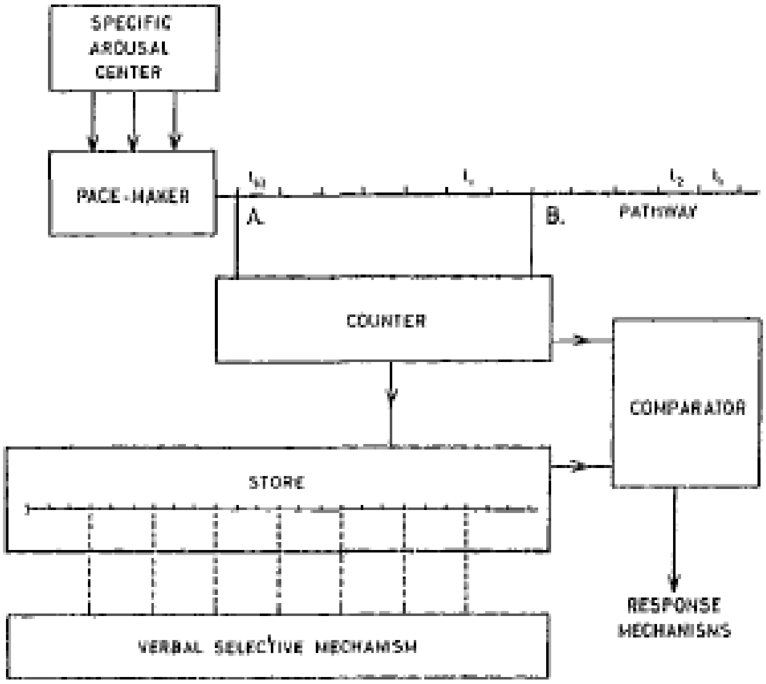

Figure 1: Conceptual model of a timekeeping mechanism, from Treisman (1963).

Gibbon, Church, and Meck (1984) embellished Treisman's conceptualisation of the internal clock with a psychological context. The three-level model (see Figure 2) consists of the clock stage, memory stage, and decision stage. At the clock stage, the pacemaker emits pulses into an accumulator via an attention-sensitive switch (or gate). The count of pulses is held in short term memory and compared with a value previously stored in reference memory. The interval length stored in the reference memory for comparison is based on a reinforced behaviour of an accurate time interval, for example tapping in synchrony to an external beat. When both values in short-term and reference memory match within a reasonable margin of variability, a decision is made to produce an estimate of time.

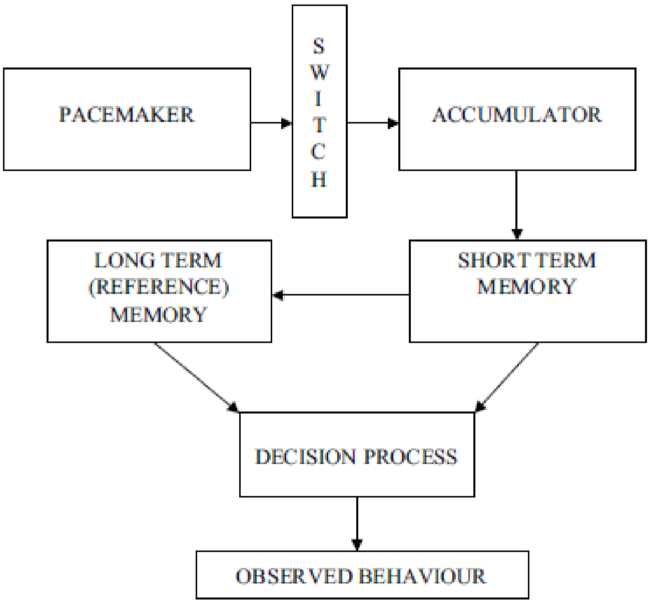

Figure 2: Outline of Gibbon, Church, and Meck's (1984) three-level process model of the internal clock, from Wearden (2004).

Efforts to map the clock onto the brain have resulted in those who support the evidence of its location in the cerebellum (Bareš, Lungu, Husárová, & Gescheidt, 2010; Ivry, Spencer, Zelaznik, & Diedrichsen, 2002), the basal ganglia (Harrington, Haaland, & Hermanowicz, 1998; Meck, 1996), and more specifically, in the subthalamic nucleus within the basal ganglia (Joundi, Brittain, Green, Aziz, & Jenkinson, 2012). Neural studies have provided evidence for the different components of Gibbon, Church, and Meck's (1984) conceptual model. The accumulator component has been associated with the left inferior frontal, superior temporal and SMA regions (Wencil, Coslett, Aguirre, & Chatterjee, 2010) whereas the comparator has been related to the bilateral inferior frontal cortices (Teki, Grube, Kumar, & Griffiths, 2011). Both hippocampal and cortical circuit damage distorts temporal memory, resulting in under and overproduction of time interval targets (Coull et al., 2011; Harrington, Haaland, & Knight, 1998). The fact that many different brain regions have been found to be involved in timing suggests the possibility that the timing mechanism is not located in a specific area but instead consists of distributed neural networks with different regions encoding duration (Mauk & Buonomano, 2004).

2.2.2 An information processing account of timing

From the information processing point of view, the clock produces discrete events, and the variability present in measurements reflects the accuracy distribution of previous clock readings. The accumulated error in the clock is a constant proportion of the target interval length, in conformity with Weber’s Law (Wing, 2002). This has been frequently observed in motor timing production studies involving finger tapping where the standard deviation increases in proportion to the mean. Variability is present at every time interval produced, but yet, we are able to generate a given duration with relative ease. The sections below consider how this could be possible with the existence of an internal clock.

As early as 1886, Stevens engaged participants in what is now a classic method for investigating timing responses: the synchronisation-continuation paradigm. Participants synchronised finger taps to auditory clicks which provided a controlled standard, and continued tapping for a further 40 to 150 taps after the clicks stopped. During continuation, participants were able to maintain the given interval with small deviations from the mean. Examining the raw recordings of interresponse intervals (IRIs) in the form of connected series of time intervals (a time time series), Stevens noticed that tap-to-tap variability took the form of zig-zag (short-long) patterns which oscillated around the target mean value. It was as though the finger was correcting itself to an internal 'standard which the mind carries' during every next tap it produced.

Stevens (1886) suggested that the judgment of an interval's accuracy is realised only after its execution has occurred and a correction is made on the subsequent tap. The source of this error seems to be rooted in its implementation rather than the internal standard to which it attempts to correct. The ability to maintain the interval without deviating too far from the mean, supposedly held by the internal standard, seemed to emerge from this tap-to-tap correction mechanism. On the other hand, there was also a variability pattern which was of a lower frequency. Their prominence especially at longer intervals led Stevens to attribute them to the variation of the internal standard.

As noted by Wearden (2004), Stevens' paper highly influenced many ideas in timing control; three of its many implications are noted here. Firstly, it suggested a possible tap-to-tap correction mechanism which allowed performance to be maintained around the target mean. Secondly, the early descriptions of a two-level control mechanism for time emerged, namely the 'standard carried in the mind' (which was later termed the central timekeeper or internal clock), and the 'execution' (subsequently known as the motor system); and thirdly, it put forth the possibility that distinguishing between the different patterns of variability could possibly identify and reveal the likely sources of these fluctuations.

2.2.2.1 W-K model

Wing and Kristofferson (1973a, 1973b) formalised the idea of a two-level mechanism in timing control by proposing a mathematical model (W-K model) describing two processes from which variability could arise, namely, inaccuracy in a hypothetical timekeeper and motor delays from response execution. Though Stevens (1886) suggested that the observed IRI patterns and adjustments could be a correction mechanism, the W-K model was able to predict the zig-zag pattern without a correction process. This two-level timing model, which was built upon the idea of an internal clock subjected to stochastic variability, described in a fundamental way, how a time interval is produced in the CNS and executed by the motor system. For the continuation (unpaced) phase of the paradigm used by Stevens (1886), the W-K model (Figure 3) describes the length of an observed interval, I_n, as the sum of the interval produced by the timekeeper, T_n, plus the difference between the motor delay of the initiating response, M_{n-1}, and the motor delay of the terminating response, M_n, expressed as (see Equation 1):

$$I_n = T_n + M_{n-1} - M_n \qquad (1)$$

Over a series of repetitive taps, interval (*I*) is maintained with variability which increases with interval length. The model posits two types of variance that contribute to the deviation, the timekeeper variance (σ_T^2) and the motor variance (σ_M^2), the former originating from the timekeeper and the latter from the implementation of the interval as it passes through the motor system. The two distinct processes have different characteristics and can be dissociated and represented using a variety of methodologies (Wing, 2002).

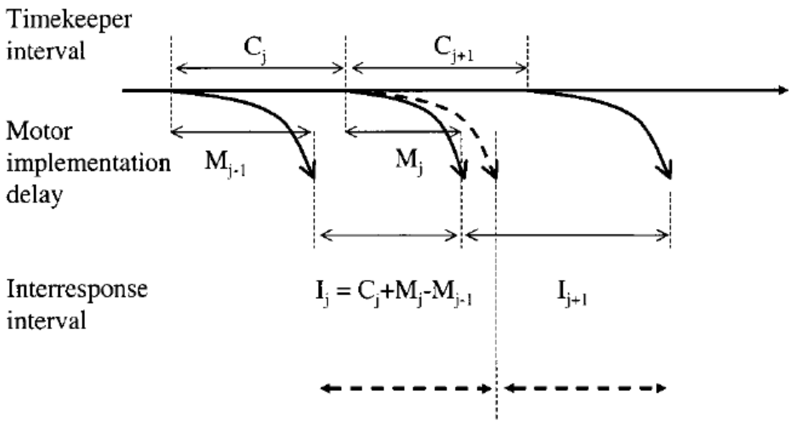

Figure 3: W-K two-level timing model (Wing, 2002). The interresponse interval (*I*) is defined by timekeeper interval (*T*) which is subjected to motor implementation delays (*M*) and has a tendency to alternate between short and long intervals (as indicated by dashed lines).

The central variance is time-dependent and increases linearly with the interval length. The motor variance is time-independent and remains constant throughout different intervals. With the assumption of statistical independence between the timekeeper and motor component, the total variance of an observed interval (σ_I^2) is the additive sum of both variances (Wing & Kristofferson, 1973a, 1973b; see Equation 2).

$$\sigma_I^2 = \sigma_T^2 + 2\sigma_M^2 \qquad (2)$$

Adjacent intervals have a statistical dependence with a lag 1 autocovariance, described by Equation 3:

$$\begin{aligned} \text{acvf } (\gamma_I(j)) &= -\sigma_M^2 && j = 1 \\ &= \sigma_T^2 + 2\sigma_M^2 && j > 0 \\ &= 0 && j > 1 \qquad (3) \end{aligned}$$

The resulting prediction of autocorrelation at lag 1 would be (see Equation 4):

$$\rho_I(1) = \frac{\gamma_I(1)}{\gamma_I(0)} = -\frac{\sigma_M^2}{\sigma_T^2 + 2\sigma_M^2} \qquad (4)$$

The relationship between adjacent intervals is present even though the system is assumed to operate as an open loop process without a feedback or correction mechanism. This equation predicts that, if the current interval is shorter than the mean interval, the subsequent interval would be longer than average and vice versa. This describes Stevens' (1886) observation of the zig-zag pattern in the curves without the use of a feedback mechanism. The autocorrelation at lag 1 is predicted to lie between 0 and -0.5. At lags larger than 1, the coefficient is predicted to be 0.

This approach was important as it allowed the partitioning of variability into distinct components, allowing subsequent investigations of time control to be targeted specifically at the two different levels.

2.2.2.2 Linear Phase Correction Model

The W-K model in its original form was described as an open loop model. A paced tapping task would then present an interesting challenge since if there was no error-correction mechanism, the accumulation of discrepancies between the tap and external pulse would cause an inevitable drift. The two-process model has since been extended to studies of paced tapping (Semjen, Garcia-Colera, & Requin, 1984), multisensory integration in tapping (Elliott, Wing, & Welchman, 2010) and increasing or decreasing interval (Schulze, Cordes, & Vorberg, 2005), amongst others. The extended W-K model includes a fourth term in the model (αA_n) which allows for correction of the clock interval by taking into account a proportion (α), of the asynchrony between the external pulse and the tap (A_n). Thus, the extended model is expressed as (see Equation 5):

$$I_n = T_n - \alpha A_{\boldsymbol{n}} + \left(M_n - M_{n-1}\right) \tag{5}$$

This extended model has been referred to as the first order autoregressive (AR1) model since alpha, α, is the first order error-correction coefficient. Alpha is an indication of the strength of error-correction, which is assumed to be a third process (Vorberg & Schulze, 2002; Vorberg & Wing, 1996).

2.2.3 Dynamical systems approach

The internal clock is replaced by an oscillator in the dynamical systems perspective. As an oscillator, it is assumed that the clock does not produce discrete events but instead represents time continuously with each repetition of an event denoting a completion of a phase or oscillation. In the timing literature, movement synchronisation is well described, for example, in tapping to syncopated rhythms (Large, 2000) and inter-limb tapping (Yamanishi, Kawato, & Suzuki, 1980).

In approaching the problem of maintaining performance accuracy around the mean tempo, the dynamical systems approach recourses to a coupling or entrainment mechanism of two independent oscillations which are assumed to interact through sensory or motor pathways. The state of one oscillator is influenced by another oscillator's state and is described by a continuous coupling function. With reference to the synchronisation-continuation paradigm, the continuation tapping phase is coupled with a virtual metronome as two individual oscillators and described by differential equations (Repp, 2005). When a perturbation causes a misalignment of phase (asynchrony), the dynamics of the system autonomously drive the oscillators back to a stable state (Schöner, 2002).

In comparison with the two-process timing model, the negative lag 1 autocorrelation is not generally predicted by dynamic timing models (Daffertshofer, 1998). This autocorrelation property was only obtained when there are two or more coupled oscillators and if the system was extended with different parameters. The strength of dynamical systems theory lies in explaining investigations of synchronisation where more than one oscillator is present, thus also supporting the idea of multiple timekeepers (Buhusi & Meck, 2005) instead of one central clock, which was proposed in information processing models (Ivry & Richardson, 2002).

In summary, although discrete and dynamical modelling approaches are distinct, the models and analysis methods of each have been expanded and influenced by the ideas of the other. The information processing approach provides a simpler and statistically sound paradigm in an experimental setting. This is complemented by the dynamical systems perspective which provides a method of investigating complex systems such as timing in speech and music.

2.3 Force

This section below discusses force production, in particular, how similar it is to timing control in terms of being conceptualised as a two-level central-peripheral process. Force production is a component of motor control which is often discussed in the context of motor programmes that control the production of sequential action. Therefore, the concept of motor programmes is firstly presented, followed by a more specific focus on variability in the force production process. There are fewer models describing the force control process in comparison with the timing literature. A brief account of the dynamical systems approach is also discussed.

2.3.1 Central controller

The theory of motor programmes suggests that an action is formed of a sequence of movements whose structure is stored in the form of a command in the CNS. This was first proposed by Lashley (1917) when describing how a patient who had lost all sensation to his lower limbs because of a gunshot wound to his back was still able to position his leg as accurately as a normal person could. Since this movement was executed with only efferent pathways intact, it suggested a central controller which operated and sent commands to limbs without needing feedback. This nature of motor control reflects an open loop process (see Figure 4) which is able to continually generate responses.

The concept of a motor programme is commonly defined as “a set of muscle commands that are structured before a movement sequence begins, and that allow the sequence to be carried out uninfluenced by peripheral feedback” (Keele, 1968, p.387). As the programme is triggered, a hierarchy of instructions are received and executed sequentially by the motor effectors involved. With practice, a sequence of movements becomes stored in the memory system and is centrally represented for future execution (Keele, 1968). The idea of motor programmes has been supported by studies which suggest that movement execution time is quicker than the time for a feedback loop to be completed, providing evidence for movement planning, and corroborated by preservation of movement accuracy in deafferented patients (Schmidt & Lee, 2011). In addition, there is also evidence for existence of central pattern generators (Morris, Summers, Matyas, & Iansek, 1994).

The idea of such a system for planning sequential action created two long standing issues, firstly, the impossibility of storing a vast amount of programmes in the CNS for all the movements humans are able to execute (the storage problem), and secondly, the inability to produce new actions unless all programmes were somehow inherited at birth (the novelty problem).

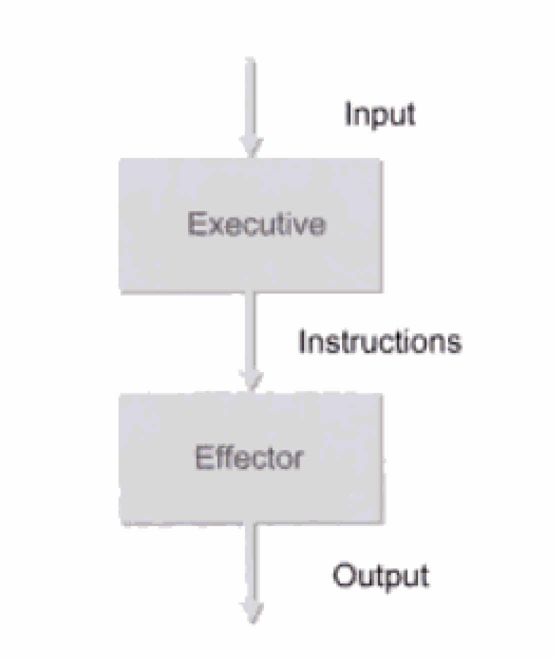

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Figure 4: Elements of a motor programme (Schmidt & Lee, 2011). A sensory input triggers the executive to produce instructions which are sent to the effector to carry out the output.

2.3.2 Generalised motor programmes

One of the prominent responses to the novelty and storage problems was the conceptualisation of generalized motor programmes (GMPs) which provide a framework of execution for a class or category of movements with parameters that can be scaled according to specific demands of the goal (Schmidt, 1975). Schmidt proposed that GMPs are open loop and have invariant features which remain constant from movement to movement (relative timing and relative force) as well as variant features that are recruited separately and flexible to change (action overall duration, overall force, and muscle recruitment). Thus, a variety of specific movements are modified by adapting and scaling the parameters of one same GMP, eliminating the need for an inordinate number of programmes.

This view posits two levels of motor control, an executive for programme selection and an effector for programme execution (Schmidt & Lee, 2011). Looking specifically at force production, Schmidt and Lee (2011) outlined a relationship between relative force and overall force. The amount of overall force produced is always a constant proportion from movement to movement when the same programme is used, directly relating to the amount of neural activity triggered by the CNS to elicit a change in the target muscles (Henneman, 1957). Thus, the measured force of any action can then be seen as a scaling of the invariant force ratio given by the motor programme, allowing the same action to be executed with different or similar amounts of force. Information regarding the sensory consequences of the action as well as the behavioural outcome of the movement is stored in memory, allowing modifications based on sensory feedback and knowledge of results to improve performance accuracy.

Therefore, a series of repetitive actions can be seen as a plan of sequential actions involving a motor programme which scales the force with similar parameters for every response. However, even repetitive actions using the exactly the same motor programme intended to produce the same amount of force, display variation in force levels. The variability reflects an inaccuracy caused by noise which is an inherent property in the nervous system. In converting neural signals from the CNS into mechanical forces in the muscles, noise from cellular firing produces variability which can be observed in trial to trial variability. Both peripheral skeletal mechanisms (Ulrich & Wing, 1991) and central command processing (Faisal, Selen, & Wolpert, 2008) contribute noise during the activation of the motor system.

2.3.2.1 Variability from the peripheral process

A conceptual example of how variability arises from muscle activation during force production is described by the Parallel Force Unit Model (PFUM) (Ulrich & Wing, 1991). Force units (FUs) reflect the underlying activity of a motor unit and the firing of each unit contributes to the overall force produced. Motor units have varying ranges of conduction velocity which affect firing rates and are also exposed to stochastic delays. As the activity of each individual FU is subjected to these delays, variability is summed over the number of FUs required to produce a particular force magnitude. The PFUM assumes the development of a force output as being controlled by the firing duration of FUs or the number of recruited FUs. Therefore, larger forces which require the recruitment of multiple motor units subsequently accumulate more noise. This can be observed in standard deviations of force in responses which are proportional to the magnitude of force produced by the muscles.

2.3.2.2 Variability from the central process

Variability may also arise from central processes and distinguishing between variability patterns provides an indication of its source. This is possible by comparing voluntary isometric contractions to electrical stimulation of the muscles involved (Jones, Hamilton, & Wolpert, 2002). Using an isometric force production paradigm, Jones et al. (2002) had participants produce varying magnitudes of force under voluntary control, neuromuscular electrical stimulation (NMES) and a mixed condition. Results showed that the scaled relationship between variability and mean force is characteristic of the discharge rates of motor neurons, therefore suggesting that the variability is more likely to arise in the execution rather than the planning of motor commands. The variability of central processes on the other hand, was reflected by the coefficient of variation (CV) in the NMES condition. As predicted, the regression slope of the combined condition reflected a slope similar to the voluntary condition with an offset comparable to the NMES condition. Though the study by Jones et al. (2002) was directed at modelling how the nervous system optimizes motor output in the presence of noise, it provided a method of distinguishing two sources of variability at the central and peripheral levels and validated the concept of two sources of noise, similar to the issue addressed by the W-K model in timing.

2.3.3 Dynamical systems approach

While motor programmes involve the structuring of central commands in advance and transmission of information for execution by effectors, the dynamical systems perspective views motor control as a decentralised system which considers a particular movement as an emergent property of structural and functional constraints (Newell, 2003). Its components are represented with oscillators that provide a continuous description of its state over time, which are expressed mathematically by differential equations. The oscillators are attracted to a stable state where they eventually converge to display consistent behaviour.

From this perspective, motor control components such as force, timing and amplitude are not pre-determined but are a consequence of the human interacting with the environment (Kugler, Kelso, & Turvey, 1982; Morris et al., 1994). In place of central mechanisms which programme commands, coordinative structures self-assemble tasks as the demand requires, according to the laws of dynamics. Oscillators at multiple levels (including sensory and motor loops) interact as described by a coupling function for movement to emerge instead of being controlled by executive functioning commands.

Constraints within the system change over time and limit the emergence of movement (Newell, 1986). These may be structural or functional (e.g. height, weight), environmental (e.g. temperature, gravity) or task-related (e.g. task rules, objects involved). For each stable state, functionally optimal coordination patterns lead to consistent performance for similar tasks (Glazier, Davids, & Bartlett, 2003). Variability in performance is accounted for by the differences between the current state and the stable state, allowing for errors and novelty. It also explains why it is possible for highly skilled athletes to perform consistently or change performance strategies. However, because the production of a motor output is seen as finding the optimal combination of constraints that meets the demand of the task, it is inappropriate to isolate force control to be studied as a property by itself.

2.4 Interactions between force and timing control

From the information processing perspective, both force control and timing control have been investigated separately as summarized above. However, an execution of any movement in time requires an accurate scaling of force generation. The discussion below focuses on whether force and time are independent, and if not, what that implies for their control processes.

Various paradigms have been used to investigate the interactions between force and time control (see Table 1). Although it is relatively simple to produce repetitive straightforward movements such as tapping, commonly used in the paradigms mentioned below, each tap would differ slightly from the previous one, perhaps slightly harder or softer, and the time interval slightly quicker or slower. Even well trained musicians are unable to completely eliminate variability from their performance (Inui & Ichihara, 2001). As discussed in force and time mechanisms above, variability is an inherent property in human control systems. Therefore, observing variability or consistency of performance is a long-standing method of investigating these mechanisms. It is then interesting to understand the nature of variability in force and time control processes in relation to each other and how they interact. Interaction effects are often observed in variability measures (standard deviation or coefficient of variation) and the structure of variability (autocorrelation, cross-correlation).

Paradigm	Task	Measures
Tapping: Synchronisation	Tap with given time and force targets	Mean, standard deviation, coefficient of variation, autocorrelation, cross-correlation
Tapping: Self-selected	Self-determined time and force targets	Mean, standard deviation, Pearson correlation
Tapping: Production	Tap according to learnt time and force targets	Mean, standard deviation, coefficient of variation, Pearson correlation
Pulse production: Synchronisation-continuation	grip to given time and force targets and continue after pacing stops	Mean, standard deviation, coefficient of variation, autocorrelation

Table 1: Summary of paradigms used to investigate force and time control.

2.4.1 Interdependence

Several studies have shown that time and force control are dependent on each other (Inui, Ichihara, Minami, & Matsui, 1998; Inui & Ichihara, 2001; Keele, Ivry, & Pokorny, 1987; Sternad, Dean, & Newell, 2000). This has been demonstrated using two different paradigms, firstly, finger tapping with eccentric and concentric contractions (finger is lifted off the surface and brought downwards in contact with the surface), and secondly, pulse production with isometric contractions (finger remains in same spatial position). In both paradigms, two protocols have been employed. Firstly, performance is observed while systematically varying either the force or timing parameter while placing a constraint on the other during a motor sequence production (Inui et al., 1998; Sternad et al., 2000). Secondly, accents which denote an increase in force are introduced and changes in timing parameters are observed (Billon, Semjen, & Stelmach, 1996; Keele et al., 1987; Piek, Glencross, Barrett, & Love, 1993). This second protocol, however, did not vary time interval as a complement to force. Table 2 below summarises the paradigms, tasks, participants, measures and results of the six studies mentioned above which have reported force-time interactions. This is subsequently followed by sections which expand on the contents of the table.

Paper	Paradigm	Summary of Task	Participants	Measurement	Results
Sternad, Dean & Newell (2000)	Tapping, synchronisation, visual feedback, metronome	1. Synchronise to different IOI with same force target 2. Synchronise to visual force target at preferred pace 3. Synchronise to different IOI and visual force target	1. 6 (4*M*; 2*F*); 23-30 y.o. 2. 6 (3*M*; 3*F*); 23-27 y.o. 3. 6 (4*M*; 2*F*); 22-28 y.o.	1. M (PF) & (IRI) 2. SD (PF) & (IRI) 3. CV (PF) & (IRI) 4. AC (PF) & (IRI) 5. CC (PF & IRI)	1. Magnitude of PF and IRI largely independent 2. SD (IRI) linearly ↑ with IOI length 3. SD (PF) ↑ when PF magnitude ↑ 4. SD (PF) ↓ when IOI length ↓ 5. SD (IRI) ↓ when PF magnitude ↑ 6. IRI (AC) –ve lag 1 when paced; +ve lag 1 when unpaced 7. PF (AC) no consistent pattern, ±0 8. PF-IRI (CC) +ve lag 1 across different force and time targets 9. No –ve CC at lag -1 (Billon, Semjen, & Stelmach, 1996)

Paper	Paradigm	Summary of Task	Participants	Measurement	Results
Inui, Ichihara, Minami, Matsui & (1998)	Tapping, self-paced (halved and doubled), no feedback	1. Tap at preferred pace and force 2. 9 combinations of preferred; half; double force and time.	12*M* (M=22.7 y.o.)	1. M (PF), (IRI), press duration, time to PF, time to PF: press duration 2. SD (PF) + (IRI), press duration, time to PF, time to PF: press duration	1. Variation in IRI lower than PF (independent control) 2. IRI-PF (coeff) more positive and sig at high pace (interdependency at shorter IOI
Therrien & Balasubramaniam (2010)	Pulse production (gripping), synchronisation-continuation, visual feedback, metronome	Produce pulse at 0.5 / 1.0 s + 8 / 16 N	10 (6*M*; 4*F*), M=24.5 y.o.	1. M (PF) & (IRI) 2. SD (PF) & (IRI) 3. CV (PF) & (IRI) 4. AC (PF)	1. SD (IRI) ↑ at 1.0 s 2. PF (AC) is –ve and becomes more positive after feedback removed 3. No systematic relationship between force as a function of feedback 4. SD (PF) ↑ with PF (M) 5. SD (PF) ↑ when IOI length ↓

Paper	Paradigm	Summary of Task	Participants	Measurement	Results
Billon, Semjen & Stelmach (1996)	Tapping, synchronisation – repetition, no feedback, metronome	Match tapping (N=5) to metronome of 0.7 s and producing taps with accents at each tap position + without accent	8 (5*M*; 3*F*), M=25 y.o.	1. M(contact duration) 2. M(contact IRI) 3. M (PF) 4. M (Velocity) 5. M (Onset time) 6. M (time of 25%, 50%, 100% max velocity) 7. M (peak amplitude) 8. M (time to peak amplitude)	Contact IRI before accent shortened; after accent lengthened

Paper	Paradigm	Summary of Task	Participants	Measurement	Results
Keele, Ivry & Pokorny (1987)	Button press, synchronisation-continuation, visual feedback, metronome	1. Button press using forefinger and forearm to untimed force, timed force and max speed 2. Button press using forefinger and foot to untimed force, timed force and max speed 3. Button press sequence of 2 short + 1 long	1. 29 2. 29 3. 12	1. M (IRI) 2. SD (PF) & (IRI) 3. CC (PF & IRI)	1. Timing control correlates across effectors (common timing mechanism) 2. Similar PF variability for Exp 1 & 2 (common force mechanism) 3. Accent alters implementation and underlying time structure of sequence 4. Force and time are separable but interact 5. PF-IRI (CC) –ve at lag 0, +ve at lag 1

Paper	Paradigm	Summary of Task	Participants	Measurement	Results
Inui & Ichihara (2001)	Tapping, no feedback, metronome, oscilloscope	Match tapping to 0.18 / 0.20 / 0.40 / 0.80 s + peak force of 50 / 100 / 200 / 400 g without pacing or feedback	23 (10 pianists M=19.70 y.o.; 13 non-pianists M=20.23)	1. M (PF) & (IRI) 2. CV (PF) & (IRI) 3. R^2 (PF) & (IRI)	1. Independence under 0.40 / 0.80 s; co-variation under 0.18 / 0.20 s 2. SD (IRI) ↓ when PF ↑ 3. SD (IRI) ↓ when IRI length ↑ 4. NP: SD (PF) ↓ when IRI length ↓ 5. P: SD (PF) ↑ when PF magnitude ↓ 6. Change in IRI affected PF in NP but not P 7. Change in PF had no effect on IRI

Table 2: Summary of studies investigating force and timing control.

Notes: 1) *M*: male, *F*: female; **2)** IOI: Interonset interval, IRI: Interresponse interval, PF: Peak force; **3)** M: Mean, SD: Standard deviation, CV: Coefficient of variation; **4)** AC: Autocorrelation, CC: Cross-correlation, Coeff: Pearson correlation; **5)** P: Paced, NP: Not paced.

2.4.1.1 Motor sequences

Conclusions of interdependence between force and time have been made from studies mentioned above using paradigms of repetitive motor sequences involving synchronising to external cues (Sternad et al., 2000), synchronising to a pacing signal and continuation after the pacing signal is removed (Therrien & Balasubramaniam, 2010) or self-determination of pacing intervals and force magnitudes (Inui et al., 1998). Performance is evaluated using variability measures such as the standard deviation (SD) or coefficient of variation (CV) of peak force (PF) and interresponse intervals (IRI). These values, extracted from PF events, as well as from the interval which lapses between those events, provide a comparison of how consistent PF and IRI are produced over a period of time. Intervals between 180ms and 1000ms as well as forces between 0.5N and 15N have been studied. Despite the wide range of intervals and forces used with different methodologies, common observations include increased IRI variability with decreased PF magnitude (Inui & Ichihara, 2001; Sternad et al., 2000; Therrien & Balasubramaniam, 2010), decrease in PF variability with decreased IRI length (Sternad et al., 2000; Therrien & Balasubramaniam, 2010) and interaction effects in comparison of means (Inui et al., 1998; Therrien & Balasubramaniam, 2010). These systematic changes indicate a coupling which is consistently observable under different conditions.

2.4.1.2 Accents

One of the earlier works investigating the effect of force alteration on timing variation was done by Keele et al. (1987) who noted a decrease in the IRI length preceding a force accent and an increase in the subsequent IRI. Correlations between PF magnitudes and IRI variability also suggest a systematic effect of PF magnitude on time (Keele et al., 1987) attributed the relationship to a force specification process, which occurs during the implementation stage of the two-level timing model. Billon, Semjen, & Stelmach (1996) subsequently reproduced those previous findings and put forth an endpoint programming model which suggests a change in the underlying timing mechanism when a change in force is anticipated. This model further supports the notion of a two-level central and peripheral mechanism and introduced the possibility of force and time control interacting at the central level.

The studies mentioned above involved an increase of force at a particular position within a motor sequence. Questioning whether attenuation (decrease) of force would affect time intervals in the same way an accentuation would, Piek et al. (1993) had participants tap on a key with diminished force and decomposed the IRI into contact interval (finger touching the key) and non-contact interval (finger not in contact with the key) components. In both attenuation and accentuation conditions, contact interval length was observed to be a function of the force exerted on the tap. However, the increase in non-contact interval length which was consistent across conditions could not be attributed to any mechanical change of force. This suggested that cognitive programming of alteration of forces results in temporal changes instead of the physical execution of taps. These few examples point towards a change of force affecting the production of a time interval.

2.4.1.3 Neuropsychological evidence

Neuropsychological studies show that force and time control are affected in different ways in patients with Parkinson’s disease (Pope, Praamstra, & Wing, 2006). Assuming force and timing control share the same neural substrates, both processes are expected to deteriorate correspondingly in these patients and vice versa if the processes were independent. Pope, Praamstra, and Wing (2006) examined patients with Parkinson’s who were compromised in timing accuracy when asked to produce force pulses at alternating intervals (0.4 s and 0.8 s). They were most affected when force levels alternated as well (8 N and 16 N). In contrast, they were able to maintain high timing accuracy when the interval lengths were equal, and their timing was unaffected by changes in force levels. The authors suggested that such a preservation of timing could either be a result of a hierarchical motor programme in which timing prevails over force specification, or that patients prioritised timing over force accuracy.

2.4.2 Conditional interdependence

It has also been argued that the force-time interaction is conditional and takes place under fast-paced conditions with intervals below the range of 0.3 s (Inui et al., 1998; Inui & Ichihara, 2001). This was first observed when participants finger-tapped to their preferred pace, half the speed of the preferred pace, and double the speed of the preferred pace, combined with their preferred force, half, and double their preferred force (Inui et al., 1998). More positive and significant relationships between PF magnitudes and IRIs were found when participants tapped at double the pace of their preferred pace. This suggests a relationship between force and time which is dependent on the tapping pace. As a follow up, coupling a combination of time constraints (0.18 s, 0.20 s, 0.40 s and 0.80 s) with force constraints (50 g, 100 g, 200 g and 400 g), resulted in a larger number of occurrences of significant Pearson correlations between IRIs and PFs for 0.18 s and 0.20 s conditions, as compared to the 0.40 s and 0.80 s conditions (Inui & Ichihara, 2001).

2.4.2.1 Range of Measures

The emergence of correlations between PF and IRIs only at certain speeds points towards a relationship between force and time which is not always observable but depends upon certain constraints which could be mechanical or cognitive in nature (Inui & Ichihara, 2001; Sternad et al., 2000). Further support for independent control of time and force comes from measurements of coefficient of variation (CV). As yet, no study has explained the relative ease with which IRIs can be maintained, yielding CV values between 3-9%, in contrast with the higher variability of producing PFs (9-35%) (Sternad et al., 2000; Therrien & Balasubramaniam, 2010). If timing and force indeed share a same mechanism, a shared source of variance should account for a strong relationship between the accuracy of producing IRIs and PFs. However, this is neither consistently seen in Pearson correlations (Inui et al., 1998) nor in cross-correlation analyses of IRIs and PFs (Sternad et al., 2000).

This leads to the consideration of two points regarding measures which are taken into account within this thesis. Firstly, the study of a sequence of responses presents the need to examine force and timing measures as a continuous series as opposed to individual responses. The relationship between successive responses is an important consideration within the force and timing processes themselves and also for paired responses between each process. Therefore, an appropriate way of characterising the relationship would be to apply time series methods which include autocorrelation and cross-correlation analyses. These methods are utilised in this thesis.

The second point relates to the use of measures for defining force and timing parameters. IRIs (time between two motor events) are considered as the standard timing measure used by studies in the literature. Unlike previous studies which used PF associated with each tap following finger movement, this thesis uses PF events in isometric force pulses without finger movement. Since the motor delay in tapping includes movement time, the rise time in the force pulse is considered to be analogous to the movement time. The use of PFs in this way results in an event definition which is more like tapping, rendering the assumptions of existing timing models (e.g. the W-K model) more appropriate. The use of PFs as a timing event also provides comparable force and timing measures for cross-correlation analysis. Events in the timing time series (time between PF to PF) can then be directly related to events in the force time series (magnitudes of PF events which define time intervals). This method of defining both force and timing from the same event is preferable since the one and same event is used to obtain both measures.

2.5 Summary

In summary, although the nature of how force and timing control affect each other in repetitive motor sequences is unclear, there is general consensus amongst all the above mentioned studies which supports the notion of an interaction between force and timing control. However, four points of divergence emerge, the first of which is the theoretical model of how the interaction could be represented in the CNS. The second is where along the force and timing control mechanism processes does the interaction occur. The third point of divergence is whether the interaction is contingent upon mechanical or cognitive factors, and the fourth relates to neurological evidence indicating the different ways the brain engages in force and timing control.

Though certain observations of this interaction have been replicable over time, converging conclusions have yet to be drawn due to differences in: experimental paradigms (tapping / pulse production), protocols (synchronisation / synchronisation-continuation / self-paced), methodologies (presence of feedback / modalities of input / length of trials) , variables for analysis (peak force / peak rate of change of force / peak velocity / contact or non-interval), and analyses methods (comparison of means / regression / correlation).

Therefore, there is a need for further studies to be directed towards an integration of methods for a clearer conclusion about the nature of the interaction. This thesis aims to address the omissions identified above in the literature review by keeping the paradigm and measures constant. Pulse production is used for all experiments as it provides a measurement advantage. Force pulse traces have clear peaks for event detection and allow attribution of behaviour observed more directly to force and timing factors since it does not involve a spatial component. Synchronisation-continuation is the protocol of choice as it provides experimental control over the mean for each trial, reducing the risk of performance drift. Trials would last approximately 60 seconds each to provide a sufficient number of responses for analysis. Comparison of means is applied for analyses as guided by previous literature. In addition, time series analysis provides an approach to characterise changes in force-time relationship to complement the comparison of means. By holding these factors constant throughout the thesis, force-time interactions are then investigated in steady-state sequences, sequences with transitions, under dual-tasking conditions, and in patients with CVAs.

CHAPTER 3

FORCE-TIME INTERACTIONS IN STEADY STATE AND ACCENTED SEQUENCES

3.1 Abstract

Force-time interactions were investigated in steady-state pulse production sequences. It was hypothesised that interactions would be present in variability measures. Accented sequences were included for exploratory purposes. A robotic haptic device was used to present force and timing feedback as a way of standardising input. In a repeated measures design, eight healthy participants (7 female; 1 male) produced repetitive force pulses on a virtual wall using a robotic haptic device. Data from 50 s trials were collected from three tasks (1) steady state pulse production at different combinations of force levels (1.5, 2.0, 2.5 N) and time intervals (0.6, 0.8, 1.0 s), (2) steady state pulse production with force or timing prioritisation (target of 2 N; 0.8 s), and (3) accented sequence with four 2 N pulses followed by one 4 N pulse. Time series of peak force values (PF) and interresponse intervals (IRI) from the pulse production task were cross-correlated up to +/- 5 lags to determine co-variation between successive force and timing pairings in steady state sequences. Mean and variability measures were calculated for both steady state and accented sequences. Force-time interactions were found in force variability measures in task (1). Force-time correlations were reliably positive at lag 1 for task (2). Mean time interval length was shortened when preceded by an accented force in task (3). Interactions between force and time processes are present in different measures under certain task conditions. Therefore, the examination of mean and

variability measures, as well as co-variation measures is necessary to provide a comprehensive description of the relationship.

3.2 Introduction

Most intentional rhythmic or repetitive actions such as playing music, dancing, or typing, generally occur within a timeframe of less than one second per action (Buhusi & Meck, 2005). Despite the short time range, these actions demonstrate our remarkable ability to control and precisely execute movements over a sustained period of time. Successful achievement of a movement goal requires accurate temporal control, coupled with the appropriate scaling of force necessary to displace the limb and complete the action. For example, a pianist keeping a regular rhythm (fast or slow) while using the fingers to strike the keys of the piano with varying amounts of force to express the dynamics (loud or soft) of a piece of music.

A classic and frequently used task employed to investigate behaviours associated with short time intervals is the production of a series of repetitive actions, commonly finger tapping (Inui & Ichihara, 2001; Sternad et al., 2000), but also foot tapping (Keele et al., 1987) and grip pulses (Pope et al., 2006). Although rhythmic timing has been systematically studied since before the turn of the twentieth century (Stevens, 1886), timing control, until recently, has often been regarded as a component of motor control operating independently of force development and spatial factors. However, when timing and spatial factors were studied together, it emerged that spatial aspects of movement have a modulating effect on timing control (Bieńkiewicz, Rodger, & Craig, 2012) and so, we ask if such effects can be observed between force and timing control.

In an elegant series of experiments studying general factors in motor coordination between people, Keele, Pokorny, Corcos, and Ivry (1985) proposed a possible relationship between speed, timing and force control, viewing them as interrelated fundamental modules which operate on multiple tasks. The interaction between two of the modules, force and timing, was then further pursued in one of the earliest systematic investigations of repetitive rhythmic movement sequences using a correlational approach. In the study, Keele et al. (1987) found moment-to-moment correlations between force and timing by cross-correlating the two time series over five positive and five negative lags. This cross-correlation analysis allowed examination of not only the strength but also the direction of the relationship. The correlations at positive lags indexed a relationship where force leads timing, whereas at negative lags, timing leads force. The correlation Keele et al. (1987) observed at Lag 1 indicated that the variability of producing a force pulse was related to the variability of the time interval initiated by the force pulse (one interval is calculated as the time between two force pulses; one initiates and other terminates the interval). Interestingly, this correlation was present when timing control was the primary intent and force control was incidental; however there was no measurement for when force control was the primary intent.

A logical follow-up to the idea that intentional manipulation of time interval length leads to a change in force control is whether the relationship is bidirectional. Sternad et al. (2000) compared the effects of imposing different constraints on the production of force and time intervals. Participants were given either explicit timing constraints by prescribing target time intervals, explicit force constraints by prescribing target force levels, or constraints for both force levels and time interval lengths. Cross-correlation analysis was also applied; however no dependence between PFs and IRIs was reliably identified as only a small proportion of the entire dataset showed correlations at Lag 1. It was unclear if the absence of correlations in comparison with Keele et al. (1987) was due to differences in kinematic trajectories of the required task (button pressing compared to finger tapping) or task instructions (constraint of less than 14 N compared with self-selected force levels).

In addition to absent cross-correlations, Sternad et al. (2000) found that although the means of peak force magnitudes and interval lengths do not exhibit interactions, variability of force was observed to be lower at shorter intervals, and timing variability was lower at higher force levels. This led the authors to conclude that the temporal structure is affected by the magnitude of forces produced and therefore, timing in repetitive movements is not merely a timing problem. Although this method of analysis using comparison of means differed from that of Keele et al. (1987), it did support the finding that interactions between force and timing are present in variability measures.

The inconsistent findings in the literature mentioned above might be due to the use of different paradigms. Three methodological refinements are proposed in this experiment to provide standardised measures of comparison. Firstly, the one factor which has been singled out by authors as contributing to variable results in the literature is that of those related to space, for example, movement kinematics (Sternad et al., 2000), tapping trajectory (Billon, Semjen, Cole, & Gauthier, 1996), or changes in non-contact parameters of tapping (Piek et al., 1993). Therefore, the first goal was to exert greater experimental control over the measurement of force levels and time intervals by using a pulse production task instead of finger tapping. A force pulse is produced by pressing against a surface without lifting the finger so that neither force nor time is confounded with trajectory or kinematics. Interestingly, Elliott, Welchman, & Wing (2009) suggested that pulse production and finger tapping have similar timing variability and error correction profiles. However, using force pulses has a clear methodological advantage for reducing variability of peak force detection since a single finger tap produces multiple peaks due to the impact of the finger coming into contact with the force sensor surface. In contrast pulse production produces a force trace with clearly identifiable peaks (see Figure 9). For this reason, a pulse production paradigm was selected. Secondly, in previous studies, presentation of timing information during the synchronisation has always been auditory, while the force information has been visual. In this study, both force and timing standards provided were matched in sensory terms, using the haptic modality (tactile and proprioceptive). This novel procedure was delivered by a robotic haptic device, and provided a standardised and comparable input modality for the perception of both force and timing. In addition, the waveform of the input was a scaled signal of a recorded force pulse instead of a computer generated force signal to imitate the production of force as accurately as possible. Thirdly, from an analysis standpoint, both Keele et al. (1987) as well as Sternad et al. (2000) have noted that autocorrelations of PF time series remained positive over several lags. This suggests a possible drift within the series itself which could introduce a bias in the cross-correlation analysis. However, in both studies, it was unclear if any procedure was applied to render the series stationary before cross-correlating. Therefore, in the analysis of this study, the time series of PFs and IRIs were detrended by removing the line of best fit before using the residuals to estimate cross-correlations.

Utilising the methodology outlined above, the fundamental relationship between force and timing control was examined using pulse production behaviour over a range of different target force levels, target interval lengths, instructions, and equal force versus accented tapping sequences. Three tasks from the literature where force-time dependence have been reported were tested using the novel paradigm with haptic input. Two of the tasks involve steady state sequences, firstly, when both force and timing constraints are provided, and secondly, when either parameter is prioritised. The third task utilises accented sequences with a force increase. The purpose of testing three different tasks was to investigate whether the use of the haptic paradigm concurred with outcomes found in the literature.

In the first task, the relationship between force and time over a pre-determined range of force (1.5 N, 2.0 N, 2.5 N) and timing (0.6 s, 0.8 s and 1.0 s) constraints was explored. It was hypothesised that mean and variability measures of force and time would vary systematically. Both force and timing variability were expected to increase for higher force levels and at longer intervals however, variability of force would decrease at shorter intervals, and timing variability decrease at higher force levels, as observed by Sternad et al., (2000) in a finger tapping paradigm.

The second task, novel to this study, explored the effects of specific force instructions on timing performance, and vice versa. It was hypothesised that varying task instructions to prioritise either force or timing might change the nature of control behaviour and this would be reflected in changes of mean and variability measures. We expected the parameter participants were asked to focus on would be higher in accuracy and lower in variability. It was also predicted that prioritisation of one parameter over the other would also be observed as differences in lagged correlations. This means that when force accuracy was prioritised, there would be a Lag 1 correlation where force leads timing, while when timing accuracy was prioritised, there would be a Lag -1 correlation where timing leads force.

The third task involved producing sequences with a force accent. From the literature, it is noted that although the relationship between force and timing control is ambiguous in cross-correlations of sequences with equal force pulses, a different approach using sequences with a force accent clearly showed that force and time are directly intertwined. It is proposed that producing an increase in force introduces momentary changes in timing control. Billon, Semjen and their colleagues have repeatedly observed that the interval length preceding a tap more forceful than others in a sequence was always shortened, and the succeeding interval lengthened. This notable finding was demonstrated in patients lacking proprioceptive and tactile sensation (Billon et al., 1996), skilled musicians (Billon & Semjen, 1995), as well as healthy adults (Billon et al., 1996). This effect has also been reliably identified in both finger tapping (Billon et al., 1996; Billon & Semjen, 1995) and button press tasks (Keele et al., 1987), indicating that it is robust against any interactions with kinematic trajectories. Therefore, it is of interest to examine the sequences with a force accent using the novel paradigm in comparison with the effects reliably identified in other paradigms as a standard. We expect to replicate previous findings and observe a decrease in interval length immediately before a force accent and a lengthened interval after the accent.

3.3 Material and Methods

3.3.1 Participants

Eight participants took part in this study (7 female and 1 male, all right-handed), with a mean age of 30 years old (range 25 to 40 years). All participants provided informed consent to participate and reported no pre-existing motor conditions affecting their arm. Opportunity sampling was used and participants were provided the option of receiving either a standard participant fee of £6 per hour of participation or research credits via the School of Psychology Research Participant Scheme.

3.3.2 Apparatus

Force data were recorded from each participant using a 3 degrees-of-freedom haptic device (model PHANToM Premium 1.5, SensAble Technologies Inc., MA, USA). Participants interacted with the PHANToM by placing a finger into a thimble that was gimbal-mounted on the last link of the PHANToM's arm. A vertical virtual wall with a spring constant of 0.3 was programmed as a response surface. The PHANToM was controlled with Matlab (Mathworks, MA, USA) using the Haptik Library (Siena Robotics and Systems Lab, Siena, Italy). Force data were recorded at a rate of 1 kHz and saved on a PC via a PCI card. The PHANToM was calibrated before every experimental session by running the initialisation procedure to define the position of the origin (0, 0, 0).

3.3.3 Setup

Participants sat facing the PHANToM robot with their arm on a cushioned surface to provide adequate height for the arm to be in alignment with the PHANToM, and for comfort. The forearm was placed in the neutral position with the elbow flexed at right angles to the torso, for the right index finger to move freely in the horizontal plane (see Figure 5). The right index finger was then placed into the thimble and padding was used when necessary to hold the finger in place within the thimble-gimbal.

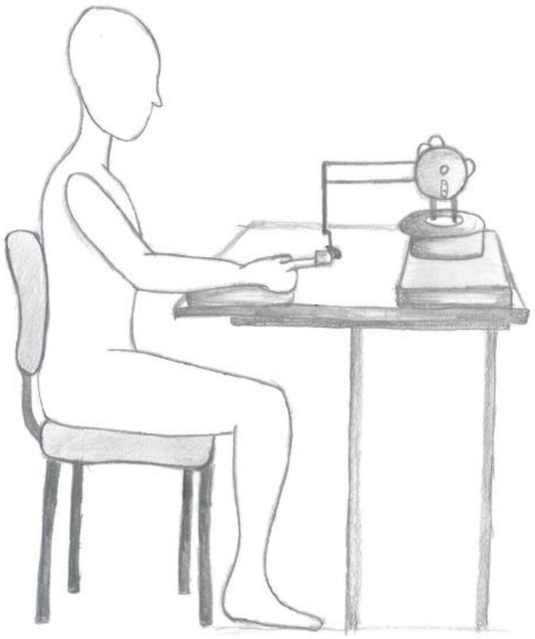

Figure 5: Participants sat facing the PHANToM robot with their right index finger in the thimble.

3.3.4 Task

The task involved repetitively responding to produce a series of 50 force pulses by pressing against the virtual wall (see Figure 6) at different combinations of force levels (1.5 N, 2.0 N, 2.5 N) and time intervals (0.6 s, 0.8 s and 1.0 s). In the accented condition, four 2 N pulses were followed by one 4 N pulse at interval lengths of 0.6 s, 0.8 s and 1.0 s. There were two phases in each trial. Firstly, a paced phase at the beginning of each trial provided experimental control over the mean force and time interval, during which participants were instructed to hold their finger still against a total of 10 force pulses applied by the PHANToM. Secondly, after the paced phase stopped, participants were instructed to continue responding at the same rate and force level by pressing against the virtual wall, for the remainder of the trial. The task was performed with eyes closed to minimise any visual anchoring, such as the angular displacement of the finger, which might be used as a cue for determining responses instead of relying on haptic feedback.

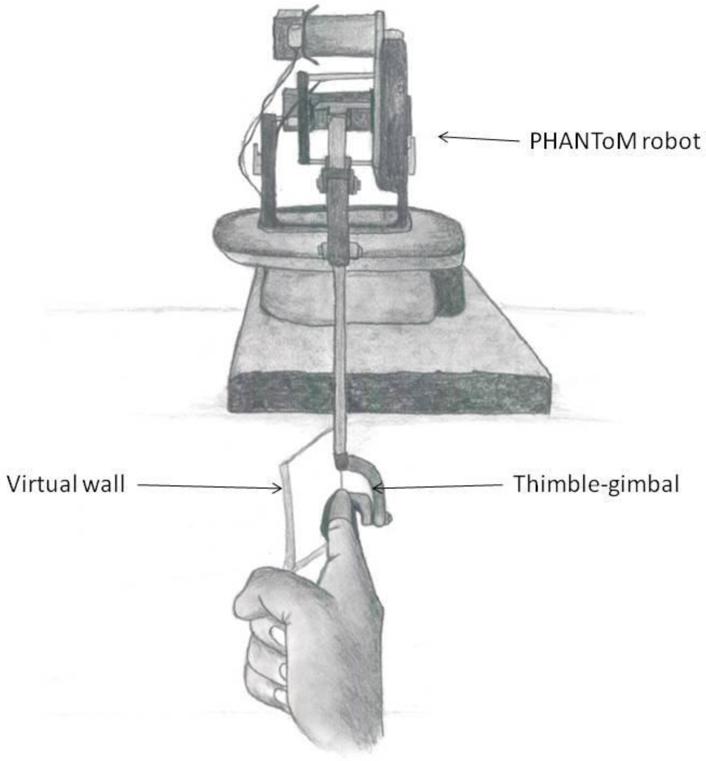

Figure 6: The PHANToM generates forces if the position of the thimble-gimbal goes beyond a pre-determined boundary. The magnitude of forces applied by the PHANToM is equal to those applied by the participant to bring the thimble-gimbal beyond the wall's boundary, in the opposite direction.

3.3.5 Procedure

Participants were presented with a minimum of three practice trials before data were recorded (more than three if requested). During the experimental trials, six blocks of 18 trials were presented to each participant.

The first three blocks consisted of a combination of a constant force level at three different interval lengths. The force levels used were 1.5 N, 2.0 N, and 2.5 N, whereas the target interval lengths were 0.6 s, 0.8 s and 1.0 s, to yield data fitting a 3-by-3 matrix. Participants were instructed: “Please reproduce both the timing and force of the pulse you felt as accurately as possible” (see Figure 7a, Figure 8a).

In the fourth block, participants were asked: “Please reproduce the timing of the pulse you felt as accurately as possible”. This block used time intervals of 0.6 s, 0.8 s and 1.0 s at the force level of 2.0 N. In the fifth block, participants were asked: “Please reproduce the force of the pulse you felt as accurately as possible”. The force levels used were 1.5 N, 2.0 N and 2.5N at the time interval of 0.8 s (see Figure 7b).

In the last block, participants were asked to produce a continuous sequence of four 2 N pulses followed by one 4 N pulse at interval lengths of 0.6 s, 0.8 s and 1.0 s with instructions to “Please reproduce both the timing and force of the pulse you felt as accurately as possible” (please see Figure 8b). The presentation order of the blocks was randomised for each participant prior to the experiment and data from six repetitions were collected for each condition.

a)

	1.5 N	**2.0 N**	**2.5 N**
0.6 s	🟥	🟥	🟥
0.8 s	🟥	🟥	🟥
1.0 s	🟥	🟥	🟥

b)

	1.5 N	**2.0 N**	**2.5 N**
0.6 s		🟨	
0.8 s	🟨	🟨	🟨
1.0 s		🟨	

Figure 7: Participants reproduced combinations of force and timing targets **(a).** The instructions were varied for two conditions **(b)** where participants either “reproduce the force of the pulse as accurately as possible” or “reproduce the timing of the pulse as accurately as possible”.

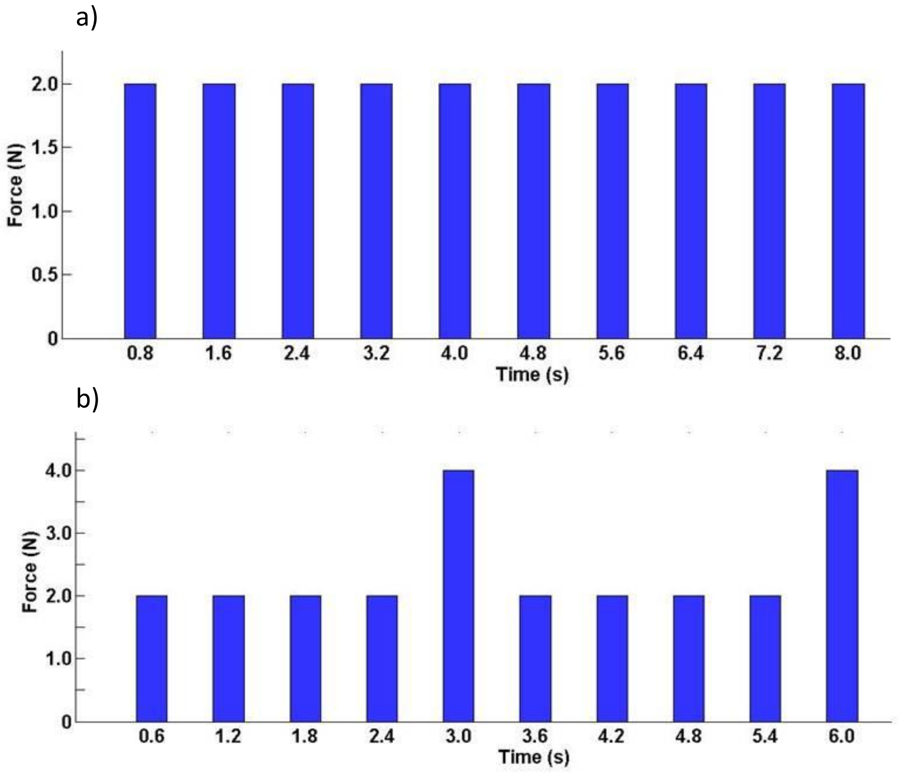

Figure 8: A representation of data for a 2.0 N force target and 0.6 s timing target **(a)** and an accented trial of four 2.0 N pulses followed by one 4.0 N pulse at 0.6 s intervals **(b).**

3.3.6 Analysis

A peak detection algorithm, (“peakdet”) written in Matlab (Billauer, 2012), was applied to the force signal to obtain a time series of local maximum responses and the time that each of those occurred. The algorithm defines a maximum by comparing if the value prior to the current point is larger than a threshold which is entered as an argument (DELTA). The peaks were plotted on the signal for checking visually and DELTA was adjusted to ensure all events of interest (PFs) were included, thus avoiding false detections. The time of the peaks was then differenced to yield the IRI between successive pairs of responses (see Figure 9). Subsequently, trial means (M) of PFs and IRIs were obtained and averaged across participants by condition. Variability measures computed included the standard deviation (SD) and coefficient of variation (CV). The first five responses from every trial were discarded to ensure that any transient effects on force and timing production resulting from the transition from synchronisation to continuation phase were excluded from analysis. This meant that on average, there were approximately 330 data points per participant for every combination. Datasets were subjected to repeated measures 3 (time intervals: 0.6 s, 0.8 s and 1.0 s) x 3 (force levels: 1.5 N, 2.0 N, 2.5 N) analysis of variance (ANOVA) using IBM SPSS Statistics for Windows, Version 21.0 (Armonk, NY: IBM Corp). Where Mauchly’s Test of Sphericity was significant, Hyunh-Feldt corrected values are reported if epsilon, ε >.75, and Greenhouse-Geisser corrected values are reported if ε <.75. On non-accented trials, autocorrelation analysis was applied individually on mean PF and IRI, and cross-correlations between both parameters were calculated.

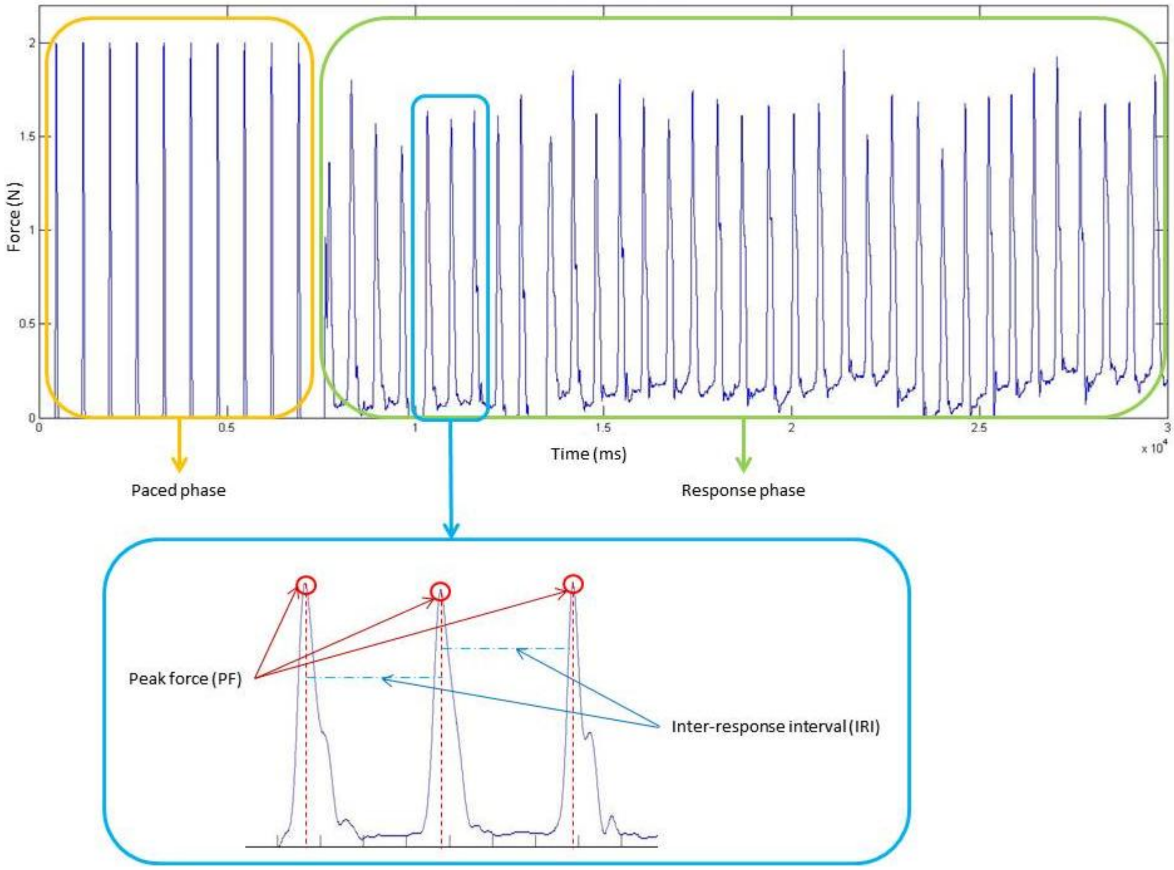

Figure 9: Sample of raw data from a single trial. Peak forces are defined as the maximum values of each force spike and IRIs are time intervals between two successive PF occurrences.

3.4 Results

To give a general sense of overall performance, descriptive statistics are first presented. Then, correlations between measures are analysed.

3.4.1 Interresponse intervals

The target interval lengths were 0.6 s, 0.8 s and 1.0 s (denoted by red lines in Figure 10) and participants accurately reproduced the intervals. In general, variability (SD) increased with mean interval.

IRI Mean

There was a significant main effect of interval length on mean IRI, *F*(2,80) = 363.448, *p*<.001. Paired comparisons revealed significant differences for nine comparisons (see Figure 10 and Appendix for statistical results). The IRI means (and SD) for the 1.0 s condition [(1.5 N = 0.915 s (0.109 s); 2.0 N = 0.955 s (0.094 s); 2.5 N = 0.951 s (0.100 s)] were longer than the 0.8 s condition [(1.5 N = 0.773 s (0.075 s); 2.0 N = 0.812 s (0.062 s); 2.5 N = 0.802 s (0.109 s)]. The shortest IRI means were from the 0.6 s condition [(1.5 N = 0.646 s (0.065 s); 2.0 N = 0.646 s (0.064 s); 2.5 N = 0.625 s (0.052 s)]. There was no main effect of force targets *F*(2,80)=3.752, *p*=.280. Interaction effects between interval length x target force were also not significant *F*(4,160)=1.737, *p*=.149 (see Figure 10).

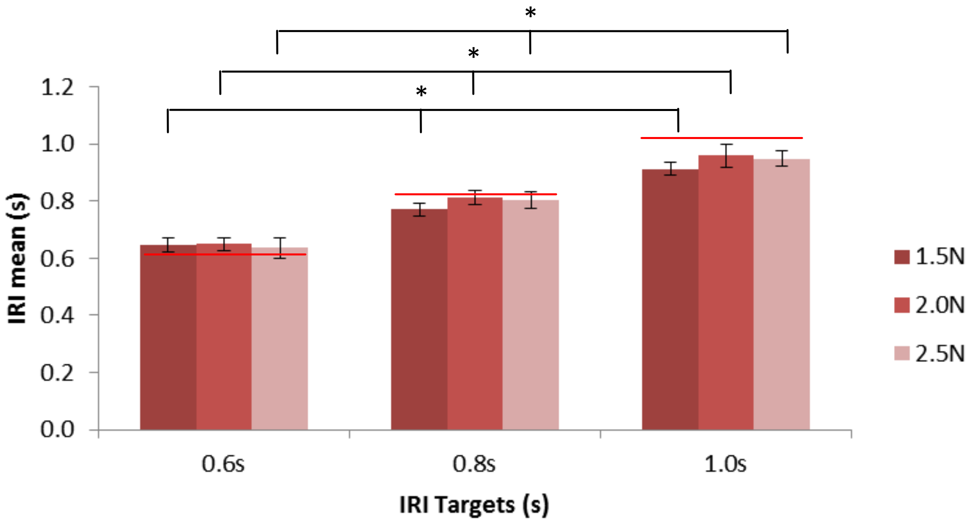

Figure 10: Means of IRIs at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N (red horizontal bars). Error bars are standard errors of the mean. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

IRI Variability

Standard Deviation

There was a significant main effect of interval length on IRI SD *F*(2,82) = 75.906, *p*<.001, but not force targets *F*(2,82)=2.937, *p*=.670 or interval x force targets interaction effects, *F*(4,164)=.855, *p*=.474 (see Figure 11). Paired comparisons revealed significant differences in seven comparisons (see Figure 11 and Appendix for statistical results). Variability (SD) was highest during the 1.0 s condition for all force levels [(1.5 N = 0.690 s (0.019 s); 2.0 N = 0.612 s (0.020 s); 2.5 N = 0.070 s (0.035 s)], followed by the 0.8 s condition [(1.5 N = 0.051 s (0.018 s); 2.0 N = 0.050 s (0.015 s); 2.5 N = 0.048 s (0.018 s)]. Variability was lowest in the 0.6 s condition [(1.5 N = 0.045 s (0.021 s); 2.0 N = 0.036 s (0.011 s); 2.5 N = 0.040 s (0.014 s)].

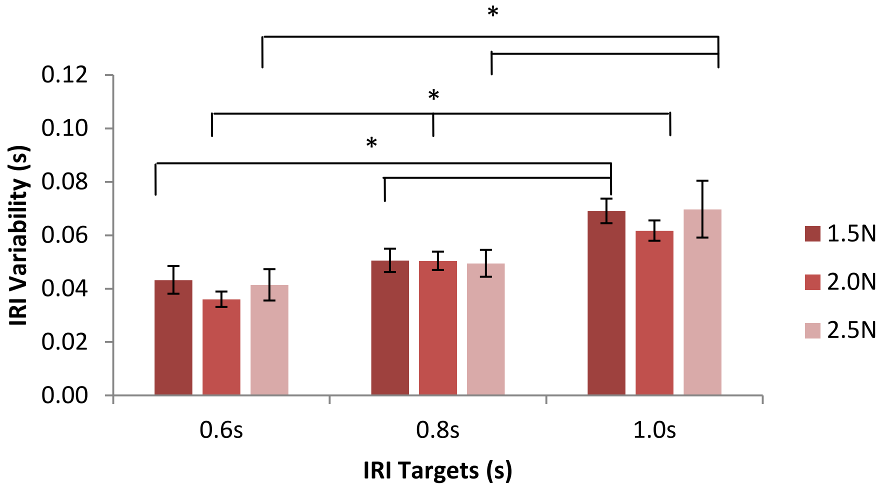

Figure 11: SD (IRI) at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N. Error bars are standard errors of the SD. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

Coefficient of variation (CV)

There were significant main effects of interval length *F*(2,82) = 6.880, *p*=.002, and force target *F*(2,82)=5.702, *p*=.008, on IRI CV. Paired comparisons revealed significant differences in two comparisons (see Figure 12 and Appendix for statistical results). However, interaction effects were not significant *F*(4,164)=1.043, *p*=.377 (see Figure 12). CV (SD) during the 1.0 s condition [(1.5 N = 0.076 (0.022); 2.0 N = 0.065 (0.021); 2.5 N = 0.073 (0.033)] was higher than during the 0.8 s condition [(1.5 N = 0.066 (0.023); 2.0 N = 0.062 (0.017); 2.5 N = 0.059 (0.017)] and in the 0.6 s condition [(1.5 N = 0.067 (0.030); 2.0 N = 0.054 (0.015); 2.5 N = 0.065 (0.025)].

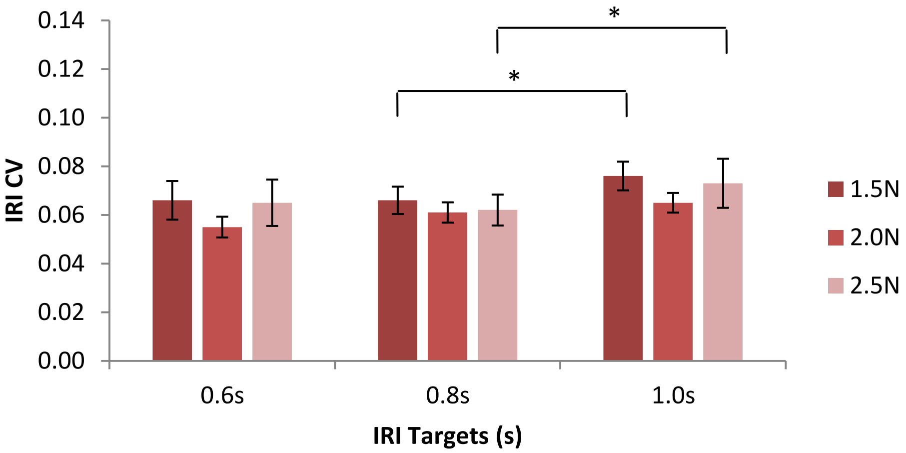

Figure 12: Means of IRI CV at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N. Error bars are standard errors of the CV. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

3.4.2 Peak Force

The target force values were 1.5 N, 2.0 N, and 2.5 N (denoted by red lines in Figure 13). In general, participants overestimated the force values for all targets.

PF Mean

A significant main effect of target force *F*(2,82) = 66.721, *p*<.001 indicated that participants differentiated the levels of force. Paired comparisons revealed significant differences in seven comparisons (see Figure 13 and Appendix for statistical results). PF mean (SD) was highest during the 2.5 N condition for all interval lengths [(0.6 s = 2.840 N (0.674 N); 0.8 s = 2.621 N (0.734 N); 1.0 s = 2.787 N (0.811 N)], followed by the 2.0 N condition [(0.6 s = 2.495 N (0.588 N); 0.8 s = 2.609 N (0.579 N); 1.0 s = 2.758 N (0.833 N)], and lowest in the 1.5 N condition [(0.6 s = 1.892 N (0.411 N); 0.8 s = 1.044 N (0.496 N); 1.0 s = 1.917 N (0.573 N)]. There were no significant main effects for interval length *F*(2,82)=.498, *p*=.610 or interval x force interaction effects *F*(4,164)=2.328, *p*=.074 (see Figure 13).

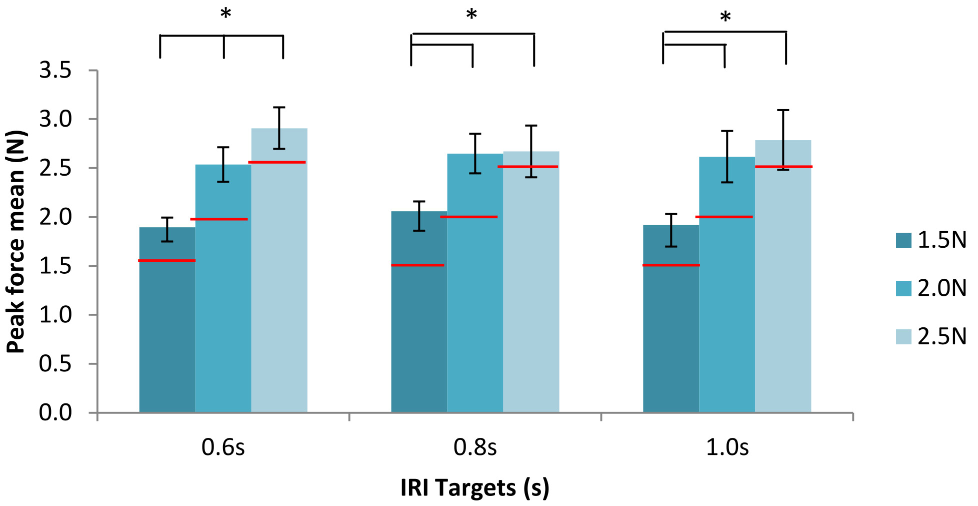

Figure 13: Means of PFs at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N (red horizontal bars). Error bars are standard errors of the mean. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

PF Variability

Standard Deviation

There was a significant main effect of force target *F*(2,82) = 35.263, *p*<.001 as well as interval length x force target interaction effects *F*(4,164) = 4.430, *p*=.002. Paired comparisons revealed significant differences in seven comparisons (see Figure 14 and Appendix for statistical results). The main effect of interval length was not significant, *F*(2,82)=1.886, *p*=.158 (see Figure 14). Force variability (SD) increased with increasing interval length during the .5 N condition [0.6 s = 0.185 N (0.056 N); 0.8 s = 0.191 N (0.074 N); 1.0 s = 0.208 N (0.077 N)]. This trend was similar for the 2.0 N and 2.5 N conditions when the interval length was 0.6 s [2.0 N = 0.249 N (0.083 N); 2.5 N = 0.309 N (0.111 N)] and 0.8 s [2.0 N = 0.267 N (0.081 N); 2.5 N = 0.244 N (0.075 N)]. However, in the 1.0 s condition, variability did not increase further [2.0 N = 0.287 N (0.092 N); 2.5 N = 0.269 N (0.094 N)].

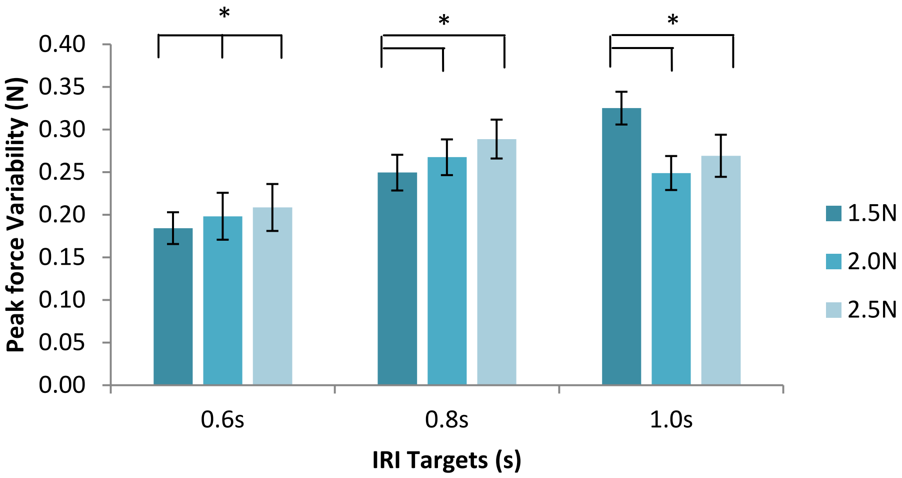

Figure 14: Means of PF variability (SD) at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N. Error bars are standard errors of the SD. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

Coefficient of variation (CV)

There was a significant interaction effect of interval length x force target *F*(4,164) = 2.625, *p*=.037, but main effects were not significant for both interval length *F*(2,82)=1.995, *p*=.143 and force target *F*(2,82)=2.625, *p*=.876 (see Figure 15). Paired comparisons revealed significant differences in one comparison (see Figure

15 and Appendix for statistical results). There were no differences in CV (SD) between the 1.5 N condition [0.6 s = 0.100 (0.025); 0.8 s = 0.093 (0.026); 1.0 s = 0.111 (0.033)], 2.0 N condition [0.6 s = 0.100 (0.030); 0.8 s = 0.103 (0.027); 1.0 s = 0.104 (0.026)], and 2.5 N condition [0.6 s = 0.111 (0.037); 0.8 s = 0.098 (0.030); 1.0 s = 0.100 (0.031)].

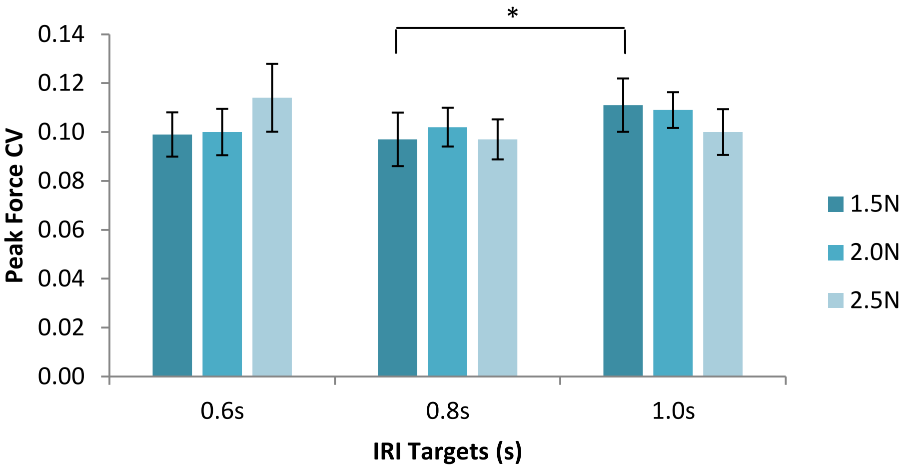

Figure 15: Means of PF CV at timing targets of 0.6 s, 0.8 s and 1.0 s in combination with force targets of 1.5 N, 2.0 N, and 2.5 N. Error bars are standard errors of the CV. Significant paired t-test comparisons between successive responses are indicated with *, Bonferroni correction, *p* = .025.

3.4.3 Comparison between instructions

Two experimental blocks were performed with instructions to focus only on producing either force or time intervals as accurately as possible. In comparison with blocks where participants were asked to focus on both timing and force accuracy, there was no difference in performance for PF and IRI in Ms, SDs, and CVs, regardless of instructions given.

3.4.4 Cross-correlations

Cross-correlation analysis was run on the time series of IRIs and PFs from lags -5 to 5, to determine whether any relationship between IRIs and subsequent PF levels was present. Within the time series of IRIs and PFs, there are N+1 number of PFs for every N number of IRIs since each interval is calculated as the time difference between two PF events. Therefore, we excluded the first PF in every series to equalize the length of both series. This meant that Lag 0 each pair of IRI and PF values referred to the interval leading up to the PF and the PF which terminated the interval.

Before the PF and IRI series were cross-correlated, they were individually autocorrelated to examine the dependence within the series. The autocorrelation functions (ACF) for both peak forces and time intervals remained positive over lags 1 to 5 reflecting a relationship between successive responses as a function of time lags, indicating non-stationarity within the series (see Figure 16). Since this would introduce a bias in cross-correlations, the trends in both series were removed by subtracting the linear line-of-best-fit calculated using the ‘Detrend’ function in Matlab. Cross-correlation functions were then calculated with the residuals of both series (see Figure 17 for detrend details).

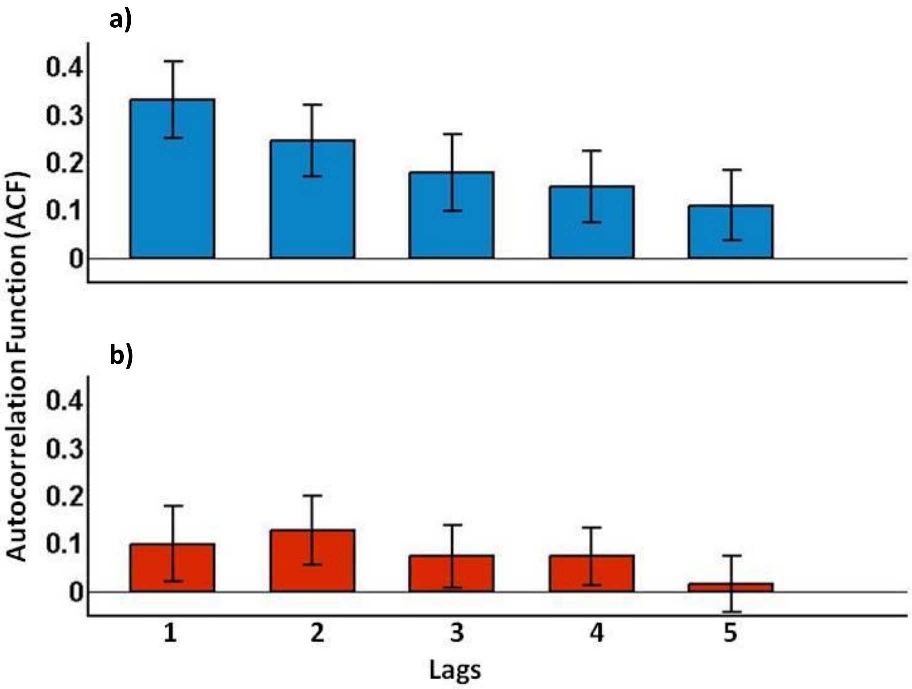

Figure 16: Autocorrelation functions for force pulses (a) and IRIs (b) collapsed across conditions focusing on both force and timing accuracy. Error bars represent ±1 standard error (SE).

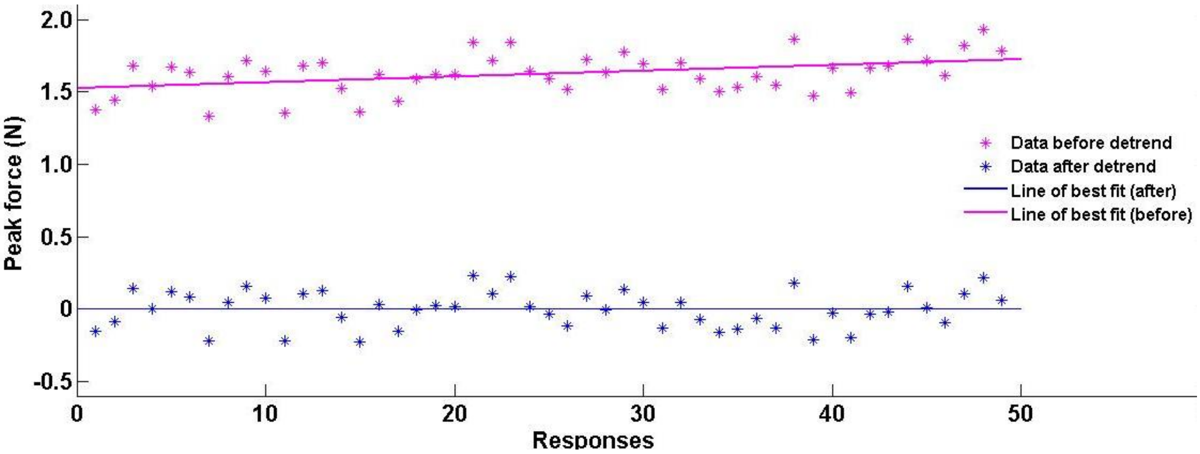

Figure 17: Example of peak force data from one trial before and after the line of best fit was removed.

Cross-correlations of the discrete events of IRIs and PFs were then calculated from -5 up to 5 lags according to Equation (6) below as defined by Matlab, where x = IRI; y = peak forces; m = lags; μ_x = mean of x; μ_y = mean of y; E = expected value operator; and, asterisk (*) denotes complex conjugation.

$$\emptyset_{xy}(m) = E\left\{\left(x_{n+m} - \mu_x\right)\left(y_n - \mu_y\right)^*\right\} \tag{6}$$

Therefore, at negative lags, the IRI is considered to lead PFs, and at positive lags, the IRI lags behind PFs. In trials where participants focused on both timing and force accuracy, independent t-tests indicated that the cross-correlations functions from -5 up to 5 lags were found to be no different from 0 (see Figure 18 and Appendix for statistical results).

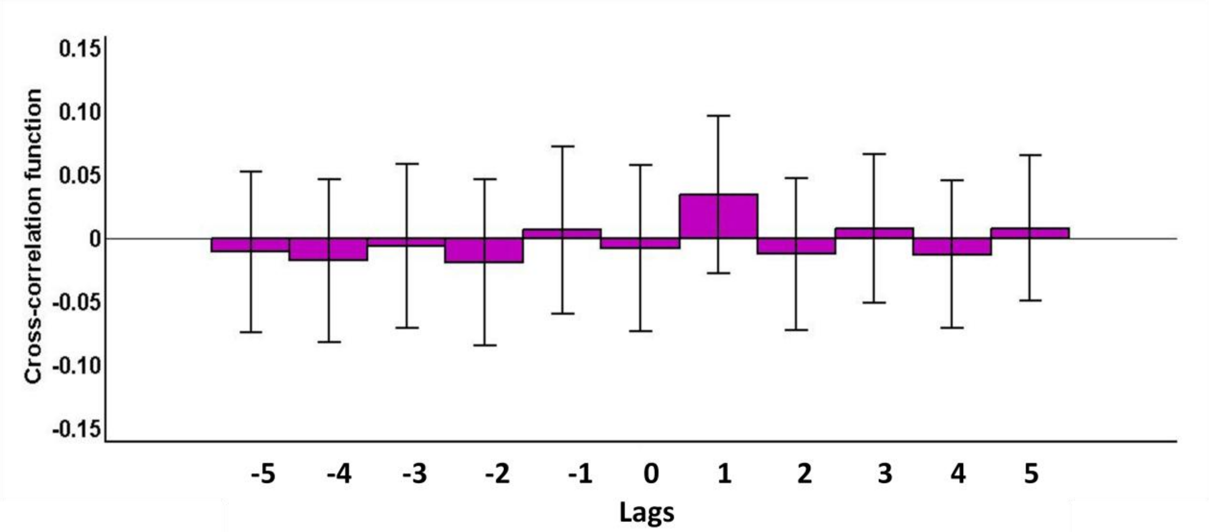

Figure 18: Cross-correlation functions between IRIs and PFs collapsed across conditions focusing on both force and timing accuracy. Error bars represent ±1 SE.

However, the cross-correlation functions under instructions to focus only on timing accuracy showed a strong positive lag 1 trend (see Figure 19a) at all three timing intervals, two of which were significantly different from 0 [0.8 s, t(14)=2.924, *p*=.011; 1.0 s, t(14)=4.069, *p*=.001]. This trend was also observed when participants concentrated on force accuracy; it was significantly different from 0 for the 1.5 N [t(14)=2.160, *p*=.049] and 2.5 N [t(14)=2.163, *p*=.048] conditions (see Figure 19b).

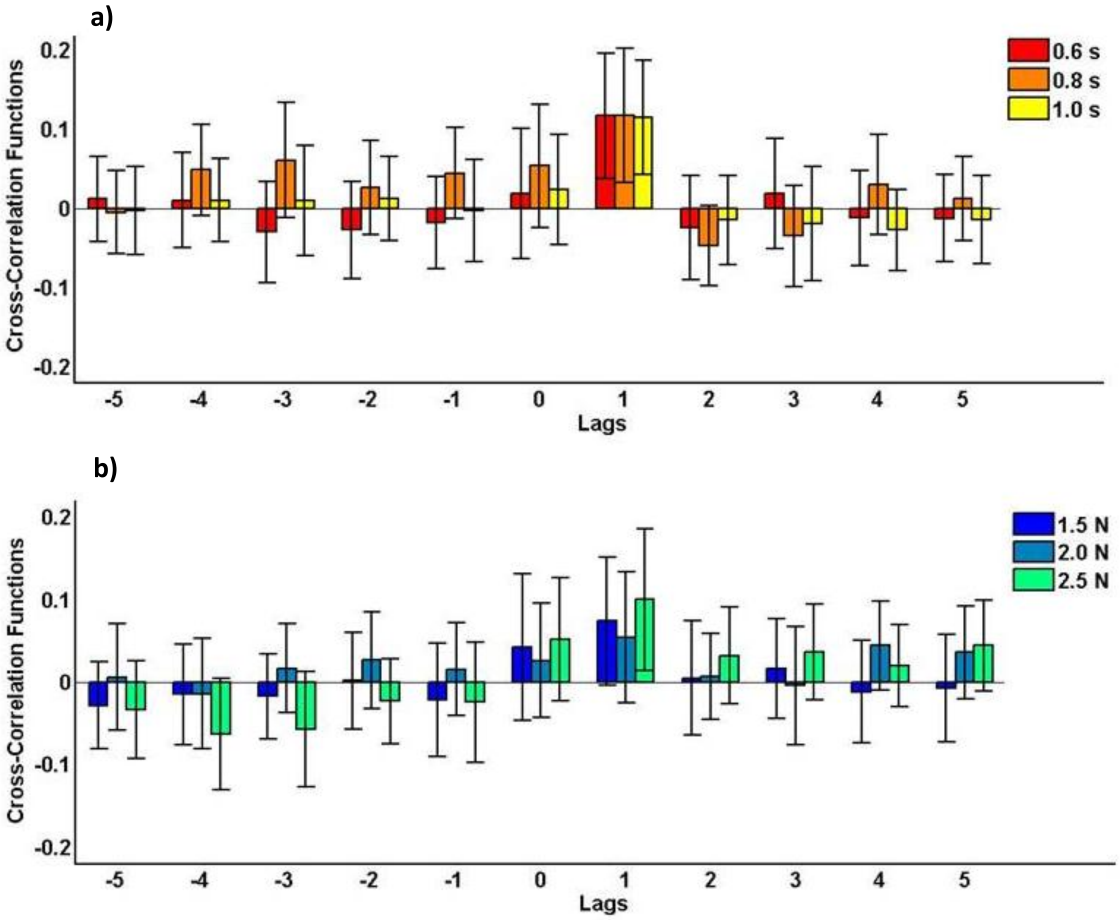

Figure 19: Cross-correlation functions of conditions where timing accuracy was prioritised (a) and force accuracy was prioritised (b). Error bars represent ±1 SE.

3.4.5 Accented Trials

In the accented trials, participants were required to produce repetitive cycles of four 2 N pulses followed by one 4 N pulse at interval lengths of 0.6 s, 0.8 s and 1.0 s. Each cycle yielded five PF values and four IRI values. However, in the following figures, six PF and five IRI values are included, the additional values being the PF and IRI immediately following the accent. PF and IRI values for each cycle were averaged by trial across participants. Overall, participants consistently overshot the 2 N target but were accurate for the accented 4 N pulse (see Figure 20 and Table 3).

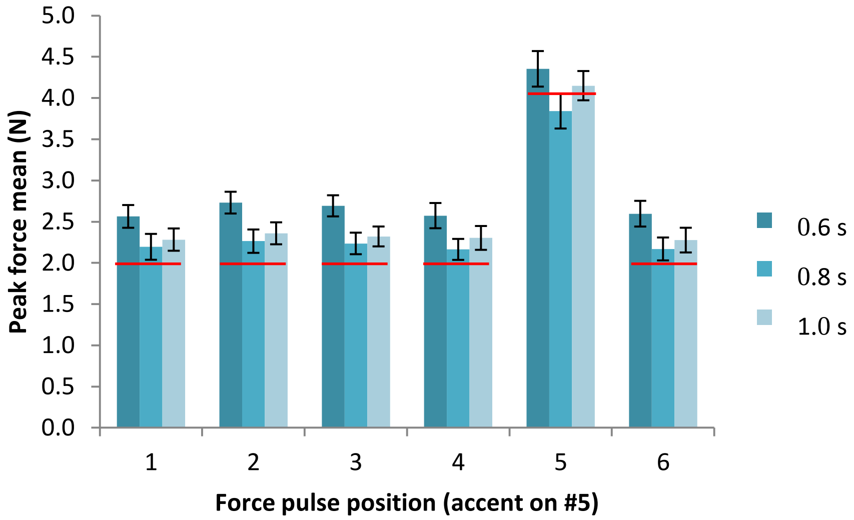

Figure 20: Means of PF at force target of 2.0 N for unaccented pulses and 4.0 N for the accented pulse (red horizontal bars), and timing targets of 0.6 s, 0.8 s and 1.0 s. Error bars are standard errors of the mean.

	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
0.6 s	2.564 (0.309)	2.731 (0.300)	2.692 (0.287)	2.573 (0.342)	4.354 (0.482)	2.597 (0.348)
0.8 s	2.195 (0.351)	2.263 (0.317)	2.236 (0.131)	2.164 (0.128)	3.841 (0.472)	2.597 (0.311)
1.0 s	2.282 (0.303)	2.359 (0.298)	2.321 (0.270)	2.303 (0.323)	4.150 (0.397)	2.276 (0.335)

Table 3: Mean (SD) PF values (N) corresponding to Figure 20.

The IRIs were accurately reproduced at 0.6 s, 0.8 s and 1.0 s target interval lengths. However, there was a deviation in the 1.0s condition where all participants underestimated the interval length. The fifth IRI in the cycle (interval immediately succeeding the accented pulse) was observed to be lengthened for all interval lengths (see Figure 21 and Table 4).

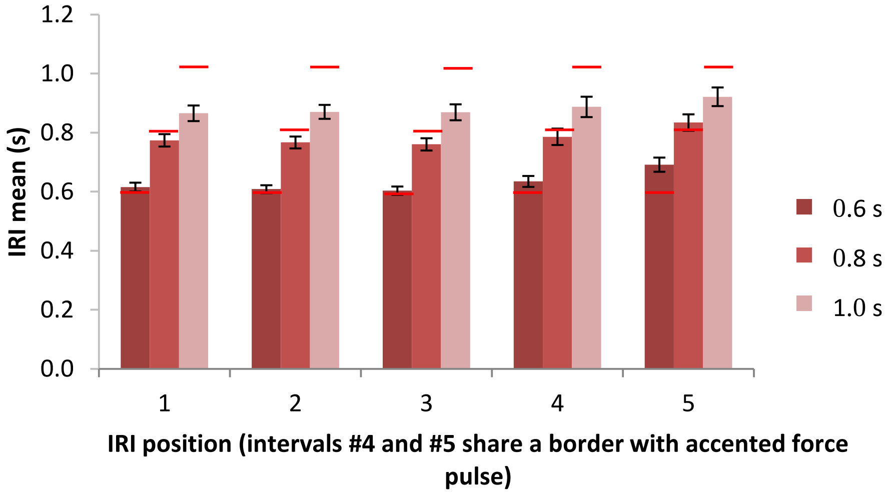

Figure 21: Means of IRI for accented trials at timing targets of 0.6 s, 0.8 s and 1.0 s (red horizontal bars). Error bars are standard errors of the mean.

	Position 1	**Position 2**	**Position 3**	**Position 4**	**Position 5**
0.6 s	0.616 (0.032)	0.608 (0.030)	0.603 (0.031)	0.635 (0.041)	0.691 (0.054)
0.8 s	0.774 (0.047)	0.767 (0.045)	0.760 (0.046)	0.786 (0.062)	0.834 (0.062)
1.0 s	0.865 (0.059)	0.870 (0.053)	0.869 (0.060)	0.887 (0.077)	0.921 (0.071)

Table 4: Mean (SD) IRI values (s) corresponding to Figure 21.

Paired T-test comparisons were calculated between all combinations of intervals. The fifth IRI was found to be significantly longer compared with IRIs at other positions, except the fourth IRI. At target interval lengths of 0.6 s and 0.8 s conditions, the fourth IRI was also significantly different from the first to third IRIs. However, this was not true for the 1.0 s condition (see Table 5).

	0.6 s					**0.8 s**					**1.0 s**				
	IRI 1	**IRI 2**	**IRI 3**	**IRI 4**	**IRI 5**	**IRI 1**	**IRI 2**	**IRI 3**	**IRI 4**	**IRI 5**	**IRI 1**	**IRI 2**	**IRI 3**	**IRI 4**	**IRI 5**
IRI 1		0.051	0.097	0.018	‡<.001		0.438	0.136	‡<.001	‡<.001		0.811	0.806	0.918	‡0.001
IRI 2			0.793	‡0.003	‡<.001			0.207	‡<.001	‡<.001			0.966	0.994	‡0.001
IRI 3				‡0.005	‡<.001				‡<.001	‡<.001				0.99	‡0.001
IRI 4					0.034					0.986					0.05

‡ Significant at *p*<.0125 (Bonferroni corrected *p* value for four comparisons per dataset).

Table 5: Significance levels of paired-t-test comparisons between all combinations of intervals.

3.5 Discussion

In producing repetitive movements, timing and force information are combined to produce movements spaced between time intervals. These two parameters produce a single end result, but to what extent are their processes dependent on or independent of each other? The present chapter introduced a novel pulse production paradigm with haptic input for examining correlations between force and timing control. This provided both force and timing information through the same sensory modality. Using this paradigm, three aims were addressed. Firstly, the effects of imposing force and timing constraints on PF and IRI measures were examined. When participants produced force pulses at combinations of different force level and time interval targets, we expected mean and variability measures of force and time to vary systematically. Secondly, the effect of different task instructions on force and timing control was explored. When participants produced force pulses under different instructions, changes in control behaviour as reflected in mean and variability measures, as well as cross-correlations were expected. Thirdly, the effect of producing accented force pulses on time intervals in this novel paradigm was characterised. A shortening of time interval preceding the force accent and lengthened interval after the accent was expected. These are three tasks in which force-time interactions have been found in previous studies and will be discussed below in the context of this experiment.

Effects of Force and Timing Constraints

Overall, a systematic relationship between force and timing was observed in timing variability (SD), where the variability increased with increasing force levels.

Force variability was observed to be lowest at the shortest interval, however, variability between the other two interval lengths were found to be similar. Both force and timing CVs remained consistent across all force levels and time interval lengths. Participants were highly accurate in producing the required time intervals, although peak forces were overestimated by 11% to 30%. As predicted, IRI variability was higher at longer interval lengths. Peak force variabilities, however, did not increase with increasing force levels. This observation is in contrast with both Sternad, Dean and Newell (2000) as well as Keele, Ivry and Pokorny's (1987) findings, nonetheless, it is noted that the force levels recorded in this study are at least 50% lower than previous studies and this could have contributed to the differences. Interestingly, timing variability (SD) did not decrease at higher force levels, but instead increased linearly with increasing force levels.

In the mean IRI and PF data, there were no interaction effects between time intervals and force levels. Only the force targets had an effect on PFs produced, and only the timing targets had an effect on IRIs. Firstly, this meant that participants were producing three distinct peak forces and the different forces did not affect interval length. Secondly, participants were accurately producing three distinct interval lengths and this was not related to peak force levels. Taken together, this supports a non-systematic relationship between force and time consistent with Sternad, Dean and Newell (2000) as well as Keele, Ivry and Pokorny (1987). Interaction effects were present in the variability measures of SD and CV, but only in PFs and not IRIs. Given that the interaction was observed in only the force measures, it is plausible to suggest that the relationship between force and timing control could be one which is hierarchical, with one controller being subordinate to the other. This possibility has also been raised by Repp (2000). One final observation was that force targets had an effect on IRI variability, as observed in the normalised CV measure. This finding is again consistent with Sternad, Dean and Newell (2000). In summary, the relationship between force and timing control is present in variability measures and the findings from the pulse production paradigm used in this study concur with those using a finger tapping task (Sternad, Dean & Newell, 2000).

Effects of Varying Instructions

Surprisingly, there were no differences in comparisons of M, SD, and CV of force and timing data under instructions to prioritise force, timing, or both. Participants maintained all measures consistently across conditions of prioritising only force or only timing accuracy, as well as both force and timing accuracy. In contrast, this was not the case in moment to moment variations identified by cross-correlation analysis. Before cross-correlating the PF and IRI time series, both series were individually autocorrelated to identify any dependencies within each individual series. Autocorrelation functions of the PF time series remained positive up to four lags indicating a persistent trend in the series where a large force pulse tends to be followed by a few large force pulses, and vice versa. This pattern of autocorrelation in the current study was also reported by Keele et al. (1987) as well as Sternad et al. (2000) who suggested that this dependence would reduce the correlation of force with the successive IRIs. Therefore, the series were detrended before cross-correlating. Detrending was also applied to the IRIs.

The cross-correlation functions showed the absence of any interactions between PFs and IRIs when both force and timing accuracy were given equal priority. However, when timing accuracy was given priority, a numerically small but significantly positive Lag 1 correlation was observed. The magnitude of the coefficient was similar to the value reported by Keele et al. (1987) when a timing goal was imposed but no force level was specified. It is clear that directing attention to prioritise one factor or another changed control behaviour. Given that significant cross-correlations were generally not found between PFs and IRIs (Sternad et al., 2000), it is highly likely that the positive lag 1 correlation reported by Keele et al. (1987) was a result of focusing attention on timing precision since no explicit instructions were given to participants regarding the amount of force. However, the position of the correlation at the positive lag suggests that force was leading time, even though the task instruction was to prioritise timing. Interestingly, when force accuracy was prioritised, the same trend of a positive Lag 1 correlation was observed. The cause and direction of the observed pattern cannot be adequately addressed in this study but taken together, it is proposed that there is perhaps a factor which is modulating the relationship between force and timing when attention is given to one parameter over the other. Since the differences lie in an intentional top-down modulation, it strongly suggests an interaction which is mediated by cognitive factors. This is further explored in the following chapters using a dual-tasking paradigm.

Sequences with Accented Force Pulses

In addition to producing sequences of equal force and equal time intervals, participants also produced sequences of pulses with a force accent at every fifth pulse. PFs for all pulses except the accented pulse were not significantly different from each other. The intervals between pulses were observed to be not equal. The interval immediately following the accented pulse was lengthened. Most notably, Billon and Semjen (1995) also reported the shortening of the interval preceding the accented tap in un-paced tapping which was not present in tapping to metronome. They attributed this finding to a lack of information about timing performance leading to a partial failure of compensating for an upcoming perturbation created by the accent. The metronome then removes this effect by providing a standard against which the internal timekeeping mechanism updates its performance.

A shortening of the interval preceding the force accent was expected, however, this was not observed. Against the background of Billon and Semjen’s model, the absence of the shortened interval preceding the accent in this study suggests that perhaps the information needed to compensate the shortening was a strategy to correct for spatial related factors. For example, a higher downward acceleration is needed to produce more force - this was not necessary in a pulse production task. Therefore, the pulse production paradigm is ideal to investigate the lengthened IRI following a perturbation as this effect is observed to be present in a context with spatial factors removed and can possibly be attributed to force or timing control. This is addressed in the next chapter.

Equal Force and Timing Feedback

A key methodological point in this study relates to the utilisation of the synchronisation-continuation paradigm where external pacing signals which convey timing and force information are presented during the synchronisation phase. The purpose of the pacing signals is to provide experimental control over the mean time interval length and force level to be achieved during the continuation phase of the task. Therefore, it is important for the pacing signals to be presented in a way which allow participants to derive the information necessary to execute the task as accurately as possible. Timing information can be directly extracted when presented in different modalities, although auditory dominance results in higher accuracy in comparison with visual presentations (Repp & Penel, 2002, 2004). In contrast, force information is usually presented visually. Force signals produced by participants are represented as impulse spikes on a monitor which are match to a horizontal target line (Keele et al., 1987; Sternad et al., 2000). Using this method, the perception of different force levels always require learning to match tactile and proprioceptive sensations to a visually scaled representation of the sensation. The additional process of extracting such information could possibly result in higher variability from an inaccurate perception of task requirement. In comparison with previous studies, the range of force CV levels in this study were lower (between 0.093 and 0.111) than Sternad et al., (2000; between 0.18 and 0.27) as well as Inui & Ichihara, (2001; between 0.30 and 0.45) possibly reflecting better force perception resulting in lower performance variability using the haptic modality. Therefore, ideally, both timing and force information would be delivered in the same modality and in a way which can be directly perceived.

To achieve this aim, a robotic haptic device was used as a novel method of presenting force and timing information during the paced phase in this study. As participants held their finger stiff against the surface of a virtual wall, the robotic haptic device delivered force pulses which were actual force traces recorded from a person performing the task, and scaled to the target force level. The pulses were spaced according to the target interval length required by the task. In this way, force perception was directly perceived via the isometric contractions of the muscles in the finger (no change in muscle length). Timing information could also be extracted from the length of time which passed between two force pulses. Although the purpose of presenting both force and timing information using the haptic modality to equate feedback in the synchronisation phase was achieved, the motors of PHANToM haptic device overheated easily and subsequently caused disruptions to data recording sessions. For practical reasons, in subsequent experiments, a different method was adopted in which visual feedback on both timing and force was provided. However, it is noted that an ideal paradigm would use a single modality to provide both force and timing information.

In summary, a novel pulse production paradigm with haptic input was used to investigate the relationship between force and timing control with tasks used in previous literature. In concurrence with literature, it has been shown that the interaction between force and time is present only in force variability measures. Explicit instructions intended to focus attention on force over timing, or vice versa, introduced a correlation between the current peak force and subsequent time interval. Time interval length was affected when it was preceded by an accented force pulse. Finally, it is proposed that follow-up studies utilise this pulse production paradigm as it reduces confounds with spatial factors, to explore the possibility of a hierarchical relationship between force and time using sequences with perturbations as well as under dual-tasking conditions. However, in subsequent chapters, limitations of the haptic device resulted in the use of load cells instead of a robotic haptic device and a new mode for presenting feedback in the force pulse task.

CHAPTER 4

THE EFFECT OF TRANSITIONS ON FORCE-TIME INTERACTIONS

4.1 Abstract

In producing repetitive rhythmic movements such as finger tapping or pulse production, there is ambiguity regarding how independently force and timing are controlled at the central level. When producing a force accent within a sequence of responses, simultaneous changes in timing suggest coupled control. It was hypothesised that force and timing control behave independently but will exhibit parallel transient changes during execution of an anticipated state transition, and subsequently revert to independence. A transition is a change in state, where stress is introduced in the system, possibly loading cognitive resources and subsequently affecting control behaviour. Twelve participants were trained on a pulse production task (tapping without lifting finger off the surface) at ‘Fast’ (0.6 s) and ‘Slow’ (1.0 s) speeds, as well as ‘High’ (2.5 N) and ‘Low’ (1.5 N) forces. They then performed either an up-switch or a down-switch on the manipulated parameter (Time manipulation: fast to slow and slow to fast; Force manipulation: high to low and low to high). Observations on the non-manipulated parameter show transient changes occurring about the point of transition before returning to a stable state, suggesting coupling. However, differences in variability patterns of time and force during stable state indicate distinct control pathways. It was concluded that force and timing control is generally independent but can be dependent during preparation and execution of an

anticipated state transition, perhaps when cognitive resources are consciously engaged.[1]

4.2 Introduction

In the previous chapter, the examination of force-time interactions in a steady state revealed three findings. Firstly, a relationship between force and timing was observed in variability measures of force; secondly, co-variation of peak forces and time intervals were present when cognitive control was introduced; and thirdly, time intervals were affected by periodic accenting of force levels. From an information processing approach, force and timing processes can be seen as two stage mechanisms with a central origin and a peripheral motor implementation process. Interactions between the parallel force and timing processes can occur at either stage. Therefore, the theoretical interest in this relationship is whether observations of these effects arise from central or peripheral interactions. This can logically be explored, firstly, by a more detailed examination of mean and variability measures (in this chapter), and secondly, in co-variation measures (in the following chapter).

The current study follows on from the finding in Chapter 3 that time intervals are affected by force accents. The ability to adjust the timing of when a movement is made and couple it with how much force is used to move is something humans appear to do with little difficulty. The appropriate scaling of force and accuracy of execution timing is essential in achieving many repetitive skilled actions, for example, sequentially striking the keys of the piano to play a piece of music. In piano playing,

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[1] *This abstract was submitted and accepted for a poster presentation at the 14th Rhythm Perception and Production Workshop (RPPW) Birmingham, UK, 2013; published in Frontiers in Human Neuroscience, DOI=10.3389/conf.fnhum.2013.214.0000.*

successfully executed actions rely on information about when to respond and with what intensity of force to respond with. Therefore, the integration of both force and timing information is essential to produce a response. With this integration, it can be logically assumed that there would be a clear interaction between force and timing control. In contrast, from the literature, it is clear that no systematic correlation between timing and force control is observed in mean measures of steady state finger tapping tasks (Keele et al., 1987; Sternad et al., 2000). This finding was supported by the study in Chapter 3 with a pulse production task where participants' abilities to produce regular time intervals were not affected by different levels of force. Conversely, the ability to consistently produce pulses at particular force levels was not affected by different interval lengths. Extrapolating from these results to consider more complex sequences of movements such as piano playing, it is then not surprising to anecdotally observe a pianist demonstrating the ability to play the same piece of music, at fast or slow tempi with dynamics (force) held constant. He or she can also play the piece of music using loud and soft dynamics, with the tempo held constant. In this example, force and timing control appear to be independent processes. However, it was found in the previous chapter that interactions between force and timing occurred when the force sequence included a periodic accent but not in the steady state, and this is further explored in the current chapter.

Force levels and time intervals are often not rigidly maintained throughout a sequence of actions but are fluid entities which can be altered under the planned control of higher level faculties. For example, musicians intentionally produce departures from a prescribed periodicity and force intensity to convey musical expression (Dahl, 2004; Repp, 2000). These departures are deliberate changes made at certain locations within the existing action sequence. Consider again the case of a pianist playing a piece of music; as opposed to keeping the exact same timing or dynamics throughout the whole piece, it is more common to encounter changes within a piece itself. Tempi, for example, may evolve from half notes to quarter notes and perhaps to whole notes; and dynamics, from '*piano'* to '*forte'* and back to '*piano'* (soft to loud and back to soft). The regular time intervals expected of a piece need to be coupled with perturbed dynamics at particular points in the piece. Similarly, irregular time intervals are required to be played at a constant dynamic. These variations enable music to be played with expression, which is an instantly recognisable element of musical performance achieved by modulation of timing and force (which affects dynamics) (Johnson, 2000).

In simpler finger tapping tasks, it has been observed that manipulation of force levels produces corresponding changes in timing control. Both accentuation (increase) and attenuation (decrease) of force are associated with a corresponding modification of the mean interval length immediately preceding and following the accent (Billon & Semjen, 1995; Semjen, Garcia-Colera, & Requin, 1984, Billon & Semjen 1996). This effect of force on timing has been interpreted as an interaction between timing control processes and the planning of a force change where preparations to increase or decrease force accelerate or decelerate the implementation of time intervals (Keele et al., 1987; Semjen & Garcia-Colera, 1986). Three implications from this representation of force and timing control are considered. Firstly, these two processes are not independent, secondly, the interaction effects are salient during instances of force modulation, and thirdly, the involvement of cognitive resources is suggested by the preparation and planning of force changes. These inferences clearly contrast with the evidence of independence presented above. Therefore, taking into consideration both the evidence suggesting independence and dependence between force and timing, we asked if the interaction between force and timing control is transient and would only be present when there is active modulation of force control. A two-level model of timing was assumed, where responses are triggered by a central internal clock and subsequently implemented by the peripheral motor system (Wing & Kristofferson, 1973b). It was also assumed a two-level model of force production where force responses are centrally mapped by the motor cortex and implemented by the peripheral motor system using either rate coding or motor recruitment to scale and achieve appropriate force levels (Clamann, 1993; Shadmehr & Wise, 2004). Following on from these models, given a known transition point, it was predicted that the central system anticipates an upcoming change by planning and preparing for an adjustment and this may cause transient interference between force and timing parameters of action.

In the current study, force modulation was defined as a change in state of the central control system, possibly loading cognitive resources and consequently affecting control behaviour. The change is introduced as an upwards or downwards transition in either the force or timing parameter. The observation of interest is whether or not there are any changes in the mean and also variability measures of the unmanipulated parameter. It was hypothesised that force and timing would generally appear independent but would exhibit parallel transient changes during the execution of the transition, and subsequently revert to independence. We predicted that cognitive resources used during the preparation phase of the transition at the central level would result in changes in performance. Therefore, in both force and timing parameters, it was expected to observe 1) increased variability and mean differences preceding the transition, 2) increased variability immediately after the transition occurs as the system stabilises to a new movement frequency, 3) simultaneous changes in both timing and force measures indicating an interaction.

Methodologically, four potential sources of confounding effects were identified and refinements were implemented to exert better experimental control over the effects. Firstly, the task used in previous studies involved producing a short sequence of between four to five taps with one of the taps either accented or attenuated. This task produced certain unintended effects, for example, the first and last interval within the sequence was observed to be consistently longer than those at other positions, possibly as a result of increased force at the beginning and end of the sequence (Piek et al., 1993; Semjen et al., 1984). This difference of force level at the beginning and end of a sequence has been termed as ‘spontaneous stress’ (Semjen & Garcia-Colera, 1986) and is not explicitly separated from intentional force accents at those very positions. Secondly, with the accented tap always bordered by taps of baseline intensities (or no tap if it starts or ends a sequence), it was not possible to extricate the effects which occur leading up to the accentuation, from the effects which occur as a result of the de-accentuation to return the force to the baseline. Thirdly, measurements taken of the effect often refer to mean values of performance accuracy, but variability measures which reveal the relationship between force and timing more clearly (Sternad et al., 2000) are less discussed. Finally, most studies have investigated the effect of a change in force on timing, but not changes of timing on force (e.g. Billon & Semjen, 1995; Semjen, Garcia-Colera, & Requin, 1984, Billon & Semjen 1996).

With these points in mind a task which incorporated the following refinements was proposed:

1) A relatively long sequence to eliminate the effects of spontaneous stress,
2) A sequence with a transition but subsequently maintaining forces (and/or timing) at the new level instead of returning to pre-transition levels to separate pre and post transition effects,
3) An examination of variability as well as mean measures, and
4) A factorial design incorporating both upwards and downwards transitions for force and timing parameters.

To exert greater experimental control over the measurement of force levels and time intervals, the task used was pulse production instead of finger tapping. The movement was performed by pressing against a surface without lifting the finger so that neither force nor time was confounded with kinematic changes in trajectory. This method would allow any observed effects to be attributed more clearly to force and timing factors. Using these modifications, we then considered if changes caused by the transition event are simultaneously present in both force and timing parameters, indicating interaction between the two parameters.

4.3 Methodology

4.3.1 Participants

Thirteen participants took part in this study (12 female and 1 male, 11 right-handed, 2 left-handed), with a mean age of 29 years old (SD = 5 years; range 26 to 39 years). All participants provided informed consent to participate and reported no pre-existing motor conditions affecting their arm. Opportunity sampling was used and participants were provided the option of receiving either a standard participant fee of £6 per hour of participation or research credits via the School of Psychology Research Participant Scheme.

4.3.2 Apparatus

Force data were recorded at 1 kHz from a single axis force sensor (Novatech, Hastings, UK). A plate was mounted on the load cell as a response surface. Data from the load cell was saved on a PC via a via a USB data acquisition device (NI USB-6229, National Instruments, TX, USA) programmed in Matlab (Mathworks, MA, USA). The load cells were calibrated and force offsets were adjusted at the beginning of each session.

4.3.3 Setup

Participants sat facing a computer monitor with their forearm at 90 degrees pronation and the upper arm parallel to the torso. The forearm was cushioned to provide comfort. The index finger rested in the middle of the plate with the thumb and other fingers closed to avoid contact with the plate (see Figure 22). The computer screen displayed visual input for the task and was programmed in Matlab

(Mathworks, MA, USA) using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007).

Figure 22: Participants sat facing the computer monitor with their right index finger on the load cell.

4.3.4 Task

The task involved the participant producing repetitive force pulses by pressing downwards onto the plate of the load cell without lifting the finger off its surface. Within each trial, a transition was introduced using a visual display (see Figure 23). A coloured bar filled continuously to denote the passing of time. The continuous movement of the bar (as opposed to stepped increases) was intended to avoid providing discrete timing information which participants might have used as an external timing reference. A vertical line in the middle of the bar indicated the point of transition. The visual of the bar gradually moving towards the point of transition was intended to encourage advance preparation for the transition.

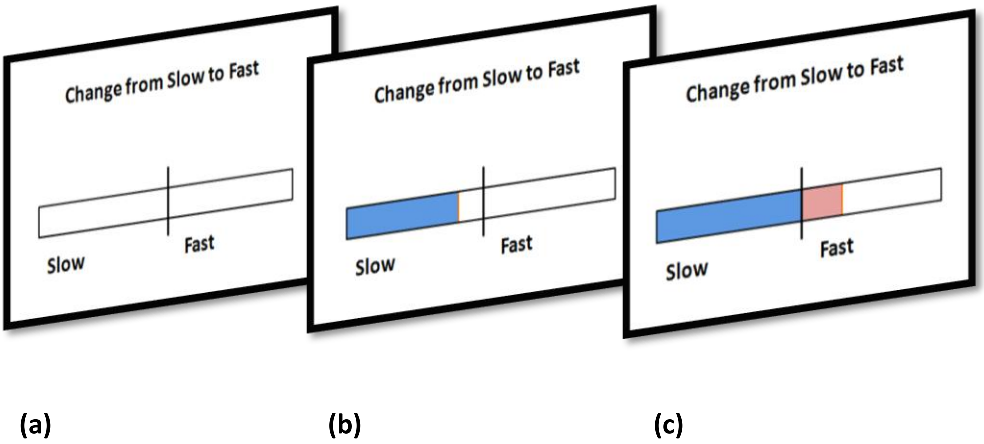

Figure 23: Progression of task from left to right, the instructions for the transition remain on the screen throughout the trial **(a).** As the trial progresses, the horizontal bar creates anticipation and preparation when approaching the transition point in the middle on the trial **(b).** After the transition occurs, the colour of the horizontal bar changes as a visual reminder of the new task state **(c).**

4.3.5 Procedure

Participants were presented with practice trials to familiarise themselves with the task. Practice sessions included producing force pulses of 1.5 N and 2.5 N, as well as time intervals of 0.6 s and 1.0 s. Feedback was provided visually by changing the colour of the target to indicate that the participant approximated the target force level or interval length within a range of ±10% (see Figure 24).

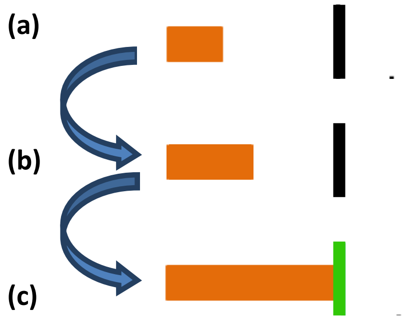

Figure 24: An example of force pulse practice sessions: The horizontal bar increases in length with increasing force applied on the load cell **(a)** and **(b)**. As the force approaches the target level, the vertical bar turns green, indicating the appropriate level of force has been achieved **(c).**

There were four experimental blocks, each with a combination of either an upwards or downwards transition within the force or timing parameter (see Table 6). The presentation order of the blocks was randomised for each participant prior to the experiment and data from 10 repetitions were collected for each block. Each trial lasted for 50 s (25 s each for pre- and post-transition).

	Force	**Timing**
Upwards	Low to high	Slow (1.0s) to fast (0.6s)
Downwards	High to low	Fast (0.6s) to slow (1.0s)

Table 6: Participants produced a series of force pulses with upwards or downwards transitions on either the force or timing parameter at force levels of 1.5 N (low) or 2.5 N (high), and time intervals of 0.6 s (fast) or 1.0 s (slow).

4.3.6 Analysis

The raw force signal recorded at 1 kHz was differenced to detect outliers. Values with a difference of more than 1 N/ms were replaced with the average between the value before and after the outlier. A 4th order low pass Butterworth filter with a cut-off frequency of 20 Hz was then applied to the force signal recorded from the load cell. The signal was filtered both forwards and backwards to remove the phase shift which occurs with digital filtering. A peak detection algorithm, written in Matlab (Billauer, 2012), was used to obtain a time series of responses defined by local force maxima and the time of each of those occurrences from the filtered force signal. The event times were then differenced to yield the interresponse interval (IRI) between successive responses (see Figure 25). Subsequently, trial means (M) of peak force and IRIs were obtained and averaged across participants by condition. Variability measures computed included the standard deviation (SD) and coefficient of variation (CV; SD/M). The analysis focused on ten pulses leading up to and following the transition point, eliminating earlier and later responses from every trial to ensure any transient effects as the trial began or ended were excluded from the data processing. For the M and SD values, paired t-tests were run between successive responses to identify significant differences at transition points. The Bonferroni correction was applied to significance (*p)* values since two comparisons were made for each dataset. The level of statistical significance for the paired t-tests was set at the level of *p*=.025. For the CV values, a repeated measures ANOVA with five factors was applied to the dataset to examine interaction effects. The factors were *Measured parameter* (force, time), *Transition parameter* (force, time), *transition direction* (up, down), *phase* (before transition, after transition), and *distance* (1, 3, or

6 pulses away from the transition point). Where Mauchly's Test of Sphericity was significant, Hyunh-Feldt corrected values were reported if epsilon, Ɛ >.75, and Greenhouse-Geisser corrected values were reported if Ɛ <.75. Pearson correlations were calculated for peak force and time intervals for three responses before and following the transition. Given dual task demands at transition, we expected increased correlation (compared to pre- and post-baselines) just before and after transition.

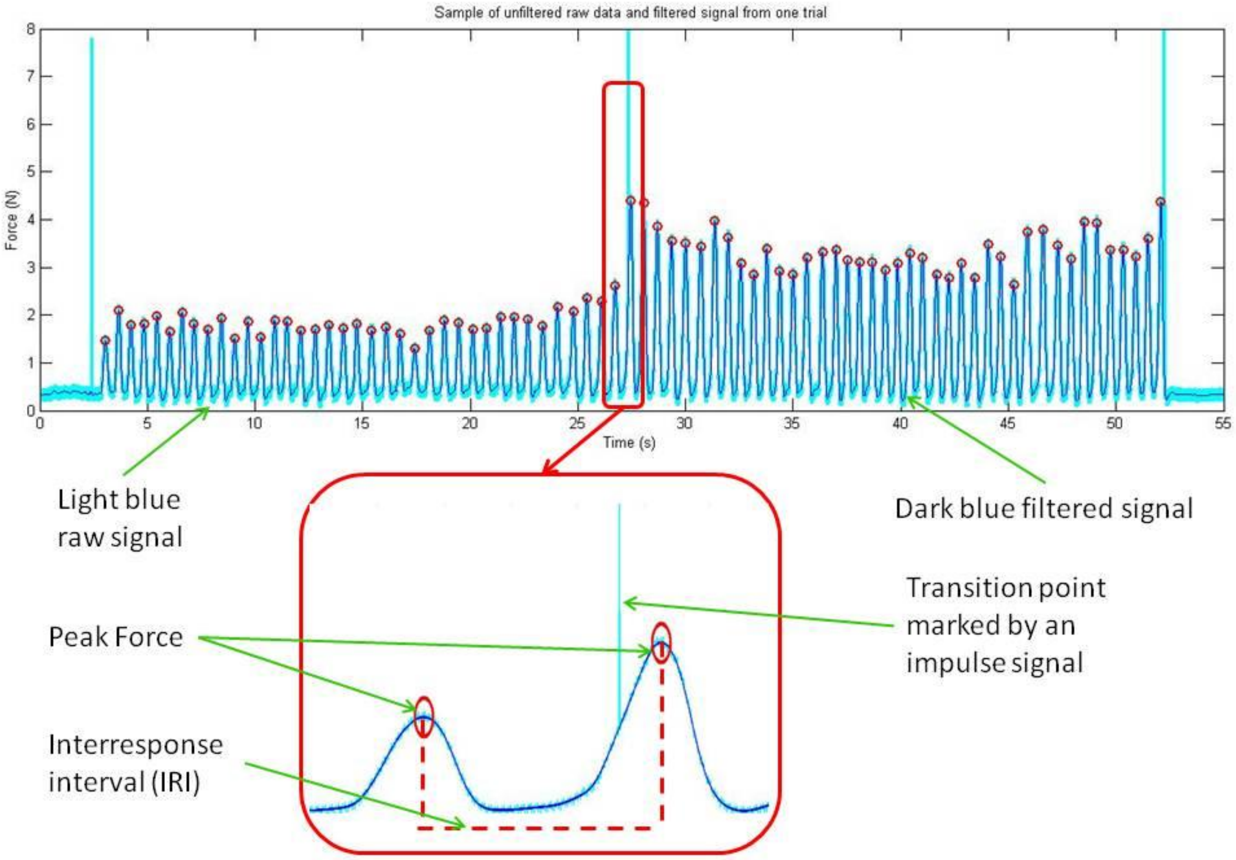

Figure 25: Sample of a force signal from a single trial. After low-pass filtering, peaks of forces are detected and the time between two PF events is calculated as the IRI.

4.4 Results

4.4.1 Means

Time Transition

On average, participants produced IRIs of 0.848 s (SD=.030 s; target IRI of 1.0 s) during the ‘Slow’ phase and 0.572 s (SD=.017 s; target IRI of 0.6 s) during the ‘Fast’ phase (see Figure 26). Thus, the target interval for the ‘Slow’ phase was underestimated by a mean of 15%. Participants distinctly switched from one interval length to another indicating that both upwards (pre-transition M=.749 s, SD=.229 s; post-transition M=.588 s, SD=.122 s); t(12)=4.245, *p*=.001) and downwards transitions (pre-transition M=.628 s, SD=.193 s; post-transition M=.795 s, SD=.226 s); t(12)=-5.464, *p*<.001, were performed successfully. PF values showed a small but non-significant increase at about the point of transition but were not significantly different from the rest of the responses.

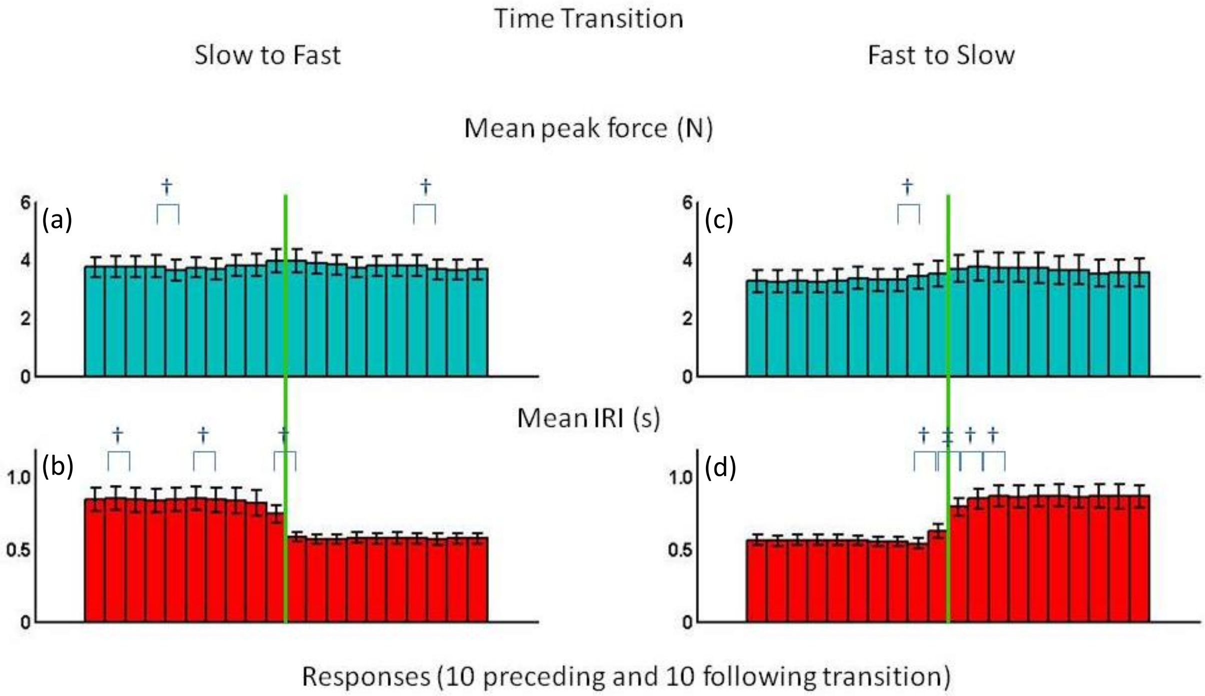

Figure 26: Mean PFs and IRIs for a Slow to Fast time transition **(a, b)** and a Fast to Slow time transition **(c, d)**. Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the mean. Significant paired t-test comparisons between successive responses are indicated with †.

Force Transition

On average, participants produced PFs of 3.97 N (SD=.15 N) during the ‘High’ force phase and 2.07 N (SD=.10 N) during the ‘Low’ force phase (see Figure 27). This is an overestimate of approximately 1.5 N in the ‘High’ force phase (target was 2.5 N) and 0.5 N in the ‘Low’ force phase (target was 1.5 N). Differences in force levels for the High to Low force condition approached significance (pre-transition M=4.35 N, SD=3.23 N; post-transition M=1.46 N, SD=.92 N); t(11)=2.553, *p*=.027). In the Low to High force conditions, pre-transition (M=2.22 N, SD=1.87 N) and post-transition (M=3.75 N, SD=2.99 N) force levels were significantly different, t(11)=-4.004, *p*=.002) indicating that participants successfully performed the required transition.

The IRIs prior to the force transition were shortened regardless of transition directions. In the high to low transition, the IRI preceding the transition (M=.732 s, SD=.195 s) was significantly different from the adjacent interval (M=.757 s, SD=.213 s); t(11)=2.980, p=.013. In the low to high transition, the IRI immediately preceding the transition point (M=.730 s, SD=.221 s) was significantly different from the following IRI (M=.789 s, SD=.251 s); t(11)=-2.588, p=.025.

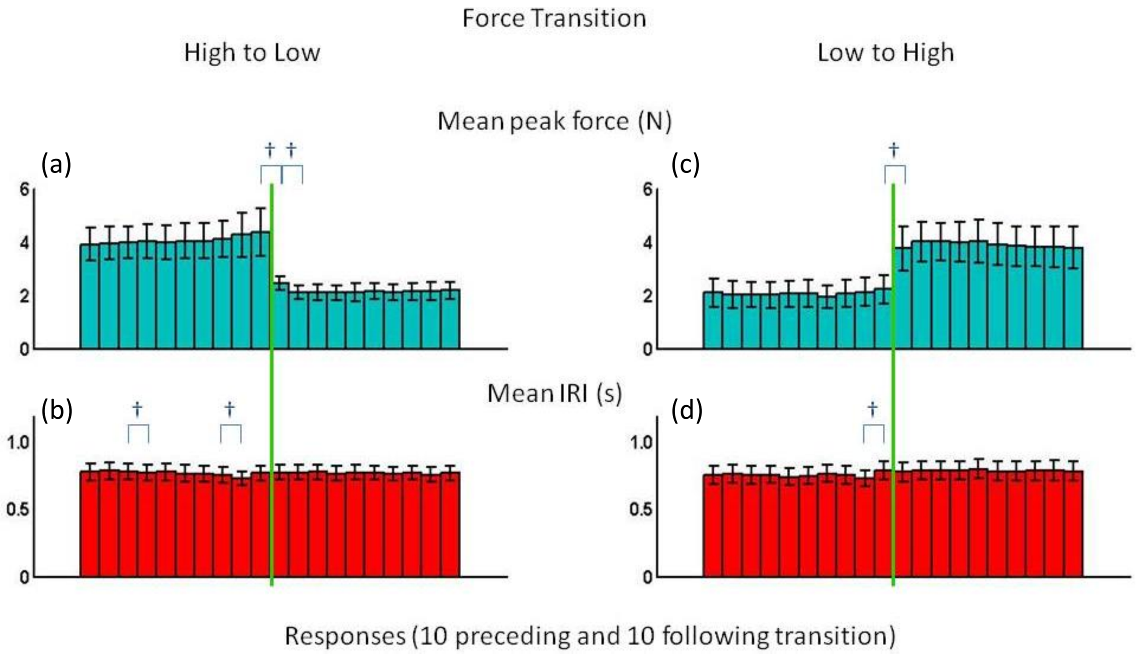

Figure 27: Mean PFs and IRIs for a High to Low force transition **(a, b)** and a Low to High force transition **(c, d).** Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the mean. Significant paired t-test comparisons between successive responses are indicated with †.

4.4.2 Variability

Time Transition

IRI variability was higher at longer interval lengths (see Figure 28). In the Slow to Fast transition, the IRI immediately preceding the transition (M=.110 s, SD=.074 s) was significantly more variable than the previous IRI (M=.086 s, SD=.052 s); t(12)=-3.153, p=.008. This was also observed for the IRI immediately following the transition (M=.080 s, SD=.030 s) in comparison with the IRI after (M=.057 s, SD=.027 s); t(12)=3.462, p=.005. In the Fast to Slow condition, the IRI preceding the transition (M=.089 s, SD=.052 s) was significantly more variable than the previous IRI (M=.056 s, SD=.030 s); t(12)=-3.607, p=.004.

PF variability remained consistent throughout all responses at an average of 0.71 N (SD=0.15 N) in Slow to Fast, and 0.63 N (SD=0.16 N) in Fast to Slow. There were no significant differences between variability of successive force pulses in either transition condition.

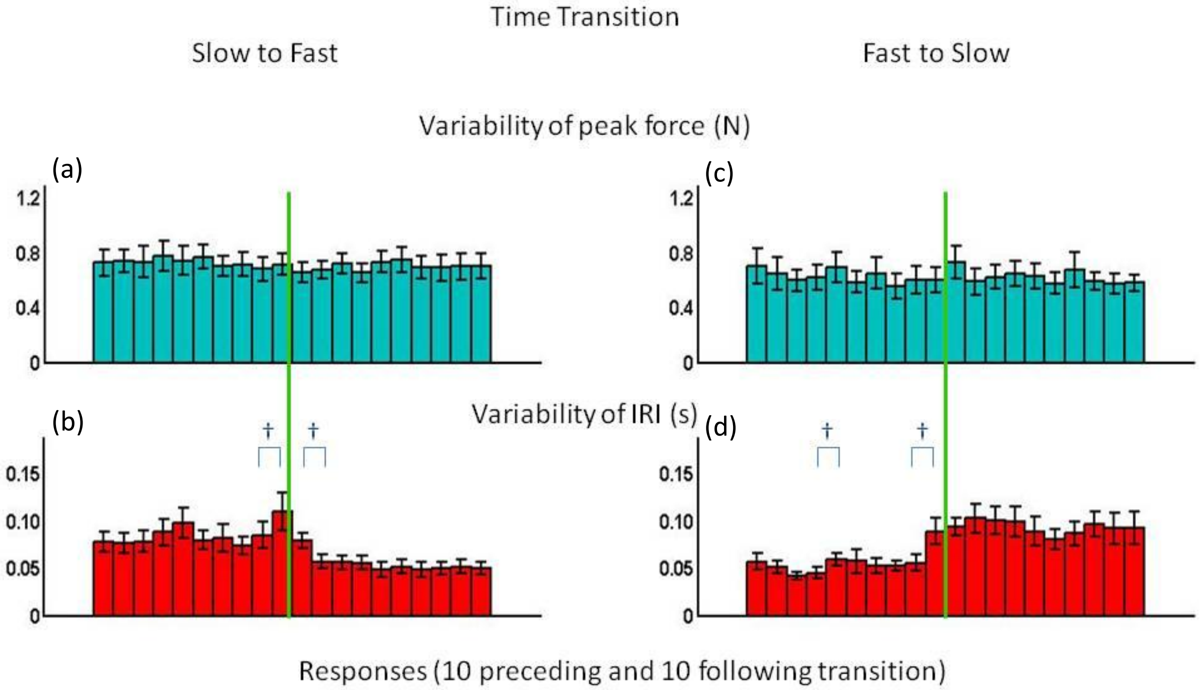

Figure 28: Variability of PFs and IRIs for a Slow to Fast time transition **(a, b)** and a Fast to Slow time transition **(c, d).** Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the variability. Significant paired t-test comparisons between successive responses are indicated with †.

Force Transition

PF variability was significantly different before and after the transition point for both conditions (see Figure 29). In the high to low force condition, variability of the force pulse immediately following the transition (M=.74 N, SD=.38 N) was significantly higher than the successive force pulse (M=.45 N, SD=.17 N); t(11)=3.008, p=.012. In the Low to High force condition, the variability of the pulse prior to the transition (M=.42 N, SD=.41 N) was significantly lower than the pulse following the transition (M=.85 N, SD=.77 N); t(11)=-3.773, p=.020. On average, variability was twice as large for High force compared to Low force for both transition directions.

The Low to High transition had an effect on IRI variability. The IRI immediately preceding the transition (M=.116 s, SD=.067 s) was significantly more variable than the IRI following the transition (M=.073 s, SD=.031 s); t(11)=2.660, p=.022. This effect was not present in the High to Low force transition condition.

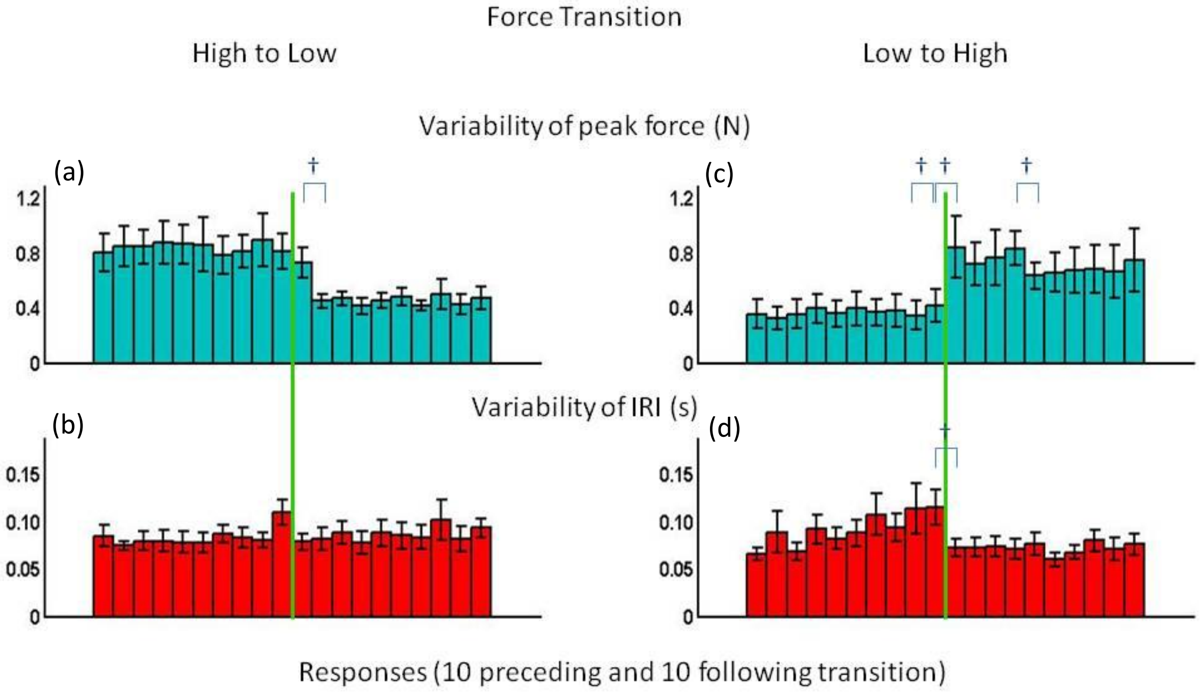

Figure 29: Variability of PFs and IRIs for a High to Low force transition **(a, b)** and a Low to High force transition **(c, d).** Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the variability. Significant paired t-test comparisons between successive responses are indicated with †.

4.4.3 Coefficient of Variation

Time Transition

The CV was calculated as a normalised measure of variability. CV of the IRI increased at the point of a time transition. In the Slow to Fast condition, the interval preceding the transition (M=.139, SD=.065) was significantly different from the successive interval (M=.100, SD=.031); t(12)=-3.530, p=.004 (see Figure 30). This difference was also observed in the interval after the transition (M=.135, SD=.011) and the subsequent interval (M=.098, SD=.035); t(12)=3.066, p=.010. In the Fast to Slow condition, the interval preceding the transition (M=.144, SD=.072) had a significantly higher CV than the successive interval (M=.100, SD=.040); t(12)=-2.929, p=.013. CV values of PF remain unchanged in the Slow to Fast condition. However, when switching from Fast to Slow, the force CV following the transition (M=.207, SD=.118) was significantly higher than the successive CV (M=.165, SD=.089); t(12)=3.150, p=.008.

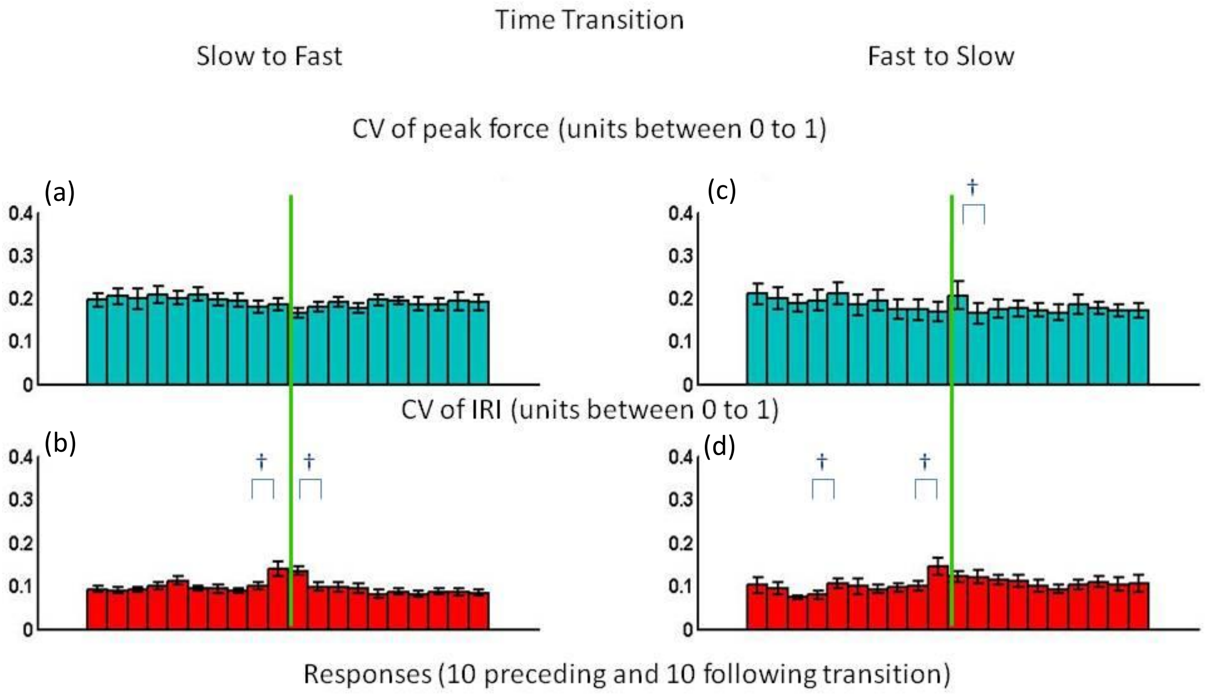

Figure 30: CV of PFs and IRIs for a Slow to Fast time transition **(a, b)** and a Fast to Slow time transition **(c, d).** Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the CV. Significant paired t-test comparisons between successive responses are indicated with †.

Force Transition

CV values of PF were significantly different for the forces at the transition points however, their exact location differed (see Figure 31). When switching from high to low force, the CV of PF after the transition (M=.302, SD=.110) was significantly higher than the CV before transition (M=.203, SD=.070); t(11)=-4.066, p=.002. In the low to high force condition, the PF CV before the transition (M=.187, SD=.051) was significantly higher than the preceding CV (M=.159, SD=.045); t(11)=-3.120, p=.010.

The force transition also had an effect on the CVs of the IRI in the low to high transition. CV of the IRI was higher when force was low (M=.143, SD=.051) and decreased after the transition to High force occurred (M=.091, SD=.030); t(11)=2.912, p=.014. There were no significant effects of force transition on the CVs of IRIs in the high to low force condition.

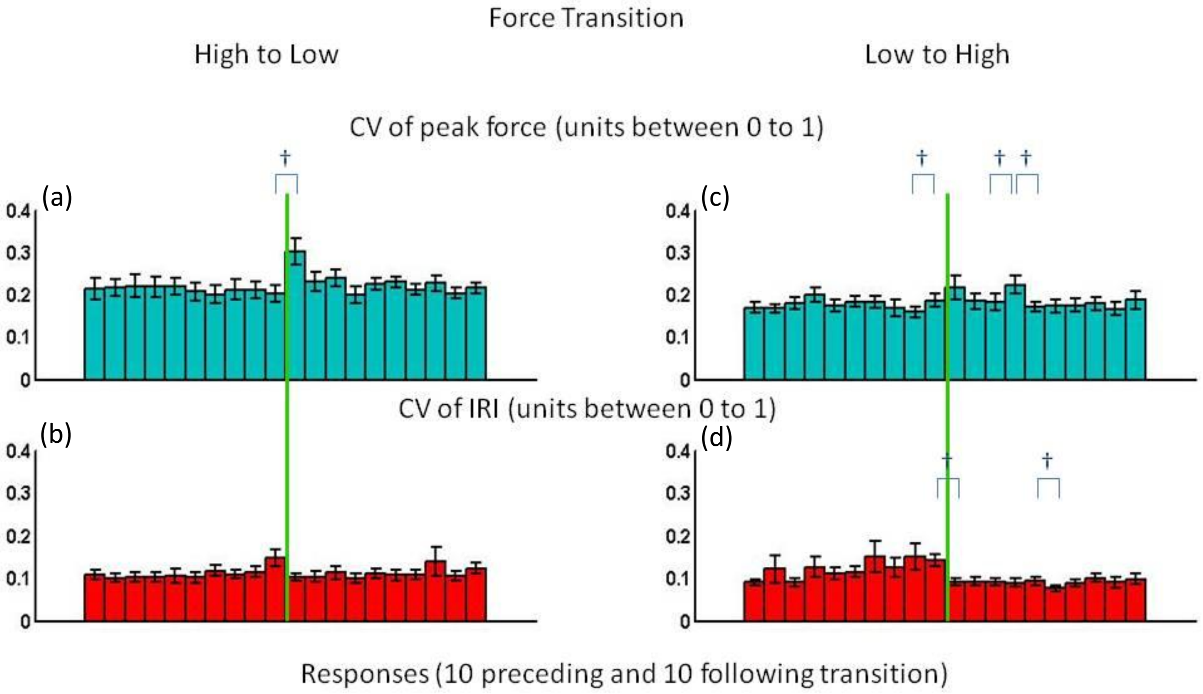

Figure 31: CV of PFs and IRIs for a High to Low force transition **(a, b)** and a Low to High force transition **(c, d).** Green lines denote the position of the transition. Responses graphed are 10 pulses preceding and 10 pulses following the transition. Error bars are standard error of the CV. Significant paired t-test comparisons between successive responses are indicated with †.

4.4.4 Analysis of Variance

The CVs of PFs and IRIs were further analysed with a 2 x 2 x 2 x 2 x 3 repeated measures ANOVA. The within subject factors were 1) *measured parameter* (force, time), 2) *transition parameter* (force, time), 3) *transition direction* (up, down), 4) *phase* (before transition, after transition), and 5) *distance* (1, 3, and 6 pulses from transition). There was a significant main effect for *measured parameter* *F*(1,11)=57.122, *p*<.001 indicating distinct CV levels for both parameters. The CV for PF was higher (M=0.197, SD=0.063) than IRI (M=0.117, SD=0.041) (see Figure 32a). There was also a main effect of *distance* *F*(2,22)=19.992, *p*<.001. The CV was lowest at six pulses away from the transition (M=0.151, SD=0.043), followed by three pulses away from the transition (M=0.151, SD=0.49), and highest when adjacent to the transition (M=0.165, SD=0.064). The remaining main effects of *transition parameter* (*F*(1,11)=1.884, *p*=.197), *transition direction* (*F*(1,11)=1.771, *p*=.210), and *phase* were not significant *F*(1,11)=.007, *p*=.936 (see Figure 32b).

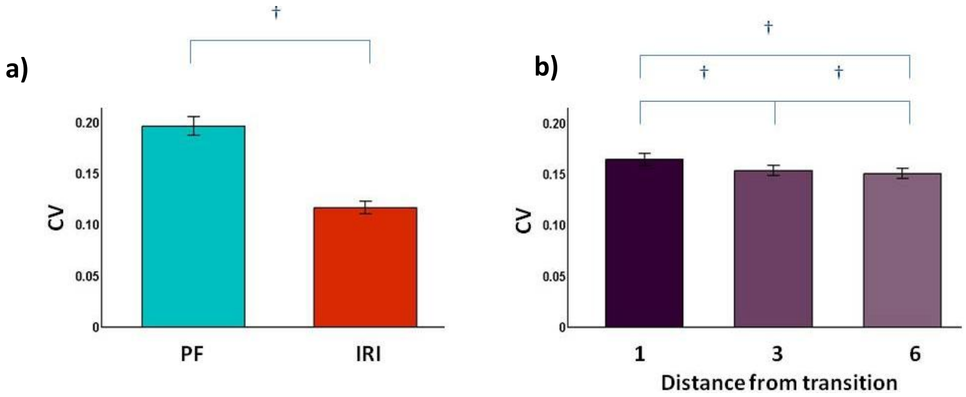

Figure 32: Main effects for **(a)** *Measured parameter* (force, time) and **(b)** *Distance from transition* (1, 3, and 6 pulses from transition). Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

An interaction effect was found between the *measured parameter and phase* *F*(1,11)=16.473, *p*=.002. PF CV (M=.187; SD=.061) increased after the transition (M=.207; SD=.080), however, IRI CV (M=.126; SD=.050) decreased after the transition (M=.107; SD=.035) (see Figure 33). All other interactions between two factors were not significant: *measured parameter*transition parameter* *F*(1,11)=2.913, *p*=.116; *measured parameter*transition direction* *F*(1,11)=1.726, *p*=.216; *transition parameter*transition direction* *F*(1,11)=2.015, *p*=.183; *transition parameter*phase* *F*(1,11)=.424, *p*=.528; *transition direction*phase* *F*(1,11)=2.798, *p*=.123; *measured parameter*distance* *F*(2,22)=1.889, *p*=.192; *transition parameter*distance* *F*(2,22)=.258, *p*=.652; *transition direction*distance* *F*(2,22)=.098, *p*=.826; *phase*distance* *F*(2,22)=.868, *p*=.383.

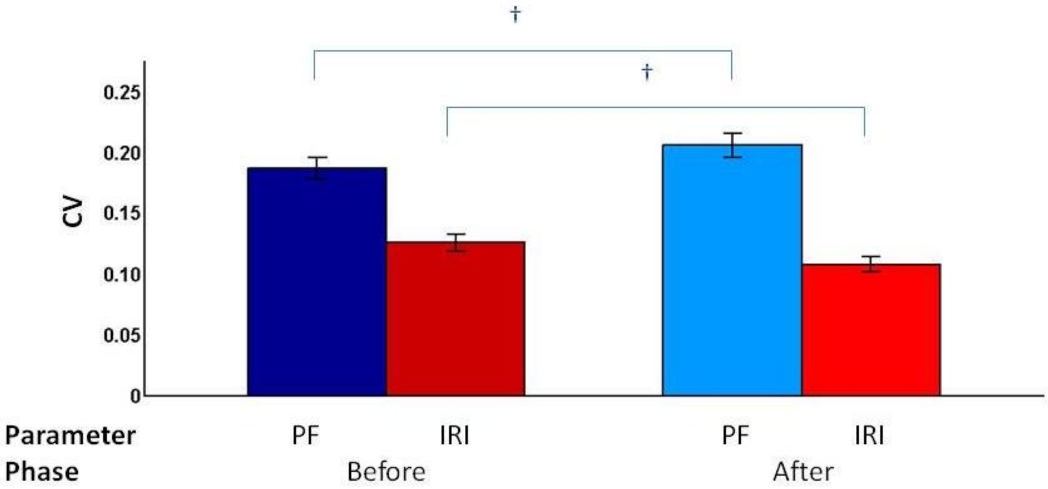

Figure 33: Interactions between *Measured parameter* (force, time) and *Phase* (before, after) for CVs of PF and IRI. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

There were four significant interaction effects between three factor comparisons. Firstly, there was an interaction between the *measured parameter, transition parameter,* and *phase F*(1,11)=20.604, *p*=.001. Post-hoc paired t-test comparisons revealed significant differences between peak force and IRI at both phases before and after the transition for time and force transitions (see Figure 34).

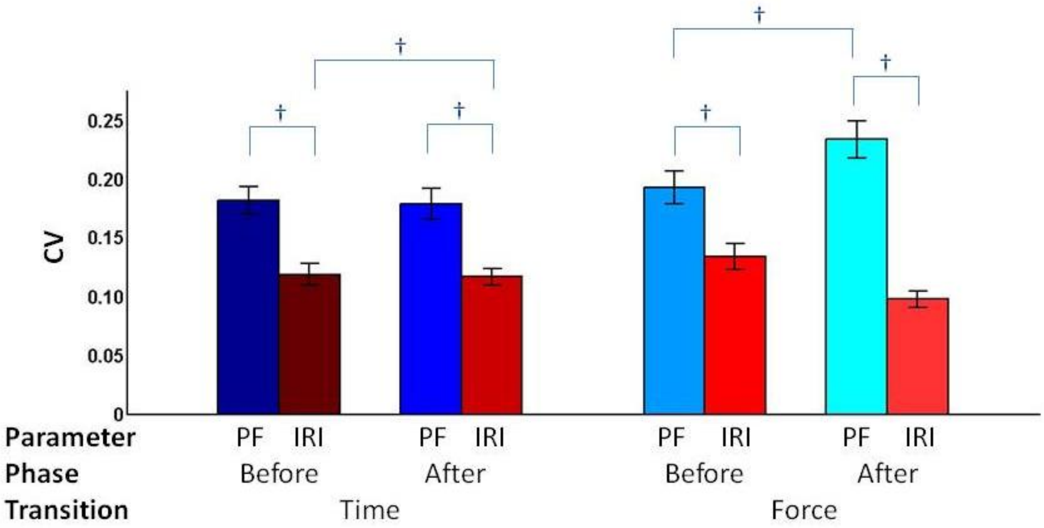

Figure 34: Interactions between *Measured parameter* (force, time), *Phase* (before, after) and *Transition parameter* (force, time) for CVs of PF and IRI. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

Secondly, there was an interaction between the *transition parameter, transition direction, and phase F*(1,11)=6.089, *p*=.031 (see Figure 35), where the CV in the upwards force transition was higher (M=.147; SD=.075) than the downwards force transition (M=.186; SD=.103) after the point of transition; *measured parameter*transition parameter*distance F*(2,22)=8.933, *p*=.011 (see Figure 36), and;

*measured parameter*phase*distance F*(2,22)=8.535, *p*=.009 (see Figure 37). The remaining interactions were not significant: *measured parameter*transition parameter*transition direction F*(1,11)=1.106, *p*=.316; *measured parameter*transition direction*phase F*(1,11)=.139, *p*=.716; *measured parameter*transition direction*distance F*(2,22)=.851, *p*=.397; *transition parameter*transition direction*distance F*(2,22)=.989, *p*=.353; *transition parameter*phase*distance F*(2,22)=.242, *p*=.676, and; *transition direction*phase*distance F*(2,22)=.281, *p*=.617 (see Figure 37).

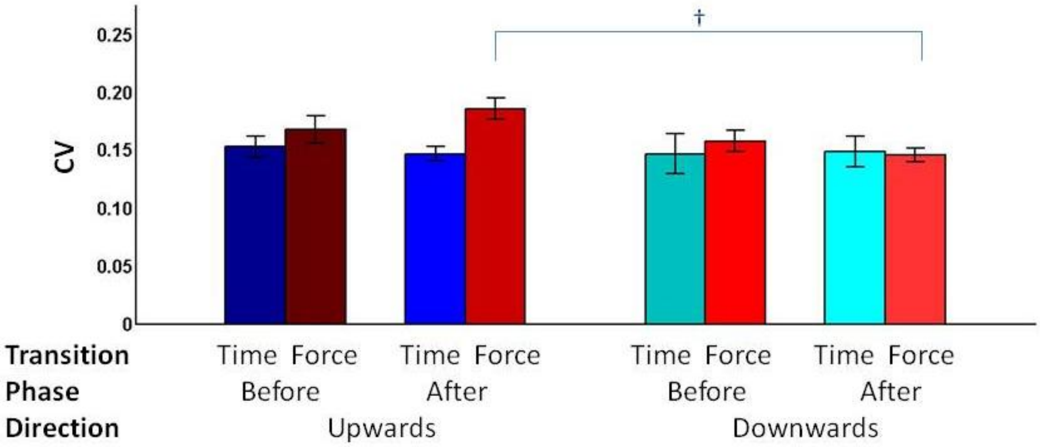

Figure 35: Interactions between *Transition parameter* (force, time), *Phase* (before, after) and *Transition direction* (up, down) for CVs of PF and IRI. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

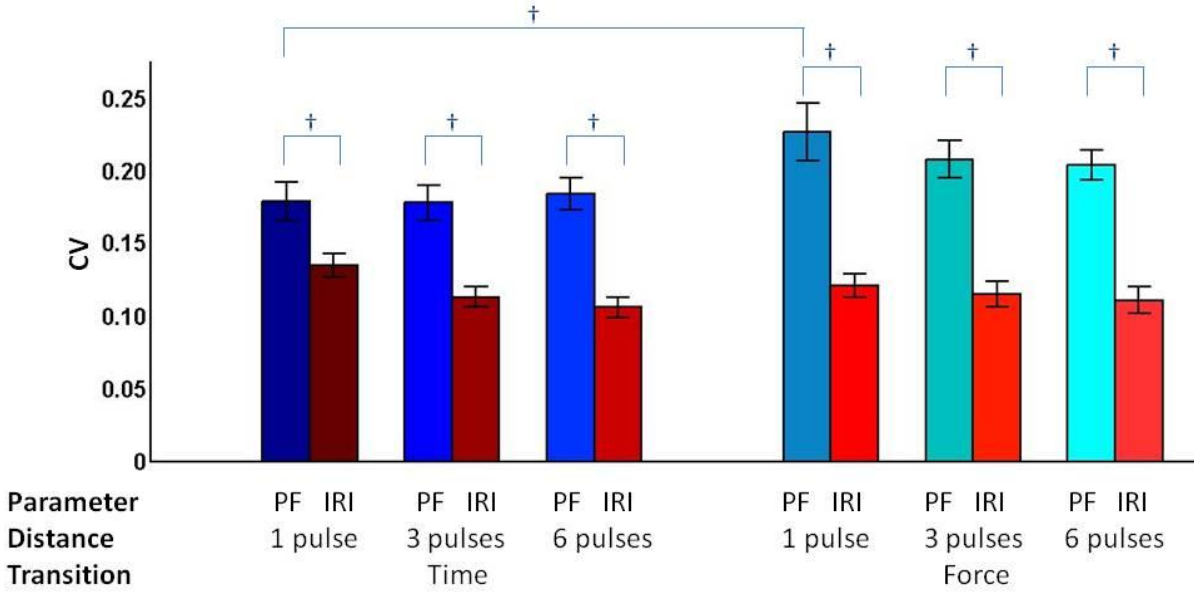

Figure 36: Interactions between *Measured parameter* (force, time), *Distance from transition* (1, 3, and 6 pulses from transition), and *Transition parameter* (force, time) for CVs of PF and IRI. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

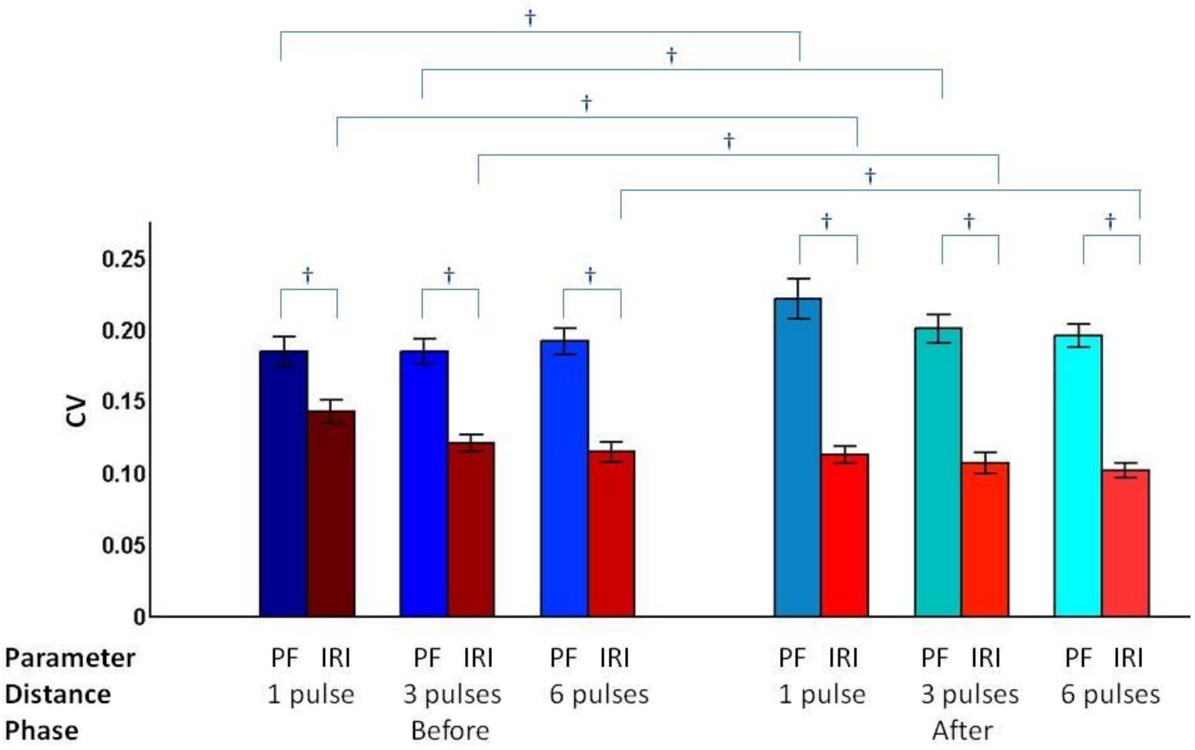

Figure 37: Interactions between *Transition parameter* (force, time), *Distance from transition* (1, 3, and 6 pulses from transition), and *Phase* (before, after) for CVs of PF and IRI. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

None of the interaction effects between four factors were significant: *measured parameter*transition parameter*transition direction*phase* *F*(1,11)=.1017, *p*=.335; *measured parameter*transition parameter*transition direction*distance* *F*(2,22)=1.390, *p*=.268; *measured parameter*transition parameter*phase*distance* *F*(2,22)=.839, *p*=.383; *measured parameter*transition direction*phase*distance* *F*(2,22)=.024, *p*=.926, and; *transition parameter*transition direction*phase*distance* *F*(2,22)=.262, *p*=.642.

Finally, there was a significant interaction effect between all five factors, *measured parameter*transition parameter*transition direction*phase*distance* *F*(2,22)=8.218, *p*=.012 (see Figure 38 Figure 39).

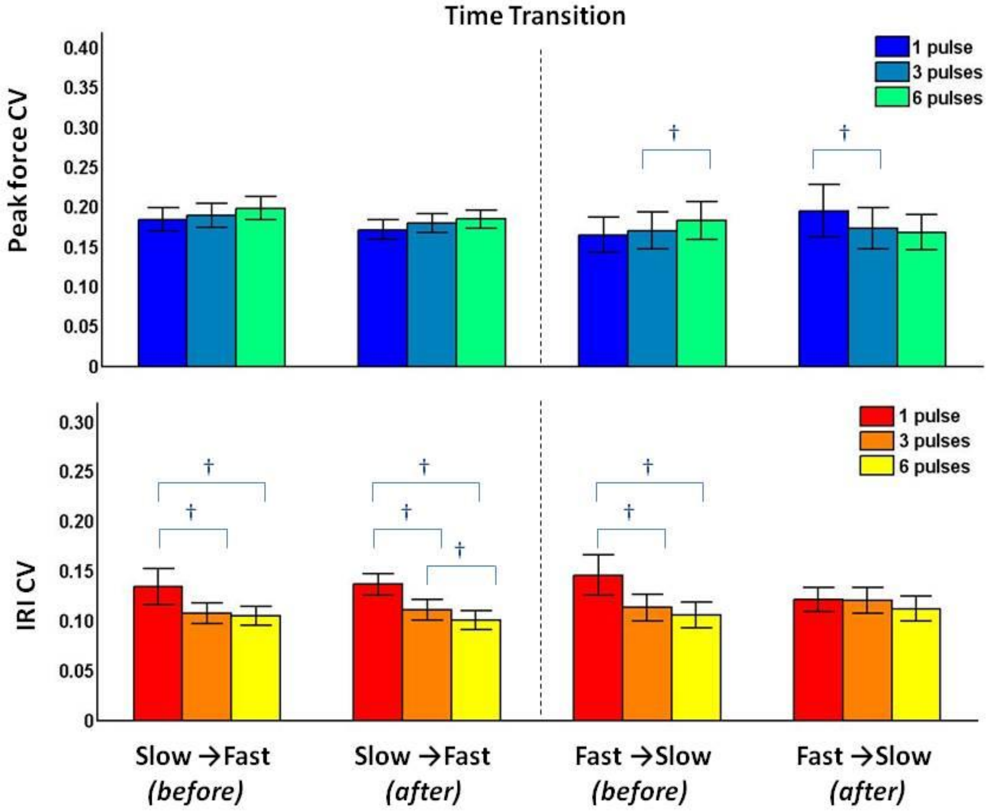

Figure 38: Interactions between *Distance* (1, 3, 6 pulses from the transition) for CVs of PF and IRI during time transitions. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

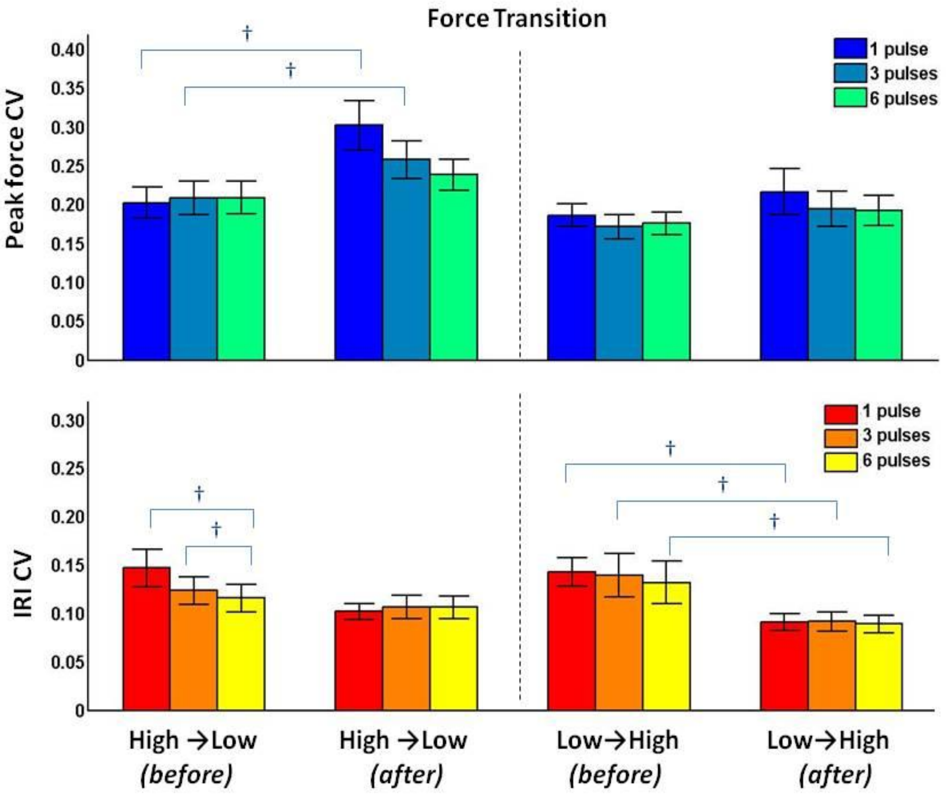

Figure 39: Interactions between *Phase* (before / after transition) and *Distance* (1, 3, 6 pulses from the transition) for CVs of PF and IRI during force transitions. Error bars are standard errors of the CV. Significant Paired t-test comparisons are denoted by † (Bonferroni corrected *p*-value for multiple comparisons).

4.4.5 Correlations

Pearson’s correlations were run on PFs and IRIs from 3 responses preceding until 3 responses following the transition. However, no significant correlations were noted, indicating that PFs and IRIs are unrelated during each individual response approaching the transition.

4.5 Discussion

Effects of Central Processes

When a transition occurs within a sequence of movements, control behaviour changes to accommodate the event. The nature of the changes which occur provide an insight into the relationship between force and timing control that is not present in steady state sequences of equal force and equal interval lengths. In this study, participants produced a sequence of force pulses and were asked to perform an upwards or downwards change on either the force or time parameter, leaving the other parameter unchanged. There were two force transitions, high to low force, and low to high force, as well as two time transitions, fast to slow and slow to fast. In all four conditions, participants performed the transitions accurately, distinguishing between pre and post transition.

The shortening of the interval preceding the force transition was observed in both the upwards and downwards force transitions. This supports the view that the shortening is not related to peripheral factors involved in scaling force levels as if this were the case the effect would have been different for increases and decreases in force levels. The magnitude of the shortening (0.025 s for High to Low and 0.059 s for Low to High) were within the range found in the literature (Billon et al., 1996; Piek et al., 1993; Semjen et al., 1984). The shortening effect in this study was observed in the absence of any change in finger trajectory present in other finger tapping studies, indicating that the movement related compensatory strategies did not contribute to the shortened interval. Thus, it is in agreement with Billon et al.'s, 1996) suggestion that the shortening is related to a central adjustment of the clock in preparation for an adjustment to force levels since there are no spatial related changes to be made.

There was no lengthening of the interval after the force transition. All intervals following the transition were not different from one another up to 10 pulses post-transition. This strongly suggests that the post accent lengthening observed previously is related to returning force levels back to baseline within a series with only one accented tap. This is consistent with previous studies which have shown that interval lengthening only occurs when one strong tap is bordered by two weak taps on either side, but not when a series of strong taps are bordered by a series of weak taps e.g. 10 strong taps followed by 10 weak taps (Fraisse & Oleron, 1954). Billon and Semjen (1995) discuss the possibility of attributing the lengthening to a refractory period induced by the accent, but they later rejected the hypothesis as there was no trend of greater lengthening at shorter interval lengths. The question remains as to whether the process which causes the lengthening is a central force control adjustment which interacts with timing. However, it is clear that it is not attributable to the scaling of force to produce the accent, regardless of its direction. A gradual increase in mean force was observed when the transition occurred in the timing parameter, but it was not significantly different from the rest of the sequence.

Variability during Transitions

Moment-to-moment variability reflects the control limitations of force and timing, thus, the nature of the variability may reveal brain mechanisms involved. Previous studies have reported the presence of a relationship between force and timing in variability measures (standardised as CVs) even though correlations were absent in mean values (Sternad et al., 2000). In this study, the first distinguishing feature of both CVs is their differences in magnitude. PF CVs were approximately twice the magnitude of IRI CVs. Since variability reflects the presence of inherent noise in the nervous system, the distinct levels of CVs between both parameters suggest differences in control but are not necessarily independent entities (Tan, Durlach, Beauregard, & Srinivasan, 1995).

Similar to mean measures, timing transitions did not have an effect on force variability, however, the CV of force in the Fast to Slow condition was higher post-transition before returning to pre-transition levels. Since this effect was not present in the Slow to Fast transition, it is possible that the abrupt slowing down induced more uncertainty as the process of “tuning down the gain” requires a larger degree of organization, thus increasing variability (Vince & Welford, 1967). Force transitions were expected to have an effect on timing variability, and this was true for the Low to High force condition. In line with the argument above, if the source of the effect is of a central origin, the organisation of scaling force to a higher level introduces an overlap between triggering the current response while planning the next accented response, drawing on more cognitive resources and subsequently increasing the variability of the current response. However, the same cannot be said for the High to Low force transition; both variability and CVs of IRIs approached significance but were not different from the rest of the sequence.

A Hierarchical Integration Process

Taken together, a change in force produces an effect on time, but not vice versa. This observation has also been noted in musical contexts where different dynamic patterns affected timing but not vice versa (Keller, 2012; Repp, 2000). If the mechanism of force and timing control is seen as a hierarchical central process, then either one of two possibilities arise; firstly, that the determination of time intervals precedes the scaling of force in a serial process. The alternative possibility is that the scaling of force and the determination of time intervals occur in parallel but the integration process is serial, giving precedence to timing. The timing mechanism is often modelled as a two-level process, with a central clock triggering motor implementation. Thus, it is plausible that the force parameter is scaled at the implementation level after the timing parameter has been determined by the central clock. Either of the possibilities above would be probable, but this remains to be determined.

Effects of Cognitive Resources

Although cognitive factors were not explicitly tested or controlled for in this study, the effect is suggested if transitions were viewed as a central process which requires additional recruitment of cognitive resources. A transition is a perturbation to the system, necessitating adjustments which draw resources away from the current response. Visual attention to the transition point on the screen, as well as memory of the interval length and force level, is only a few of the many possible ongoing cognitive processes which might affect performance in addition to those related to the transition. Both attention and memory are known to bias production of force and temporal responses (Keller, 2012; Repp, 2000). Furthermore, situations with higher uncertainty seem to facilitate the interaction and increase the strength of the relationship between force and timing control in a musical context (Keller, Weber, & Engel, 2011). This would be of interest for further investigation.

One weakness identified in this study related to representations of force and timing learnt by participants during the practice phase. Participants were required to maintain force and timing accuracy across a number of trials. This meant that memory of the required force levels and time interval lengths learnt during the practice phase would be exposed to decay over the time course of the experiment. In an effort to reduce this effect, the synchronisation phase was repeated between blocks to control for any drift in performance. Although participants performed the synchronisation phase to the level of required accuracy, it would be inevitable that performance might vary within a block. Several adjustments could potentially be implemented in future studies using this procedure, for example, including the synchronisation phase within a block instead of only between blocks; reducing the length of each trial, which would decrease the total time taken for the experiment and increase the probability of keeping task requirements in memory; and finally, including probe measures within a block (e.g. have participants produce force levels or time interval lengths from memory) which would provide an objective indication of whether drift did occur.

In summary, this study investigated the effects of a change in force levels on time intervals and vice versa. We firstly predicted that the effects have a central origin, and this was supported by finding that the shortening of the interval prior to the transition was present in a pulse production paradigm which minimised if not eliminated confounds with peripheral strategies related to spatial factors. We did not find a lengthening of the interval following the transition, confirming that this effect was not a faulty compensation for the scaling of force for the accent, but would be attributed to the return of force to the baseline level post-transition. Secondly, we predicted that dependence between force and time is transient at the vicinity of the transition, and would subsequently revert to independence. This was supported by the observation that significant differences in both parameters as well as increased variability were found at transition points. In conclusion, it is shown that force and timing control mechanisms are affected when a transition occurs, resulting in simultaneous changes of control behaviour. In conclusion, the results suggest that force and timing processes are autonomous but not independent; due to cognitive involvement, the interaction will be open to dual-task interferences.

CHAPTER 5

COGNITIVE EFFECTS OF DUAL-TASKING ON FORCE-TIME INTERACTIONS

5.1 Abstract

In finger tapping sequences, force and timing interactions have been found when a change in force levels is required. The present study examined whether cognitive factors in performance of a secondary task modulate force-time relations. If this adjustment is attention demanding, the interaction could reflect a control strategy when availability of cognitive resources is limited. Therefore, variations in interaction patterns with the execution of a concurrent cognitive task were predicted. In a repeated measures design, young healthy participants (N=12) produced repetitive force pulses on a force sensor (target of 2 N; 0.75 s), while performing a secondary numeric visual search task. Data from eight 60 s trials were collected for each of three conditions (1) prioritise pulse production, (2) prioritise visual search, and (3) equal priority to both tasks. Time series of peak force (PF) values and interresponse intervals (IRI) from pulse production were cross-correlated up to +/- 5 lags to determine co-variation between successive force and timing pairings. Dual-tasking resulted in force-time correlation patterns which were reliably positive in conditions (1) and (3). The force-time dependence was absent when pulse production was prioritised. The maintenance of force and timing production requires corrections against an internal standard and is attention demanding. Results suggest that a secondary task forces resource sharing between force and timing to maintain

performance and causes dependence. Thus, prioritising pulse production increased resource availability for this task and a different correlation pattern was observed.[1]

5.2 Introduction

Motor timing and force control are two essential components in movement production. The scaling of appropriate force levels at the correct moments requires the integration of information from both components to produce a successful movement. A fundamental question surrounding this process is whether the control mechanisms for these two elements are autonomous or dependent upon one another. In this chapter, we revisit the use of cross-correlation analysis to investigate the relationship between force and timing control, and propose that cognitive factors facilitate the coupling strength.

In producing repetitive responses such as a series of finger taps, magnitudes of force levels and lengths of time intervals are largely independent of each other (Keele et al., 1987; Sternad et al., 2000). However, in variability measures such as the coefficient of variation, a decrease of force variability has been associated with faster tapping rates, and a decrease of timing variability with increased force levels (Sternad et al., 2000). In an attempt to understand this phenomenon, we assumed that both force and timing pass through two stages – the central (stage 1), during which the production command is issued, and the peripheral (stage 2), when the command is implemented. Either one or both stages might be the locus of an interaction between force and timing when performed together. We also consider the possibility of a third stage, that of feedback adjustment, during which any discrepancy

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[1] *This abstract is a modified version of an original submitted and accepted for a poster presentation at the Donders Discussions: Cognitive and Neuroscience Conference, Nijmegen, Netherlands, 2014.*

between the command and actual execution is detected and the subsequent command adjusted to reduce the error. This third stage might be divided into sensory transmission (with a delay) and central perceptual components. Based on the assumptions regarding the stages, a large force command from the central system would result in a triggering of an increase in the recruitment of motor units and subsequently, an advance of motor implementation timing. Thus, any variation in the current peak force might be expected to result in changes in the time interval immediately following the force event leading to observed correlations in variability measures (Keele et al., 1987).

This force-time relationship was supported by the finding of a cross-correlation pattern which was negative at lag 0 and positive at lag 1 for responses of a repetitive key press task in a study by Keele et al. (1987). The authors noted that the magnitude of the cross-correlations were small (< .20), but significantly different from zero. Interestingly, a similar analysis by Sternad et al. (2000) failed to confirm the presence of this pattern. Cross-correlations over the same range of lags yielded no detectable structure as less than 10% of the dataset concurred with Keele et al.'s (1987) findings. In a comparable analysis in this thesis (Chapter 3), the investigation into the relationship at different force levels and time intervals revealed correlation functions that were no different from zero when pulse-to-pulse peak forces were cross-correlated with time intervals, similar to those found by Sternad et al. (2000).

Although the literature has been equivocal regarding the relationship between force and timing control in repetitive sequences of equal force levels at equal time interval lengths, it is clear that the dependence between force and time is present when a force perturbation occurs within the sequence. Executing one force pulse with more or less force than the preceding pulse lengthens the interval before and after the accented response when intervals are less than 0.3 s (Semjen et al., 1984). In longer responses, the interval before the force change has been reported to be shortened and the following interval lengthened (Billon & Semjen, 1995; Semjen & Garcia-Colera, 1986). This effect was also observed in the previous experiment (Chapter 4) which required participants to separately perform upward and downward transitions in force and timing parameters. Adopting the two-stage architecture for timing in movement production, Semjen and Garcia-Colera (1986), as well as Billon, Semjen and Stelmach (1996) have proposed that the effects of force on time intervals can partly be attributed to a reorganisation of the control mechanism of a dedicated central timing process, such as a clock. As preparations are made to increase or decrease the force level, there is a tendency for peripheral force-time interaction which is strategically compensated by a ‘trick’ adjustment of the central clock. If adjusting the clock is attention demanding, timing stability would be affected, increasing timing variability. Similarly, the force adjustment might itself be attention demanding and increase force variability. Thus, the central clock modulates its timing pattern to accommodate the force change. This modulation is thought to be transient at the point of change, indicating that the salient relationship between force and timing control is temporary (Billon, Semjen & Stelmach, 1996).

The studies mentioned above have assumed that the effects of force and timing coupling are related to central mechanisms. Although exact identification of these central mechanisms remains unclear, it has been postulated that attention resource allocation and memory processes are involved in temporal judgement (Block, 2003). Pacemaker-accumulator timing models usually contain several modules such as (but not limited to a) pacemaker, switch, accumulator, working memory, reference memory, and comparator. It has been postulated that attention operates a ‘gate’ between the pacemaker and the accumulator to control impulses entering the accumulator (Zakay & Block, 1996, 1997). Therefore, within these theoretical constructs, attention may contribute to the variability of timing control. This is further supported by a study with a clinical population: boys with co-morbid attention deficit hyperactivity disorder (ADHD) and developmental coordination disorder (DCD). These boys were found to display higher levels of peak force and time interval variability (Pitcher, Piek, & Barrett, 2002). The authors proposed that these observed variabilities are reflective of an interaction of force with underlying timing dysfunction. Therefore, it is plausible to consider that cognitive factors, in particular, attention, have an effect on force and timing control and, as a result, alter the coupling relationship between these two parameters.

In this chapter we asked how the interaction between force and timing control is affected when available cognitive resources are limited by a secondary task. From an information processing approach, finite cognitive capacities necessitate capacity sharing and implementation of adaptive strategies while dual-tasking, resulting in compromised performance on one or both tasks (Kahneman, 1973). Thus, in dual-tasking paradigms, the time intervals of repetitive responding tend to be more variable when performed with a concurrent secondary task as both tasks compete for available resources. This increase in interval timing variability has been observed over a wide range of tasks such as solving anagrams (Bathurst & Kee, 1994), N-back tasks (Johannsen et al., 2013), running memory span (McFarland & Ashton, 1978), pursuit rotor tracking, visual search and mental arithmetic (Brown, 1997) amongst others. In force control, reduced force output magnitude and increased variability when dual-tasking have been reported in N-back tasks (Voelcker-Rehage, Stronge, & Alberts, 2007), memory recall (Salmon & Thomson, 2007), and choice reaction tasks (Lorist, Kernell, Meijman, & Zijdewind, 2002).

A numerical visual search was selected as a secondary task because it presents a consistent load throughout a trial by requiring a continuous updating of working memory and has been shown to interfere with timing control (Brown, 1997). Such a task demands constant attention to identify a target within an environment of distractors while holding the target in memory. It was also important that the secondary task did not contain any information which might entrain force or timing behaviour. Two difficulty levels of the secondary task were used in this experiment. It is possible that the relationship between force and timing reflects a control strategy which frees cognitive resources to engage in a secondary task. If so, the relationship would become stronger when the secondary task is more difficult. In addition, selective attention towards the secondary task is also expected to increase correlational strength.

Two hypotheses were tested. Firstly, it was predicted that force and timing variance would increase with the presence of a dual-task, even more so with a) a more difficult task, and b) priority (attention) shift to the secondary task. The expected variability increase is assumed to reflect the interference effects of the secondary visual search task on the primary force pulse production task, and vice versa. By testing two different levels of difficulty for the secondary task, effects of a larger magnitude were expected with increasing task complexity. Specifically, in dual task conditions, we predicted 1) longer reaction times (RT) in the secondary task, 2) increased variability in force and timing measures, and 3) that the magnitude of these effects would differ in accordance with selective prioritisation of tasks. Secondly, we hypothesised that the correlation between force and timing will a) increase with priority shift to the visual task (if correlation reflects a control strategy), or b) decrease with priority shift to vision (if correlation reflects difficulty in control). For either possibility, RT and response accuracy are expected to remain unchanged.

A methodological consideration which had been taken into account was the observation by both Sternad et al. (2000) and Keele et al. (1987) who noted that, unlike time intervals, autocorrelation functions of the peak force time series tended to remain positive over two to five lags. The sizable correlations between successive force responses were taken to mean that adaptations in force occurred over a number of responses, resulting in dependence between responses within a particular range before and after the current response. This dependence then was conjectured by both Sternad et al. (2000) as well as Keele et al. (1987) to be related to the small or absent cross-correlation functions, since the relative dependence of successive forces over a number of time lags would tend to reduce the correlation of force with successive time intervals. If force and time separately use feedback control with a similar time span and produce autocorrelated patterns in force and time respectively, the similarities in pattern can produce a spurious cross-correlation. Therefore, it was considered important to remove the autocorrelated process before checking if the residuals are cross-correlated.

5.3 Methodology

5.3.1 Participants

Twelve participants took part in this study (9 females and 3 males, 11 right-handed, 1 left-handed), with a mean age of 27 years old (range 19 to 41 years). All participants provided informed consent to participate and reported no pre-existing motor conditions affecting the arms. Opportunity sampling was used and participants were provided the option of receiving either a standard participant fee of £6 per hour of participation or research credits via the School of Psychology Research Participant Scheme.

5.3.2 Apparatus

Force data were recorded from two single axis load cells (Novatech, Hastings, UK). A plate was mounted on each load cell as a response surface. The force data were saved on a PC via a USB data acquisition device (NI USB-6229, National Instruments, TX, USA) programmed in Matlab (Mathworks, MA, USA). Both load cells were calibrated and force offsets adjusted at the beginning of each session.

5.3.3 Setup

Participants sat facing a computer screen with both forearms at 90 degrees pronation with the upper arm parallel to the torso. The forearms were cushioned to provide comfort. Both index fingers were placed in the middle of the plate with the thumbs and all other fingers closed to avoid contact with the plates (see Figure 40). The computer screen displayed visual input for the task and was programmed in Matlab (Mathworks, MA, USA) using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007).

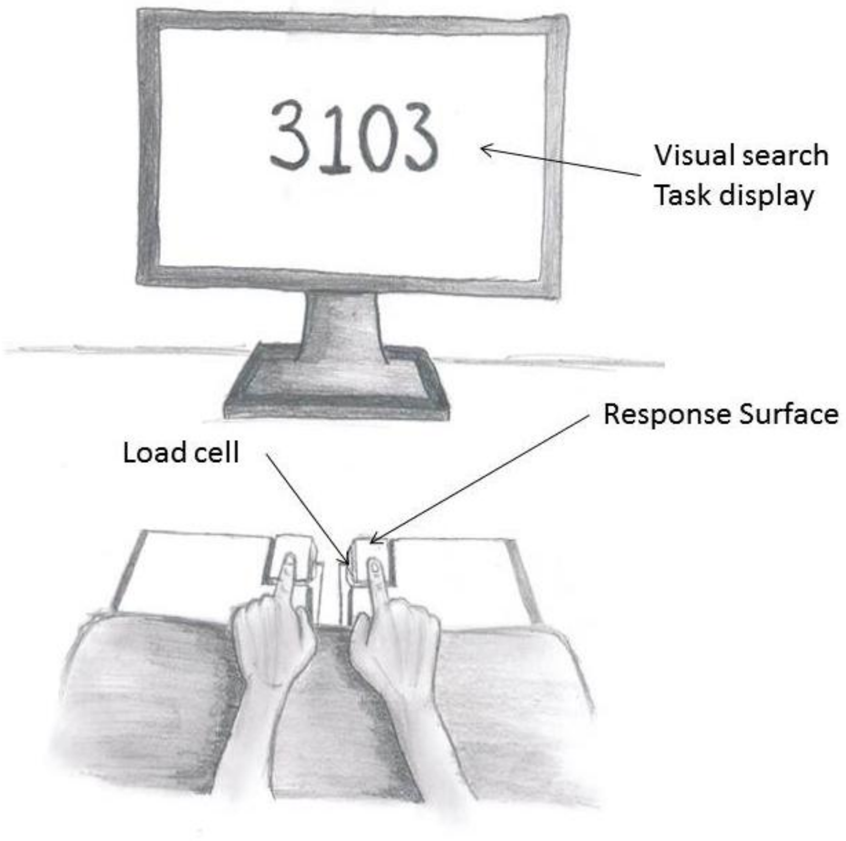

Figure 40: Participants produced pulses using the index finger of their dominant hand and responded to the visual search task using the index finger of the non-dominant hand.

5.3.4 Task

For the primary task, participants were asked to produce repetitive force pulses with the index finger of the dominant hand by pressing downwards onto the plate of the load cell without lifting the finger off its surface. Experimental control over the mean force and time interval produced during the response was obtained by presenting a paced phase at the beginning of each trial. Participants synchronised their responses to a coloured square flashing on-off to indicate timing, and a bar, which increased proportionally in length in accordance with the amount of pressure applied to the load cell to indicate force. The secondary task was a visual search for a target number in a sequence of digits presented 0.3 s apart. The presentations had an inherent jitter related to the use of the ‘Flip’ function in the Psychophysics Toolbox. This resulted in an average presentation interval of 0.3 s with a standard deviation of 0.015 s. The presence of the jitter is seen as an advantage as it discouraged the possibility of synchronising force pulses with multiples of the presentation time (e.g. for a target of 0.75 s and presentation time of 0.3 s, a press can be synchronised to every 2.5 presentations). When a target was detected within the presentation sequence, the response was to produce a pulse using the index finger of the non-dominant hand by pressing down on the load cell as quickly as possible. There were no constraints for the amplitude or duration of the response. Participants were also required to count the number of targets and report the total at the end of each trial. A reaction (as opposed to only counting) was required firstly as a behavioural indication that the secondary task was performed optimally, and more importantly, as a measure of whether task prioritisation was successfully performed. Reaction times when the secondary task was prioritised were expected to be shortest.

5.3.5 Procedure

Participants had a practice session to familiarise themselves with the pulse production task. The target interval was 0.75 s and the target force was 2 N. A square, flashing on and off at an interonset interval of 0.75 s, was presented as a visual metronome to provide the time interval for the task. Participants were asked to synchronise their pulses with the flashing. Force information was presented in the form of a vertical bar which increased in height according to the pressure applied on the load cell. A horizontal bar at the 2 N mark indicated the target force. When the force level approximated the target level, the colour of the horizontal target bar changed from white to green to indicate that the force they were producing was within a range of ±10% of the 2 N target. Participants learned to synchronise achieving the green bar in time to the flashing of the square.

In the experimental trials, a visual search target consisting of numerical digits was presented at the beginning of each trial for 4 s. Then the paced phase (similar to the practice session) commenced and lasted for 10 pulses. Participants were instructed to continue the pulses until the end of the trial after the paced phase stopped. A fixation cross was briefly presented for 1 s to focus the participants' attention on the middle of the screen where the sequence of numbers was presented (see Figure 41). If the target appeared, they were required to respond as quickly as possible with a non-dominant index finger pulse. The number of targets was monitored and reported at the end of each trial. The sequences of numbers were generated using the random number generator in Matlab. The random number generator was shuffled based on the current time so that a different sequence of numbers was generated for every trial. From the sequence, one number was randomly selected to be the target. All other instances of this number in the sequence were removed and replaced with another random number. Ten target locations were then randomly selected and the target number was reinserted into the sequence. All targets were constrained to appear more than 2 s between each presentation to allow adequate time for a response. The digits in the sequence ranged between zero and nine, as well as between 1111 and 9999 for different difficulty levels.

There were two levels of visual search target difficulties (one and four digits) and three different instruction conditions (no prioritisation, prioritise pulse production, and prioritise visual search). The experimental conditions were:

1) dual-task one digit visual search with no prioritisation, D1N,
2) dual-task four digit visual search with no prioritisation, D4N,
3) dual-task one digit visual search with pulse prioritisation, D1P,
4) dual-task four digit visual search with pulse prioritisation, D4P,
5) dual-task one digit visual search with visual search prioritisation, D1V, and
6) dual-task four digit visual search with visual search prioritisation, D4V.

There were also three control conditions which consisted of only pulse production (S) or only the reaction time task, one digit (S1) as well as four digits (S4). In total, there were nine blocks of conditions consisting of eight repetitions in each block and lasting 60 s per trial. The presentation order of the blocks were randomised for each participant but was constrained to always start with either D1N followed by D4N, or vice versa (D4N followed by D1N).The use of this order ensured that participants did not carry over any prioritisation effects if D1N and D4N were presented after blocks with prioritisations. The experiment was split into two one-hour sessions conducted on different days to minimise fatigue effects.

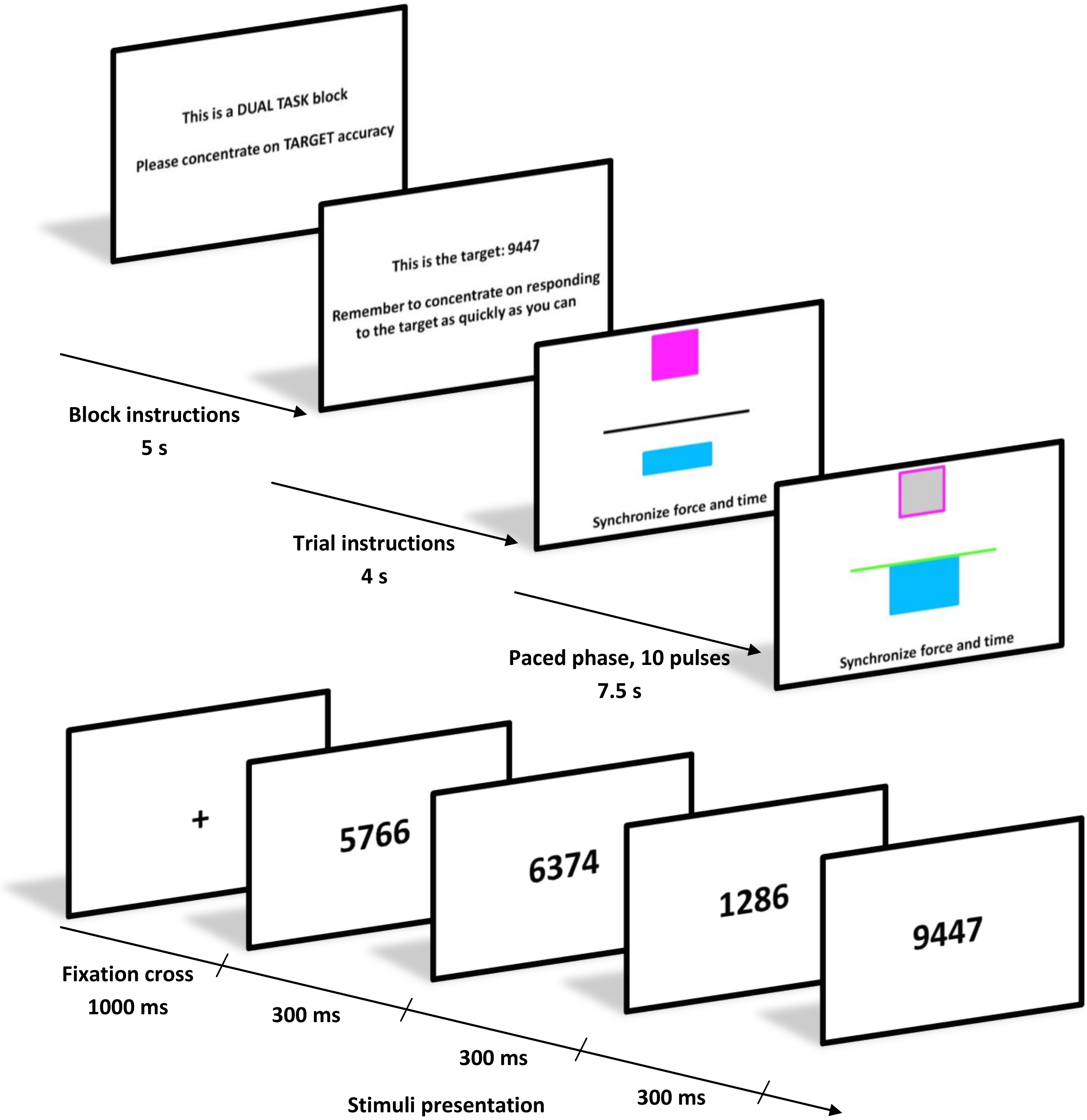

Figure 41: Illustrative trial event sequence with 4-digit visual target appearing in the fourth position.

5.3.6 Analysis

The raw force signal recorded at 1 kHz was passed through a 4th order low pass Butterworth filter with a cutoff frequency of 20 Hz. The signal was filtered both forwards and backwards to remove the phase shift which occurs with digital filters. A peak detection algorithm, written in Matlab (Billauer, 2012), was used to obtain a continuous time series of local maximum responses and the time of each of those occurrences from the filtered force signal. The event times were then differenced to yield the IRI between two responses (see Figure 42(b)). The reaction time for the visual search task was obtained by calculating the time difference between a generated pulse which was triggered when the target appeared, and the reaction force pulse produced by the non-dominant index finger on the load cell. The peak rate of change of force (dF/dt) of the reaction pulse was used as the event of the reaction time (see Figure 42(b)).

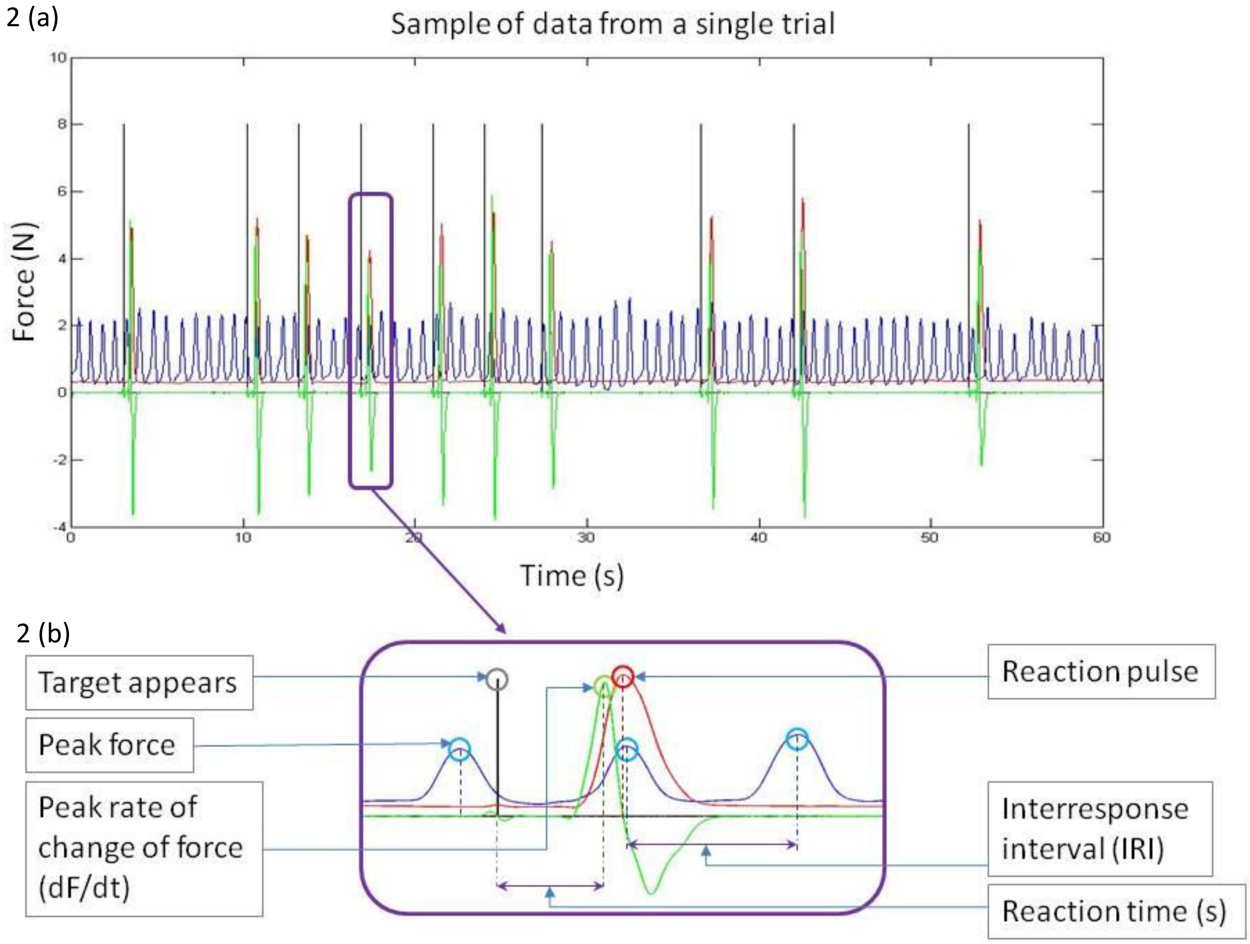

Figure 42: Overlay of force traces depicting a single pulse production trial with concurrent visual search (a). Peak detection algorithms were applied to the signals to obtain PF values, IRIs and reaction times (b).

Trial means (M) of peak force and IRIs were obtained and averaged across participants by condition. Variability measures computed included the standard deviation (SD) and coefficient of variation (CV; SD/M). The M and SD datasets were subjected to a 2-way repeated measures analysis of variance, ANOVA, using IBM SPSS Statistics for Windows, Version 21.0 (Armonk, NY: IBM Corp). The two within subject factors were 1) visual search difficulty (one digit; four digits), and 2) prioritisation (none; pulse; visual search). The CV yields a standardised value between 0 and 1 for both peak force and IRI, allowing a comparison between these two parameters. Therefore, the CV was subjected to a 3-way repeated measures ANOVA [additional within subject factor being parameter (PF; IRI)] to explore interaction patterns for force and timing parameters. Paired t-tests were applied to all three datasets (M, SD, CV) for comparison against single task performance which served as the control condition. Means of reaction times (RTs) were subjected to a 2 x 4 repeated measures ANOVA. The within subject factors were 1) visual search difficulty (one digit; four digits), and 2) task condition (single task; dual task no prioritisation; dual task pulse prioritisation; dual task visual search prioritisation). For all ANOVAs, where Mauchly's Test of Sphericity was significant, Hyunh-Feldt corrected values were reported if epsilon, $\varepsilon > .75$, and Greenhouse-Geisser corrected values were reported if $\varepsilon < .75$. Significant effects were further explored with paired t-tests. Where multiple comparisons were made, the Bonferroni correction was applied to the significance level of $p = .05$ by adjusting the significance to *p*/number of comparisons.

Cross-correlation functions were calculated for IRIs and PF as a measure of relationship between the two time series as a function of time-lags. To ensure both series were stationary, the line-of-best-fit linear trend was removed from each series in every trial before cross-correlating the residuals. The cross-correlation functions were then averaged between participants and independent sample t-tests were applied to determine if the functions were significantly different from zero.

While it is interesting to look at cross-correlation functions across many lags, we are specifically interested in lags -1, 0 and 1, and therefore have chosen to discuss these three lags.

5.4 Results

Overall, PF were overestimated by 25% compared to the 2 N target with an average of 2.493 N (SD=.395 N) across all conditions. In contrast, interresponse intervals (IRIs) were accurately produced at the target of 0.75 s (M = 0.746 s; SD = 0.085 s).

5.4.1 Means

Results for PF and IRI means are summarised in Figure 43 below. For both parameters, ANOVAs revealed one significant main effect each but no significant interaction effects. None of the dual-task peak forces differed from the single task condition, indicating that participants performed the task as required. Of the two factors tested on PF means in a 2-way repeated measures ANOVA, there was a significant main effect of Prioritisation, F(2,22)=6.312, *p*=.017 but not Visual search difficulty, F(1,11)=1.004, *p*=.338. Paired t-test comparisons subsequently showed significant differences between D4N and D4P, t(11)=4.118, *p*=.002. No interaction effects were found between Prioritisation and Visual search difficulty, F(2,22)=.428, *p*=.657. Three comparisons showed trends towards significance and two of these were D4N compared with D1P (t(11)=2.471, *p*=.031) as well as with D1V (t(11)=2.192, *p*=.051). The third comparison was between D1N and D4P (t(11)=2.400, *p*=.035).

Dual-task IRI performance was similar to the single task when pulse was prioritised, as indicated by no significant differences between S and D1P (t(11)=1.822, *p*=.096), as well as with D4P (t(11)=2.810, *p*=.017; *p*<.008 after Bonferroni correction). The remaining four comparisons, involving no prioritisation and visual search prioritisation while dual tasking, differed from the single task control condition. These involved S compared with D1N (t(11)=3.711, *p*=.003); D4N (t(11)=5.624 *p*<.001); D1V (t(11)=3.957, *p*=.002); and D4V (t(11)=3.993, *p*=.002). The ANOVA outcome for IRIs was similar to peak forces. There was a significant main effect of Prioritisation, F(2,22)=3.820, *p*=.038, but not Visual search difficulty, F(1,11)=.174, *p*=.684. Interaction effects between Prioritisation and Visual search difficulty was not significant, F(2,22)=.693, *p*=.510. Two other t-test comparisons showed a trend towards significance, and they involved D1P compared with D4N (t(11)=-2.323, *p*=.040) and D1V (t(11)=2.201, *p*=.050). Overall, dual-tasking affected timing control, however for force, accuracy remained similar to single task performance.

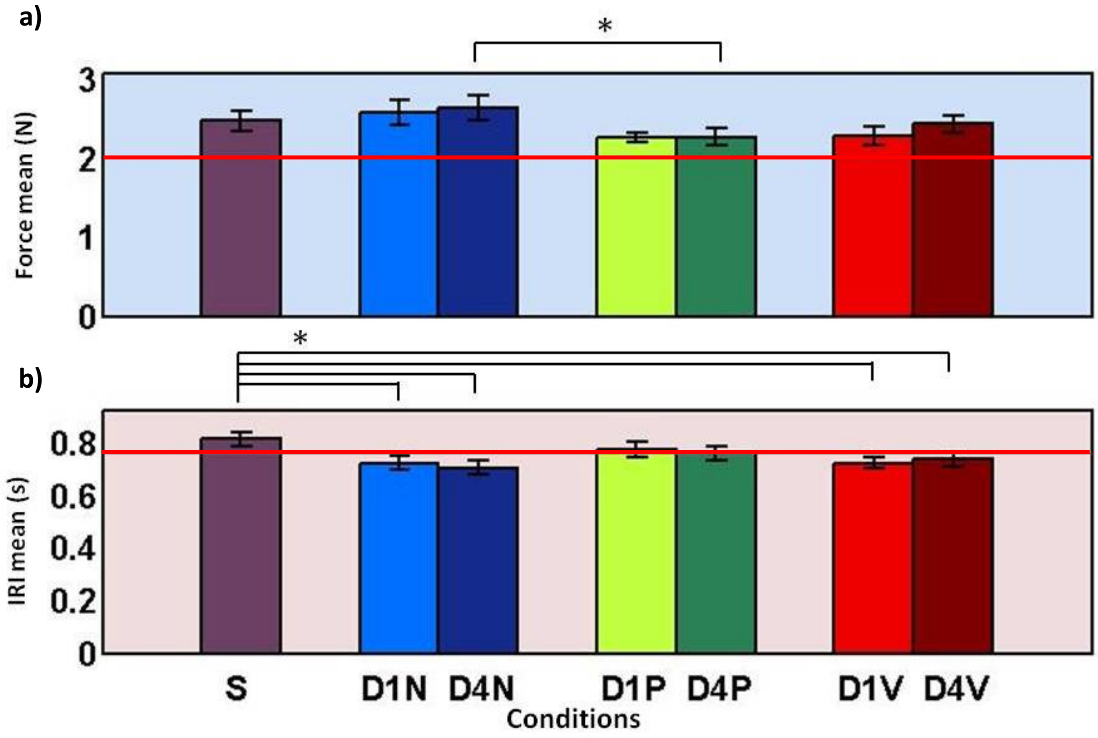

Figure 43: Means of PF (a) and IRI (b) grouped by prioritisation type (None [N], Pulse [P], Visual search [V]) for both visual search difficulty levels (one [1] and four [4] digits). Bar S, refers to performance in the single task control condition. Significantly different t-test comparisons (*p*<.008 after Bonferroni correction) are indicated with a star (*). Red horizontal lines denote target force (2 N) and IRI (0. 75 s). Error bars represent ±1 SE.

5.4.2 Variability

Figure 44 summarises the results for PF and IRI variability. Similar to the means, ANOVAs revealed one significant main effect each but no significant interaction effects for both parameters. Paired t-test comparisons on PF variability showed that none of the dual task conditions were significantly different from single task performance, although there was a trend towards significance in the comparison between S and D4N (t(11)=-2.885, *p*=.015). The 2-way ANOVA revealed that task prioritisation had an effect on peak force variability F(2,22)=3.804, *p*=.038. Subsequent paired t-tests indicated trends towards significance involving D1N compared with D1P (t(11)=2.292, *p*=.043) and with D4P (t(11)=2.277, *p*=.044), as well as D4N and D1V (t(11)=2.351, *p*=.038). In contrast, there was no significant main effect of Visual search difficulty F(1,11)=1.485, *p*=.248, or interaction effects between both factors F(2,22)=.975, *p*=.393.

For IRI variability, single task performance was significantly different from all dual task conditions. This was indicated by paired t-test comparisons between S and D1N (t(11)=-8.169, *p*<.001); D4N (t(11)=-6.510, *p*<.001); D1P (t(11)=-5.009, *p*<.001); D4P (t(11)=-5.433, *p*<.001); D1V (t(11)=-6.612, *p*<.001); as well as D4V (t(11)=-5.559, *p*<.001). The 2-way ANOVA showed a significant main effect of task prioritisation F(2,22)=3.860, *p*=.037, supported by a trend towards significance between D1N and D1V (t(11)=2.336, *p*=.039). There was neither main effect visual search difficulty F(1,11)=.080, *p*=.782, nor interaction effects between task prioritisation and visual search difficulty F(2,22)=.650, *p*=.532. In a trend similar to mean values, dual-tasking affected timing variability but not force variability.

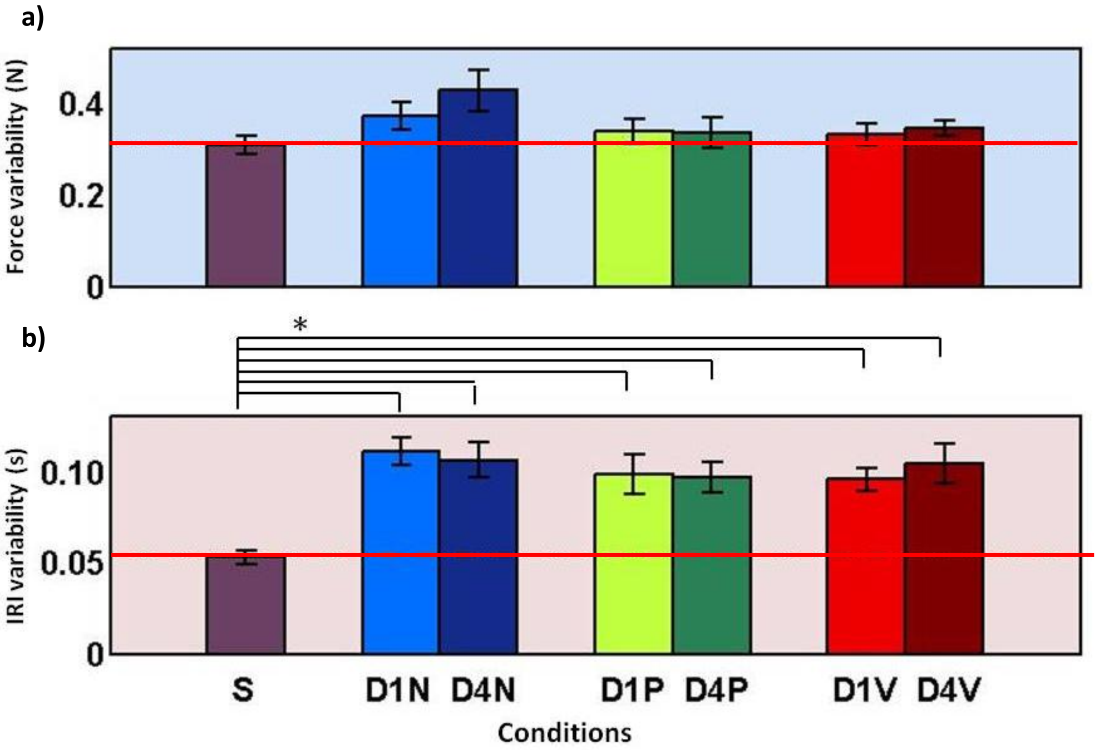

Figure 44: Variability of PF (a) and IRI (b) grouped by prioritisation type (None [N], Pulse [P], Visual search [V]) for both visual search difficulty levels (one [1] and four [4] digits). Significantly different t-test comparisons (*p*<.008 after Bonferroni correction) are indicated with a star (*). Red horizontal lines represent performance in the single task condition (S). Error bars represent ±1 SE.

5.4.3 Coefficient of Variation

The coefficient of variation (CV) was calculated as a standardised measure of variability. Figure 45 presents an overview of CV results. Out of the three factors tested in the ANOVA, there was one significant main effect. No interaction effects were found. In comparisons with single task CVs, PF CV in S was significantly different from D4N (t(11)=-3.764, *p*=.003). There were trends towards significance when S was compared with D1P (t(11)=-2.338, *p*=.039), D1V (t(11)=-3.142, *p*=.009) and D4V (t(11)=-2.363, *p*=.038). All dual task IRI CVs were significantly different when compared with single task CV. These involved S compared with D1N (t(11)=-9.942, *p*<.001), D4N (t(11)=-8.855, *p*<.001), D1P (t(11)=-5.628, *p*<.001), D4P (t(11)=-5.773, *p*<.001), D1V (t(11)=-6.960, *p*<.001), and D4V (t(11)=-6.461, *p*<.001).

A 3-way ANOVA with factors: 1) Parameter – peak force, IRI; 2) Visual search difficulty – one digit, four digits; 3) Prioritisation - none, pulse, visual search; revealed a significant main effect of Prioritisation F(2,22)=5.706, *p*=.010. Neither parameter F(1,11)=.823, *p*=.384, nor visual search difficulty F(1,11)=.567, *p*=.467 had a significant effect on CVs.

Subsequently, one paired t-test showed significant differences and this involved the comparison between D1N and D1P (t(11)=3.359, *p*=.006). Five other comparisons showed trends towards significance. Two of these involved D1N compared with D4P (t(11)=3.133, *p*=.010) and with D1V (t(11)=3.093, *p*=.010). The other three were comparisons between D4N and D1P (t(11)=2.746, *p*.019), D4P (t(11)=2.413, *p*-.034), and with D1V (t(11)=2.208, *p*=.049).

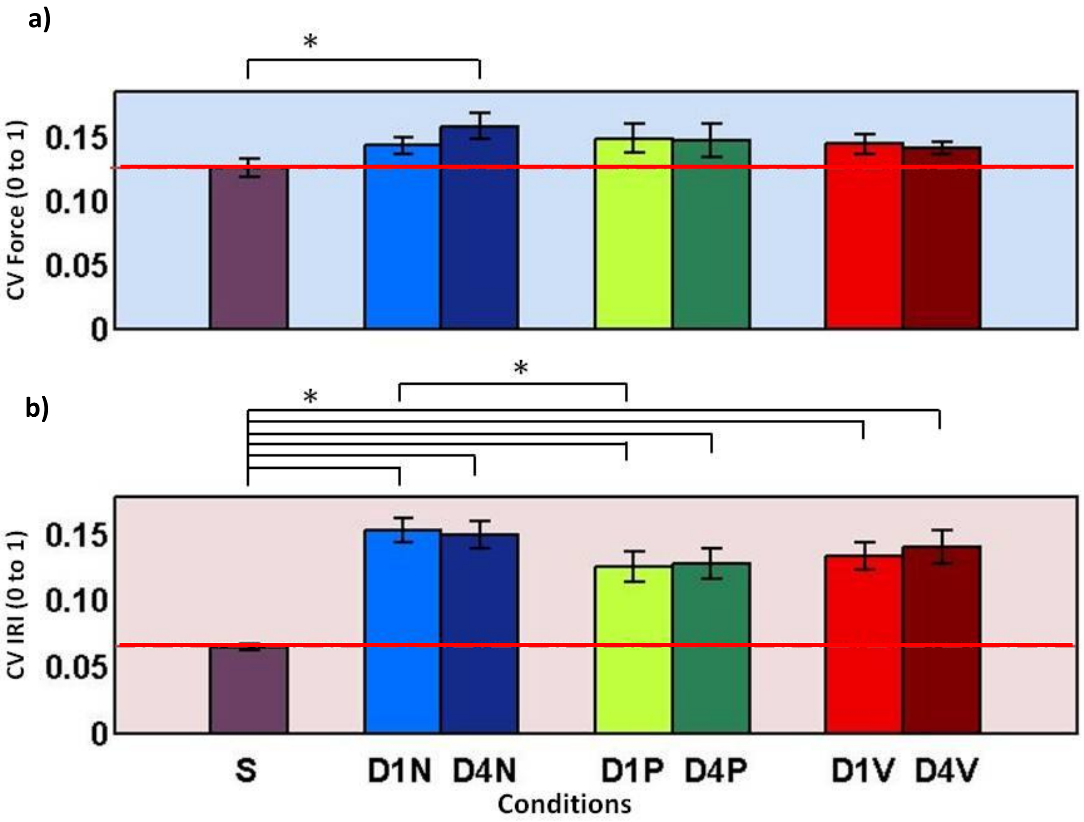

Figure 45: CV of PF (a) and IRI (b) grouped by prioritisation type (from left to right: None [N], Pulse [P], Visual search [V]) for both visual search difficulty levels (one [1] and four [4] digits). Significantly different t-test comparisons (*p*<.008 after Bonferroni correction) are indicated with a star (*). Red horizontal lines represent performance in the single task condition (S). Error bars represent ±1 SE.

5.4.4 Cross-correlations

Cross-correlation analysis was run on the time series of IRIs and PFs to determine if there was any relationship between IRIs and PFs as a function of time lags. Within the time series of IRIs and PFs there are N+1 number of PFs for every N number of intervals, since each IRI is calculated as the time difference between two PF events. Therefore, we excluded the first PF in every series to equalise the length of both series. This meant that at lag 0, each pair of time interval (IRI_n) and peak force (PF_n) values referred to the interval leading up to the PF and the PF which terminated the interval (see Figure 46). Lag -1 denotes the relationship between the current time interval (IRI_n) and the following peak force (PF_{n+1}), whereas the lag 1 correlation describes the relationship between the current time interval (IRI_n) and the previous peak force (PF_{n-1}).

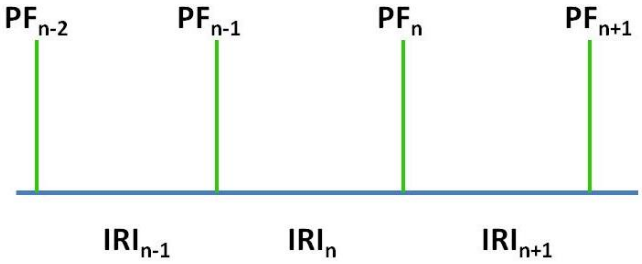

Figure 46: Positions of PF and IRI as described in cross-correlations.

The cross-correlation functions were not significantly different from zero in the single task condition [lag -1, *p*=.344; lag 0, *p*=.660; lag 1, *p*=.196]. However, this was not the case in dual task conditions (see Figure 47).

No Prioritisation

When the one digit visual search task was paired with no prioritisation, cross-correlations were negative at lag -1 [t(22) =-3.670; *p*=.001], and positive at lag 0 [t(22) = 2.657; *p*=.014]. Lag 1 was not significantly different from zero (*p*=.218). During the four digit visual search task, none of the three lags of interest were significantly different from zero [lag -1, *p*=.080; lag 0, *p*=.841; lag 1, *p*=.945].

Pulse Prioritisation

When participants were asked to prioritise pulse production, the cross-correlation functions were not significantly different from zero for both the one digit visual search task [lag -1, *p*=.944; lag 0, *p*=.133; lag 1, *p*=.079] as well as the four digit visual search [lag -1, *p*=.775; lag 0, *p*=.856; lag 1, *p*=.652].

Visual Search Prioritisation

When the visual search task was given priority over pulse production, the cross-correlation functions were negative at lag -1 for both one [t(22) =-2.277; *p*=.033], and four digit [t(22) =-2.703; *p*=.013] conditions. Lags 0 and 1 were not significantly different from zero in the one digit [lag 0, *p*=.150; lag 1, *p*=.832] as well as four digit [lag 0, *p*=.279; lag 1, *p*=.575] conditions.

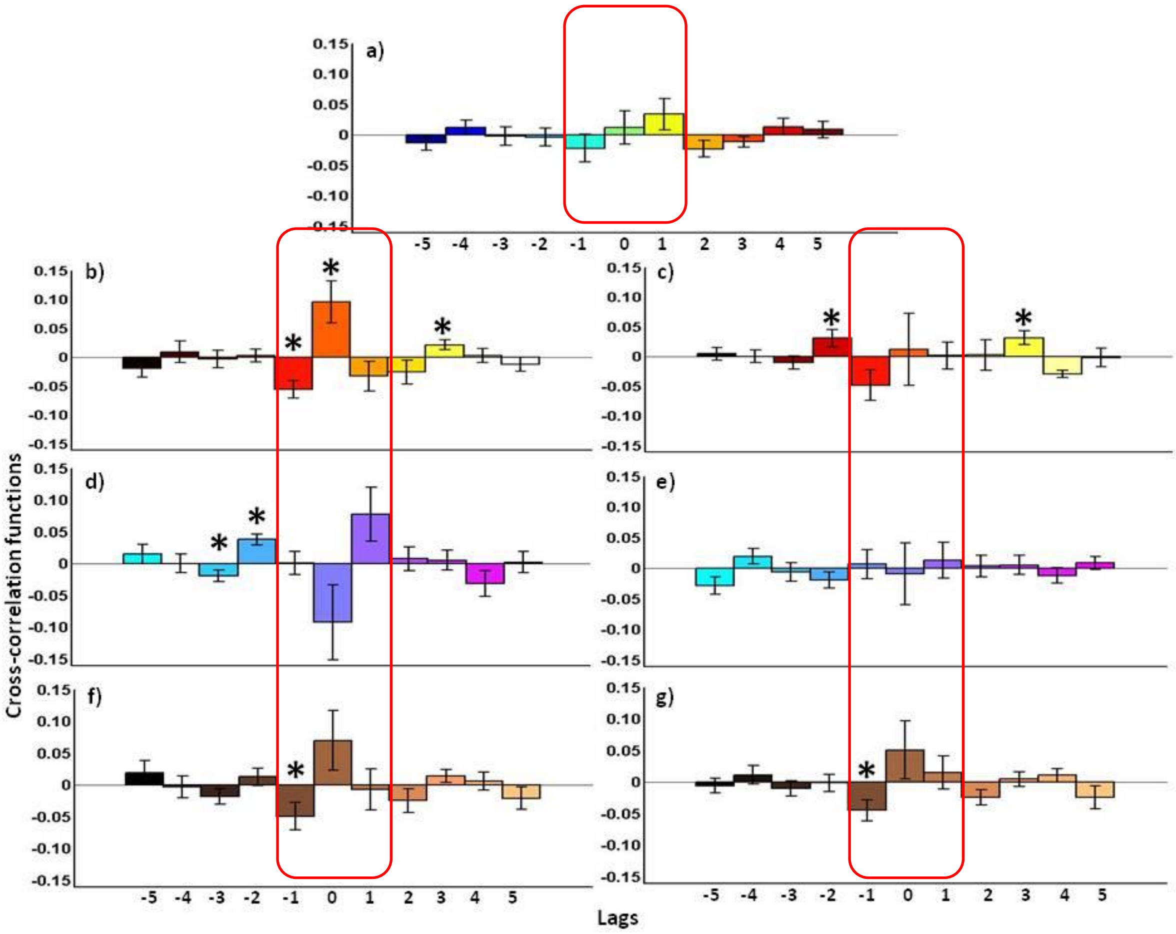

Figure 47: Cross-correlation functions between IRIs and peak forces between lags -5 and 5 by condition: Single task (a) and Dual task (b) – (g). Columns: left 1-digit; right 4-digits. Rows from top to bottom: no prioritisation, pulse prioritisation, visual search prioritisation. Highlighted regions (rectangles) indicate lags of interest, -1, 0 and 1. Lags significantly different from 0 (*p*<.05) are indicated with an asterisk (*). Error bars represent ±1 SE.

5.4.5 <u>Visual Search Task</u>

Figure 48 and Figure 49 present the RTs and targets reported in the visual search task, respectively. Overall, participants had quicker RTs in the one digit visual search (M=.488 s, SD=.013 s) compared to the four digit condition (M=.630 s, SD=.018 s). A 2 x 4 ANOVA was run on the RTs with the within-subject factors of visual search difficulty and task condition. There were significant main effects of both visual search difficulty F(1,11)=158.236, *p*<.001 and task condition F(1.464,16.104)=9.869, *p*=.003, but no visual search difficulty*task condition interaction effects (F(3,33)=.830, *p*=.487). Post hoc tests with Bonferroni correction indicated that all RTs in the one digit visual search were significantly different from four digit task RTs (*p*<.001). This was supported by t-test comparisons of visual search difficulty RTs by task condition, all of which were significantly different, S1-S4 t(11)=-14.127, *p*<.001; D1N-D4N t(11)=-8.350, *p*<.001, D1P-D4P t(11)=-5.047, *p*<.001, and D1V-D4V t(11)=-9.873, *p*<.001.

In addition, t-tests also revealed that RTs in S1 (M=.432 s; SD=.037 s) were significantly quicker than all other one digit task conditions, D1N (M=.497 s, SD=.054 s, t(11)=-5.978, *p*<.001), D1P (M=.552 s, SD=.102 s, t(11)=-4.153, *p*=.002), and D1V (M=.469 s, SD=.042 s, t(11)=-3.799, *p*=.003). RTs in D1N and D1V were also significantly different, t(11)=3.269, *p*=.007.

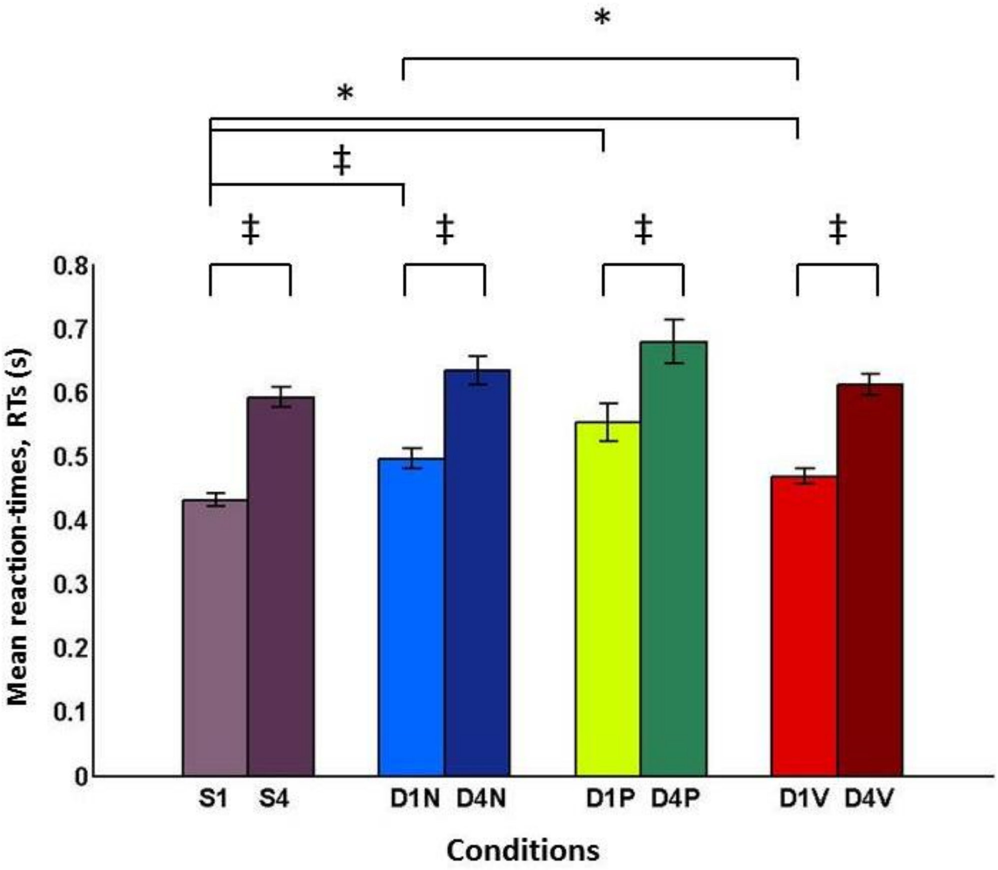

Figure 48: Reaction times (s) for the visual search task grouped by task condition, from left to right: single task, no prioritisation, pulse prioritisation, visual search prioritisation. Within each group, one digit and four digit conditions are on the left and right, respectively. Significantly different t-test comparisons are indicated with a star (*) where *p*<.008 (with Bonferroni correction for multiple comparisons) and a double plus (‡) where *p*<.001. Error bars represent ±1 SE.

Participants reported noticing more visual search targets for one digit conditions in comparison with four digit conditions. This was supported by significant paired-test comparisons between the one and four digit responses in the single task (t(11)=4.126, *p*=.002), no prioritisation (t(11)=4.023, *p*=.002), pulse prioritisation (t(11)=3.915, *p*=.002) and visual search prioritisation (t(11)=4.212, *p*=.001) conditions. However, there were no differences between task conditions (see Figure 49).

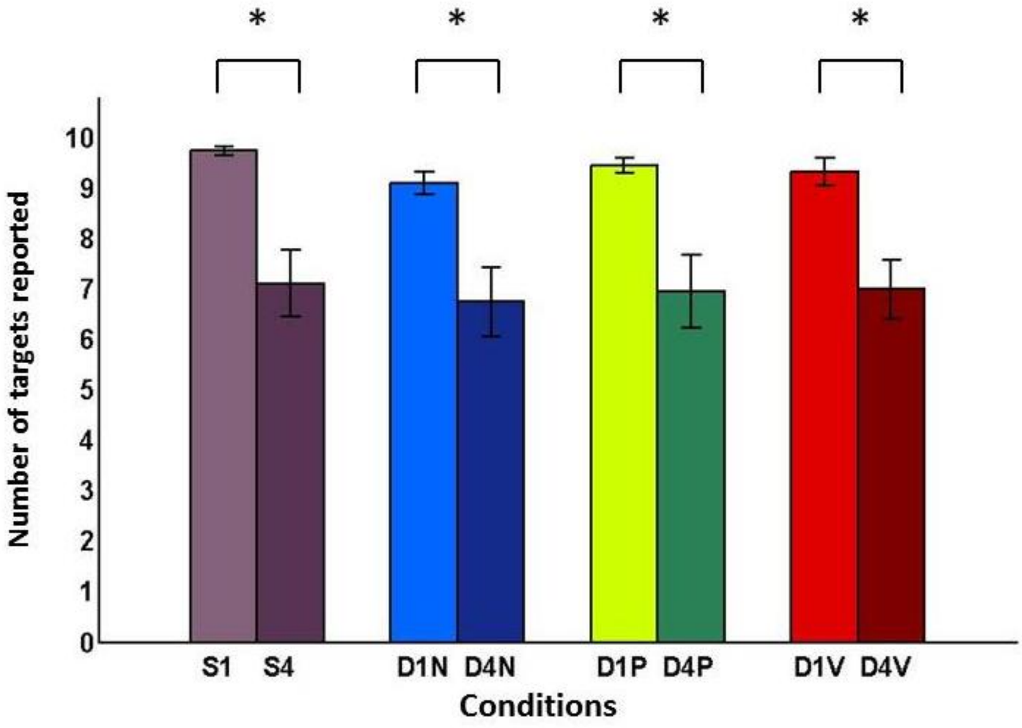

Figure 49: Number of targets reported for the visual search task grouped by task condition, from left to right: single task, no prioritisation, pulse prioritisation, visual search prioritisation. Within each group, one digit and four digit conditions are on the left and right, respectively. Significantly different t-test comparisons are indicated with a star (*) where *p*<.008 (with Bonferroni correction for multiple comparisons). Error bars represent ±1 SE.

5.5 Discussion

Demonstrating interactions between force and timing control has been elusive in previous literature. Although it might seem almost trivial that timing and force development are tightly related in producing movements scaled with appropriate force levels at varying times, correlational measures of both these parameters have been inconclusive. In this study, we tested whether the presence of the relationship between force and timing control is mediated by cognitive factors.

In addition to producing force pulses, participants engaged in a secondary visual search task and were asked to either prioritise the pulse production task or the visual search task. The main aim of the study was to examine if a concurrent secondary task altered the pulse-to pulse relationship between peak forces and time intervals by applying cross-correlation analysis to the time series of peak forces and time intervals. Subsequently, the secondary aim of the study was to investigate if directing attention to one or another task had an effect on the interaction.

Overall, both force and timing control were affected by the secondary task, more so for timing than for force. Although time intervals were very accurately produced under all conditions, both variability measures indicated that participants were twice as inconsistent when dual-tasking. However, neither the task difficulty level nor the prioritisation of tasks affected the magnitude of the variability. Interestingly, when priority was given to the pulse production task, timing performance was more similar to that of the single task. The effects of the secondary task on force control were less clear. Mean peak force values were very similar during both one digit and four digit visual search tasks. The variability of force was slightly higher when dual-tasking without directing attention to either task. With prioritisation of either task, performance was no different from the single task condition. These findings suggest that timing is more affected by force control with the addition of a secondary task and this is reflected in variability measures even though average performance accuracy remains the same.

Although task prioritisation did not have a significant effect on the pulse production task, reaction time performance was clearly compromised. RTs were longest when pulse production was prioritised and shortest when the visual search task was given priority. This effect was even more prominent for the one digit search task than the four digit trials. This difference in RT was present despite no difference in participants' reports of number of targets spotted. Taken together, performance of both primary pulse production and secondary visual search tasks deteriorated under dual-tasking conditions. Neither the difficulty levels of the visual search task, nor prioritising one task over the other affected pulse production. However, both task difficulty and prioritisation produced a one way interference which increased reaction times in visual search. Participants did not report any perceptual differences of spotting the visual target under different prioritisation conditions.

By examining mean measures, neither visual search difficulty nor different prioritisation strategies seemed to have had a significant effect on force and timing control apart from increasing variability measures. However, the cross-correlation functions between time intervals and peak forces revealed a different picture. It was found that cross-correlation functions for pulse production without the secondary task were no different from zero indicating no relationship between time intervals and force pulses over 10 time lags. This is consistent with previous findings by Sternad et al. (2000) as well as those reported in Chapter 3. However, with the inclusion of the secondary visual search task, different patterns emerged, corresponding with different prioritisation strategies. This variation in correlation patterns distinguish between the effect of higher cognitive processes and lower motor interactions since the latter would be expected to produce similar patterns across all conditions.

When the visual search task was prioritised, there was a positive correlation at lag 0 and a significant negative correlation at lag -1. This correlation pattern means that a longer time interval terminates with a higher peak force which is subsequently followed by a lower peak force. The higher peak force would have triggered a necessary correction to the subsequent force pulse. It is possible that because more attention was given to the visual search task, an over-correction occurred on the following response. Evidently, this effect could be caused by the persistent positive autocorrelation functions which have been observed within the force time series in this and other studies (Keele et al., 1987; Sternad et al., 2000) rather than a result of prioritisation. Although detrending was applied, there could still be autocorrelation trends which remain if they did not correspond to the model of the line of best fit applied during detrending. However, despite this consideration, the cross-correlation pattern was absent when the pulse production task was prioritised, indicating that the task condition contributed to the effect rather than the properties of the time series. We expected the effect to be larger when the visual search task was more difficult, but the magnitude of the cross-correlations remained similar to those of the simpler search. Therefore, we interpret the correlation pattern as a reflection of a ‘global control strategy‘, which is applied to make cognitive resources available for a secondary task when attention is intentionally focused away from pulse production. This reasoning is supported by the quicker reaction times observed.

An exception to this interpretation would be the finding of similar cross-correlation patterns when neither pulse production nor visual search was prioritised. However, this was only observed when the visual search was simple whereas when the visual search was difficult, the cross-correlations were more similar to those when pulse production was prioritised. This finding is interesting. Although somewhat counterintuitive, it is possible nonetheless that a simple secondary task requires less attention to be focused on maintaining the primary task, therefore, the cross-correlations are similar to when the visual search task is prioritised. In a more difficult secondary task, more attention needs to be given to the primary task, and the correlations are as though pulse production was prioritised. This could be a plausible strategy of maintaining primary task performance which resulted in very consistent force and timing control despite the different difficulty levels. Switching between task prioritisation strategies has been described in repetitive movements (e.g. walking, Yogev-Seligmann, Hausdorff & Giladi, 2012). However, to the best knowledge of the author, the use of cross-correlations as a method of characterising these strategies is novel and therefore further investigation would be necessary to confirm these conjectures.

Two limitations were identified in this study. Firstly, timing information was presented using a box flashing on and off. The time interval was derived from the length of time between an ‘on’ box (pink square) changing to ‘off’ (grey square) and an ‘off’ box changing to ‘on’. In contrast, force information was presented as a blue bar which increased in height as pressure was applied. A horizontal line across the screen represented the target force level to achieve. It turned green when the force level fell within ± 10% of the target force. Therefore the aim during the synchronisation phase was to match the flashing of the box with the horizontal line turning green. Both force and timing information were presented in the visual modality in an attempt to control for any auditory bias towards timing and for possible performance differences attributable to modality specific effects if two types of pacing signal were used. However, one inconsistency of this method was the presence of feedback for force but not timing. Since the purpose of the paced phase was to provide as much information as possible to achieve a steady performance during the continuation phase, future studies could include feedback for timing synchronisation to equalise both force and timing input. Using a visual stimulus has also been recognised as a poor cue for synchronisation (e.g. Chen, Repp, & Patel, 2002). Synchronising with a moving visual target has been showed to improve performance (Hove, Iversen, Zhang, & Repp, 2013) and was considered for this study. However, the displacement would be a distraction from observing the force target which remained static. Therefore, the timing target was presented at a consistent position in the middle of the screen with the force target, to encourage optimal performance for both parameters. Presenting timing information with the method chosen for this study was effective as indicated by overall timing performance for all participants which was precise and achieved with low variability (M = 0.746 s; SD = 0.085 s).

Secondly, although the visual search was considered effective in demonstrating the effect of attention on force-time dependence, it has to be noted that because this task required a motor response, it is not entirely clear how much the cognitive task by itself affected force-time control. It has been reported that concurrent verbal tasks disrupted timing more than nonverbal tasks, and that this effect is more prominent in left-handers (Bathurst & Kee, 1994). Therefore, it would not be surprising if the requirement of producing a response during the dual-task contributed to the variability of pulse production. In an attempt to control the effects of interference, right-handed participants were preferred for this study, however there was still one left-handed participant's dataset in this experiment. It would be interesting for future studies to compare the differences in performance variability between left- and right-handed participants. From an experimental design point of view, the inclusion of a condition where participants performed the visual search task but without a motor response would provide an objective quantification of the effects of the cognitive task by itself.

In summary, participants achieved the primary force and time interval task requirements. Reaction-times were slower with the more complex four digit visual search, and faster with visual task priority. Variability for both force and timing increased with dual-task but the more complex four digit task and visual priority did not increase the magnitude of the effect. Cross-correlations departed from zero in dual-task compared to single task suggesting that correlation reflects a loss of control, which was handled differently when priority was given to the pulse. However the expected increased correlations with four digit visual search task were absent; it remained similar to the single digit performance.

CHAPTER 6

CASE STUDIES OF FORCE-TIME INTERACTIONS IN PATIENTS MH AND SM

6.1 Abstract

The motor expression of a repetitive rhythm requires a combination of precise motor timing and force control. Cognitive factors have been shown to have an effect on cross-correlations between peak forces and time intervals while dual-tasking, suggesting that the interaction reflects a control strategy when availability of cognitive resources is limited. The present study explored the performance of two cerebrovascular accident (CVA) patients with cognitive difficulties in the praxis domain as identified by the Birmingham Cognitive Screen (BCoS; Humphreys et al, 2012). Force-time dependence of a larger magnitude was predicted. Two patients (left-brain damage) produced repetitive force pulses on a force sensor (target of 2 N; 0.75 s). Data from eight 60 s trials were collected. Time series of peak force (PF) values and interresponse intervals (IRI) from the pulse production task were cross-correlated up to +/- 5 lags to determine co-variation between successive force and timing pairings. Data were compared with the equivalent task performed by 12 healthy participants. Force-time correlations were reliably positive at lag 0, and negative at lags -1 and 1 in patients. Correlation magnitudes were twice as large as those observed in controls. Patient SM had elevated force variability whilst patient MH had elevated timing variability in comparison with controls. The maintenance of force and timing production which requires corrections against an internal standard is attention demanding. Results suggest that in CVA patients, the larger correlation

magnitude reflects the additional attention demands required to produce pulses successfully. [1]

6.2 Introduction

As demonstrated in the previous chapter, the control of force and timing can be influenced by cognitive factors, in particular, attention. The dependence between force and timing could be a control strategy to free resources for engaging in a secondary task. This was implied by significant cross-correlation patterns which were not present in single task performance. Controlling both parameters simultaneously as one unit possibly utilises less resources than individual control for more efficient execution of two simultaneous tasks. Assuming this were true, we would expect larger dependence between force and time with increasing cognitive limitations. In this chapter, we investigate the force-time relationship in patients who experience cognitive difficulties in the praxis domain as a result of cerebrovascular accidents (CVAs).

Lower levels of cognitive function have been identified as a risk factor for decline in motor functioning (Alexander & Hausdorff, 2008). The relationship between cognitive impairment and motor abnormalities has been extensively studied in gait (Buracchio, Dodge, Howieson, Wasserman, & Kaye, 2010; Camicioli, Howieson, Oken, Sexton, & Kaye, 1998). When the attention demands of gait have been tested using dual-tasking methodologies, increasing the attention demand of a simultaneous cognitive task resulted in a decrease of resources available to perform gait. This trade-off is most commonly observed as a slowing down in gait speed and increase

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[1] *This abstract was submitted and accepted for a poster presentation at the Rhythm Perception and Production Workshop (RPPW) to take place at Amsterdam, Netherlands, July 2015.*

of step-to-step variability in healthy elderly adults (Dubost et al., 2006; Lindenberger, Marsiske, & Baltes, 2000) as well as in patients with Parkinson’s disease (Stegemöller et al., 2014; Yogev et al., 2005), Alzheimer’s disease (Cedervall, Halvorsen, & Åberg, 2014; Sheridan, Solomont, Kowall, & Hausdorff, 2003), dementia (Verghese et al., 2002), brain injuries (Haggard, Cockburn, Cock, Fordham, & Wade, 2000; Parker, Osternig, Van Donkelaar, & Chou, 2006), and CVAs (Bowen et al., 2001; Yang, Chen, Lee, Cheng, & Wang, 2007).

Finger tapping, much like gait, involves repetitive cycles of a smaller movement according to a particular rhythm. Therefore, it might be expected that finger tapping ability changes with cognitive decline in a pattern similar to that of gait (Buracchio et al., 2010). Although less cognitively demanding than gait, finger tapping ability has been frequently assessed as a measure of sensory-motor function during neuropsychological evaluations. Changes in this simple motor task have been shown to precede cognitive impairment in the elderly population (Buracchio et al., 2010; Camicioli et al., 1998). Timing abnormalities such as irregular interval lengths and increased timing variability have also been observed in patients with Parkinson’s (Hausdorff et al., 2006), Alzheimer’s (Bangert & Balota, 2012) and CVAs (Harrington, Lee, Boyd, Rapcsak, & Knight, 2004; Roy, Clark, Aigbogun, & Square-Storer, 1992).

Since attention plays a critical role in timing control, it is plausible that the decline in performance of neurological patients with cognitive impairment is related to deficits at the central level. Although timing abnormalities have been examined in detail in a large number of previous studies in the patient population (for review, see Yogev-Seligmann, Hausdorff, & Giladi, 2008), relatively less is known about force production and its relation to timing in such repetitive motor tasks which require a combination of both components for successful execution.

We do know however, that quite surprisingly, patients with Parkinson’s disease are as accurate as control participants at producing different target force levels without visual feedback, suggesting that their ability to compute and execute the required force is intact (Stelmach & Worringham, 1988). The patients’ impairments in performance were instead found to be related to timing components of force production, resulting in observations such as a substantially slower rate of change of force (Stelmach, Teasdale, Phillips, & Worringham, 1989). In contrast with the high accuracy of force production in a single event observed by Stelmach and Worringham, (1988) and Stelmach et al., (1989), both force and timing accuracy were compromised in comparison with healthy controls in a repetitive force pulse production task (Pope et al., 2006). In addition, timing was disproportionately affected in patients when the task required them to alternate between long and short intervals as well as hard and soft forces, despite the structure of force control remaining consistent. The authors proposed that this could be the result of a hierarchical ordering in the central motor program where timing is specified before force. Such a structure would have led to a unidirectional effect where changes in force affect timing but not vice versa. Here, we ask whether this dependence can be elucidated with the use of cross-correlations; it is expected that a change in the current interval length is related to a change in the peak force which terminates the interval but not the one which commences the interval.

The studies mentioned above which involve patients with Parkinson's disease implicate the basal ganglia and its role in co-regulating force and timing in contributing to the abnormalities. However, it is unclear how cognition is involved in this process. In comparison with the basal ganglia and cerebellum, there is less research into the role of the cerebral cortex, even though it is always reported to be involved in higher cognitive functions such as attention (for a summary, see Mesulam, 1990). Indeed, in one of the few studies looking into the role of the cerebral cortex in timekeeping, temporal perception deficits linked to working memory functions were observed in patients with focal lesions in the right hemisphere (Harrington, Haaland, & Knight, 1998). Although specific networks of the cerebral cortex which underlie cognition and its relation to force and timing control remain elusive, there is behavioural evidence of their relationship from neuropsychological studies. For example, we know that in tasks which involve repetitive motor movements (such as walking) and a cognitive component (carrying out a conversation), the execution of the cognitive task can impair motor performance, resulting in slower performance (Bond & Morris, 2000), or a prioritising of the cognitive task over the motor (Bloem, Valkenburg, Slabbekoorn, & Van Dijk, 2001).

In a case study of a musician who sustained an infarct to the right hemisphere (temporoparietal region), Wilson, Pressing, and Wales (2002) introduced the use of the extended W-K model (Vorberg & Wing, 1996) for deconstructing motor timing skill in the clinical setting. Using data generated by finger tapping to a paced auditory tone, Wilson et al. (2002) showed that patient H.J. had increased variability in the cognitive clock component while maintaining a relatively unimpaired error-correction capacity. H.J.'s motor process remained mostly stable, apart from when the interval length was the longest (1 s). The deconstruction indicated that the right temporoparietal infarct selectively affected the central cognitive process which led to H.J. being unable to generate regular intervals. Contrary to studies involving patients with Parkinson’s disease, H.J.’s performance appears to suggest that the basic functions of timing control relies on the integrity of the right neocortex rather than subcortical structures such as the basal ganglia. Although data from H.J. was collected using force-sensitive keys, force data was not discussed in this study. However, given the distributed nature of motor control across motor cortex, premotor cortex, supplementary motor area, cerebellum and basal ganglia, it is highly likely for H.J.’s force control to be affected by the temporoparietal infarct as well.

The literature above suggests that the central clock process can be affected by both cortical and subcortical lesions. Such lesions are common in CVA patients who also typically present with cognitive deficits (Jaillard, Naegele, Trabucco-Miguel, LeBas, & Hommel, 2009). Attention and memory processes are domains frequently identified as impaired in CVA patients. Assuming that both processes are involved in the control of timing and force, we can expect their performance on a pulse production task to be affected. The present study expanded on the findings from the previous chapter to examine whether CVA patients have larger dependencies between force and timing control in repetitive pulse production, especially when attentional resources are limited by a simultaneous visual search task. CVA patients who were involved in this study have been assessed using a stroke specific neuropsychological assessment, the Birmingham Cognitive Screen (BCoS; Humphreys et al, 2012) as part of a wider study (Howe, 2014) and were found to have difficulties in the praxis domain. The BCoS assesses praxic deficits with five tasks: 1) Multistep object use, 2) Gesture production, 3) Gesture recognition, 4) Gesture imitation, and 5) Complex figure copy (see Table 7 for task description). The scores of the first four tasks have been shown to relate to functional deficits for detecting apraxia (Bickerton et al., 2012). Apraxia is defined as a neurological disorder of learned purposive movement skill that is not explained by deficits of elementary motor or sensory systems (Rothi & Heilman, 1997). The earliest theories of apraxia proposed by Liepmann (for a historical description, see Goldenberg, 2003) postulated that the specification of spatial and temporal aspects of movements in an action sequence involved the left parietal cortex. To date, functional neuroimaging studies have implicated both the parietal and frontal regions of the left hemisphere as well as bilateral posterior parietal cortex (for a review, see Koski, Iacoboni, & Mazziotta, 2002). Thus, neurological patients with damage to these regions would be prone to difficulties in performing sequences of actions.

BCoS praxis tests	Description	Measures
Multi-step object use	Carry out a multistep task with objects while ignoring distractor objects	Everyday action object selection, step production, perseveration
Gesture production	Produce familiar gestures to names	Gesture production for transitive and intransitive actions
Gesture recognition	Identify familiar gestures produced by the tester	Gesture recognition for transitive and intransitive actions
Meaningless gesture imitation	Copy meaningless gestures produced by the tester	Gesture imitation
Complex figure copy	Copy a complex figure	Constructional apraxia

Table 7: Description of praxis items in the BCoS (Bickerton et al, 2012).

To elucidate force and timing control in this study, we exploited the use of a dual-task paradigm combining a cognitive visual search task with repetitive pulse production used in Chapter 5. By cross-correlating the time series of peak force and time intervals as a measure of dependence, two possible outcomes relating to the force-time relationship can be expected. If the dependence were a control strategy to free cognitive resources, dependence would increase while performing a secondary cognitive task. Alternatively, if the dependence reflects difficulty in control, it would decrease with the secondary task. In the previous chapter with neurologically healthy participants, we showed that cross-correlations revealed the presence of force-time dependencies when attentional resources were directed towards one task or the other by prioritising either pulse production or visual search while dual-tasking. The cross-correlation patterns suggested the use of force-time dependence as a control strategy. However, when no task prioritisation was imposed, the cross-correlation patterns tended towards reflecting difficulty in control.

It was firstly hypothesised that there would be an increase in variability measures for both force and timing, with the coefficient of variation (CV) for timing increasing more than force, as observed in healthy participants. Secondly, we hypothesised that there would be force-time dependence during pulse production as a single task, which was not observed in healthy controls. Producing repetitive force pulses at a target force of 2 N and target interval of 0.75 s is thought to be a process which does not demand attention in healthy adults. However, in patients with cognitive difficulties, this process may become more attention-demanding and the expected correlation would reflect a control strategy in which both parameters are controlled simultaneously instead of individually, as a more efficient method of maintaining task performance. Thirdly, if the dependence was indeed a control strategy, it was expected that the correlation would increase during dual-tasking. Alternatively, it would decrease if it reflects difficulty in control. Imposing a secondary visual search task reduces the availability of cognitive resources available to maintain pulse production. Therefore, the coupling between force and timing in the primary pulse production task could be increased so that more attention can be diverted to the secondary task. In contrast, it is also possible that difficulty in controlling two attention demanding tasks results in the selection of one task over the other (Hyndman & Ashburn, 2004). Thus, it was then expected that correlations would decrease with the execution of a simultaneous visual search task as the search task is prioritised.

6.3 Methodology

6.3.1 Participants

Two participants, MH and SM, performed a pulse production task with their preferred hand (MH right hand; SM left hand). Both participants provided informed consent to participate.

Patient MH's age at the time of the CVA is unknown. The CVA resulted in damage to the left hemisphere in the temporal, parietal and frontal lobes. MH was right-handed prior to the CVA and continued using his right hand post-stroke. The Birmingham Cognitive Screen identified MH as having difficulties in the praxis domain, having failed all five items related to control and planning of action (see Table 8). MH had difficulties in communication due to aphasia, but demonstrated adequate understanding of task instructions as evident by achieving task requirements during the practice sessions. He communicated using both oral and written forms.

Patient SM was 62 years old at the time of the CVA in September 2009. Prior to the CVA incident, SM was diagnosed with a brain tumour which was surgically removed. The CVA resulted in left hemisphere damage. SM is right-handed but has been using her left since the CVA because she experiences paresis on her right side.

The Birmingham Cognitive Screen identified SM as having difficulties in the praxis domain having failed items on gesture recognition and gesture production (see Table 8). SM is fluent in her speech and displayed comprehension of task requirements.

BCoS praxis items	**SM**	**MH**
Multi-step object use	11/12	2/12
Gesture production	7/12	7/12
Gesture recognition	4/6	3/6
Meaningless gesture imitation	3/6	2/6
Complex figure copy	42/47	30/47

Table 8: SM and MH's scores on BCoS praxis items. Failed items are highlighted in red.

6.3.2 Apparatus

The apparatus used was the same as the one described in Chapter 5. However, only one load cell was used for recording responses instead of two.

6.3.3 Setup

Participants sat facing a computer monitor with their forearm at a comfortable position. The forearm was cushioned to provide comfort. The index finger used for responding rested in the middle of the plate with the other fingers avoiding contact with the plate. The computer screen displayed visual input for the task and was programmed in Matlab (Mathworks, MA, USA) using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997).

6.3.4 Task

The primary task of producing repetitive force pulses with the index finger of the preferred hand was the same as previously used in Chapter 5. The goal of the secondary visual search task was to monitor the number of times a given target appeared and report the total observed at the end of each trial.

6.3.5 Procedure

The procedure for each trial was the same as previously used in Chapter 5. In total, each participant completed two blocks of trials with eight repetitions in each block. During the dual task condition, the digits for the visual search task consisted of only single digits between zero and nine. The single task condition consisted of only pulse production. The single task condition was always presented first, followed by the dual task block. The experiment was completed within a one-hour session with breaks where necessary.

6.3.6 Analysis

The raw force signal was processed using the methods described in Chapter 5 to obtain PF and IRI values (see Figure 50).

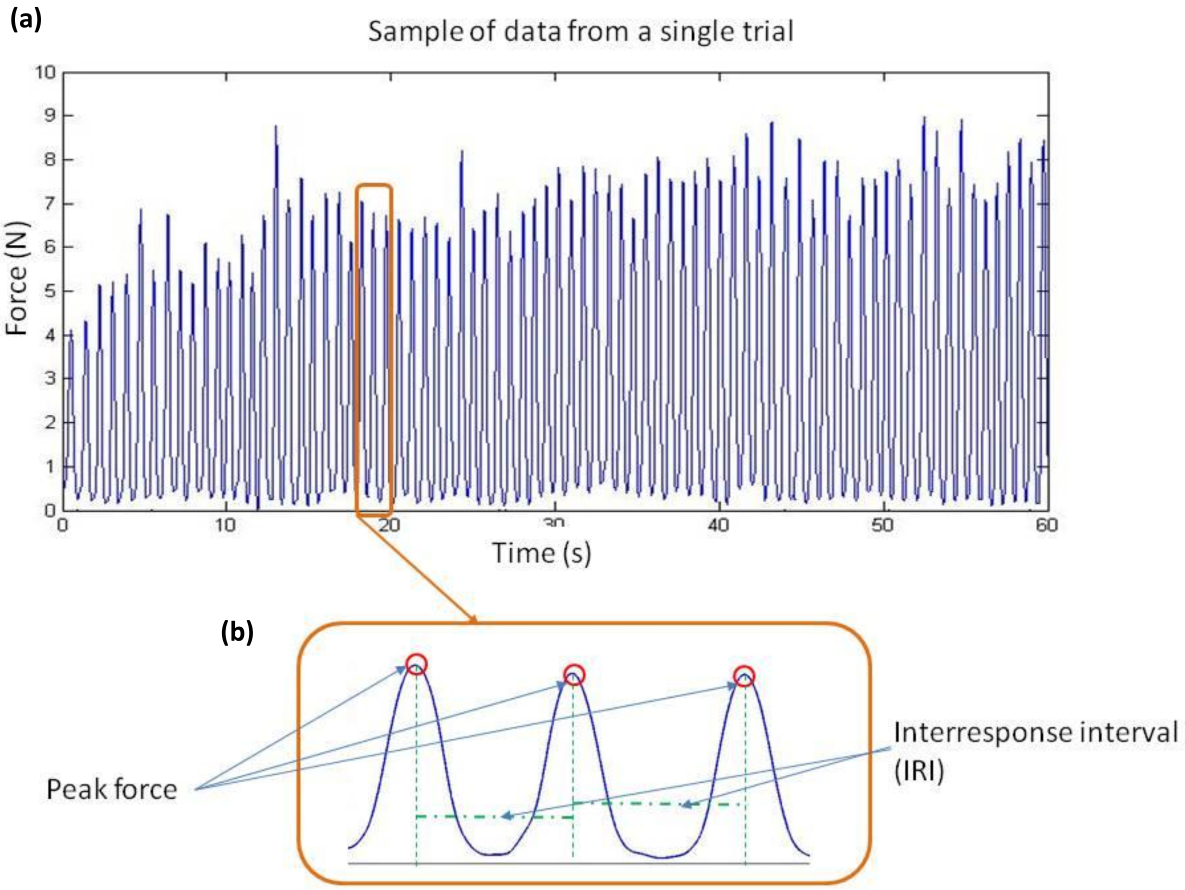

Figure 50: Sample of a filtered force signal for one 60 s trial **(a)**; Peak detection algorithms were applied to the signals to obtain peak force values and IRIs **(b)**.

Means (M) of PFs and IRIs were obtained and averaged within participant. Variability measures computed included the standard deviation (SD) and coefficient of variation, CV (SD/M). The variables were analysed with paired t-test comparisons, using IBM SPSS Statistics for Windows, Version 21.0 (Armonk, NY: IBM Corp). Where multiple comparisons were made, the Bonferroni correction was applied to the significance level of *p* = .05 by adjusting the significance to *p*/number of comparisons.

Cross-correlation functions were calculated for IRIs and PFs as a measure of relationship between the two time series as a function of time lags. Procedures were applied to ensure stationarity and subsequently determine if the functions were significantly different from zero. The procedures were identical to those used in Chapter 5.

6.4 Results

6.4.1 Patient 1: MH

MH overestimated the target force pulses during the single task by approximately 26% (M=2.528 N; SD =0.126 N), which is comparable to healthy participants (see Figure 51). While dual-tasking, however, PFs were almost three times larger than the target (M=7.650 N; SD=2.880 N). This resulted in a significant mean difference between both conditions [t(7)=-5.175, *p*=.001]. The same pattern was observed in variability [t(7)=-5.258, *p*=.001; single task M=0.258 N; SD=0.034 N; dual-task M=2.787 N; SD=1.363 N] as well as the CV [t(7)=-4.002, *p*=.003; single task M=0.145; SD=0.083; dual-task M=0.352; SD=0.086].

MH’s mean IRI was 65% longer than the target interval (M=1.238 s; SD=0.084s). When dual-tasking, it increased to over 2.5 times of the target (M=2.722 s; SD=0.603 s). This difference was significant at t(7)=-7.858, *p*<.001. There were also significant differences in variability [t(7)=-5.978, *p*<.001; single task M=0.079 s; SD=0.017 s; dual-task M=0.942 s; SD=0.410 s] and CV [t(7)=-8.191, *p*<.001; single task M=0.063; SD=0.012; dual-task M=0.341; SD=0.095].

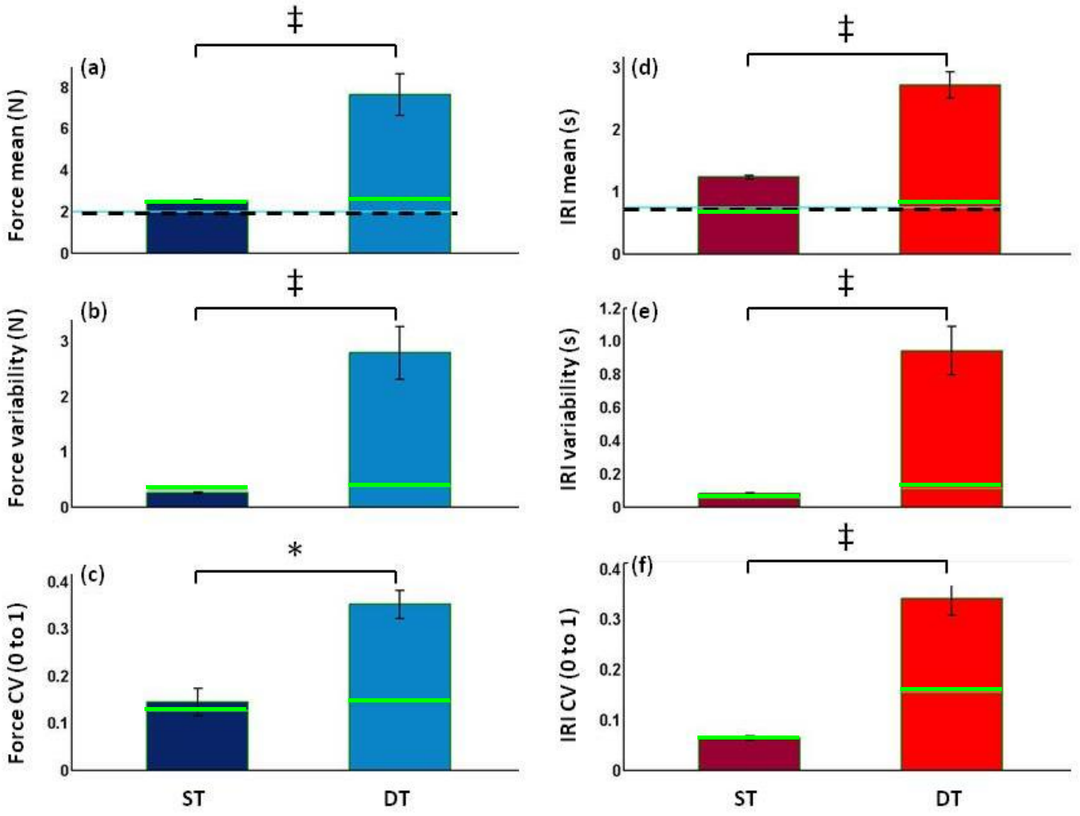

Figure 51: Mean and variability measures of patient MH for force **(a)-(c)** and IRIs **(d)-(f)** with healthy participant data depicted with green horizontal lines. Single task and dual-task performance are on the left and right respectively. In figures **(a)** and **(d)**, dashed horizontal lines denote the target force and target time interval levels. Error bars represent ±1 SE.

During the single task, correlations were positive at lag 0 [t(7) = 5.570, *p* <.001] and negative at lag 1 [t(7) = -6.82, *p* <.001] (see Figure 52). No correlations were significantly different from zero during dual-tasking.

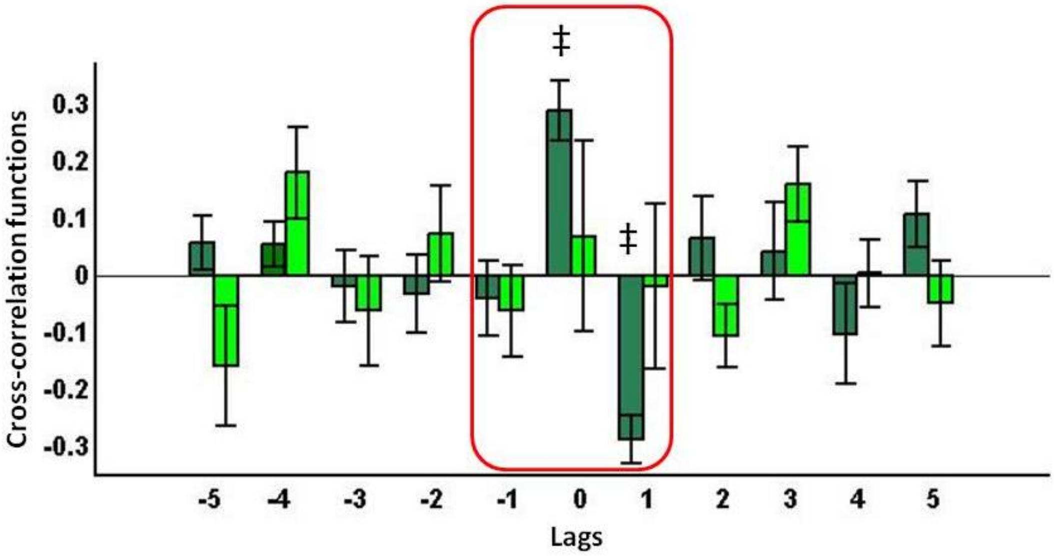

Figure 52: Patient MH's cross-correlation functions between IRIs and PFs between lags -5 and 5 for single task (darker green) and dual-task conditions (lighter green). Highlighted region (rectangle) indicates lags of interest, -1, 0 and 1. Error bars represent ±1 SE.

6.4.2 Patient 2: SM

SM overestimated force by 250% (M=7.121 N; SD=0.398 N) while single tasking (see Figure 53). During the dual-task, PF means decreased but were still 1.5 times larger than the 2 N target (M=4.880 N; SD=0.939 N). A paired t-test revealed significant differences between these two conditions [t(7)=5.653, *p*<.001]. The decrease in force variability was also significantly different [t(7)=2.471, *p*=.02; single task M=1.144 N; SD=0.308 N; dual-task M=0.817 N; SD=0.163 N]. PF CV remained consistent.

The IRI target of 0.75 s was accurately reproduced during single task (M=0.778 s; SD=0.057 s) but was significantly shorter while dual-tasking (M=0.660 s; SD=0.100 s), [t(7)=5.168, *p*<.001]. Paired t-tests also revealed increases for both IRI variability [t(7)=-5.423, *p*<.001; single task M=0.057 s; SD=0.009 s; dual-task M=0.101 s; SD=0.028 s] and CV [t(7)=-5.4737, *p*<.001; single task M=0.073; SD=0.011; dual-task M=0.154; SD=0.049] during dual-task.

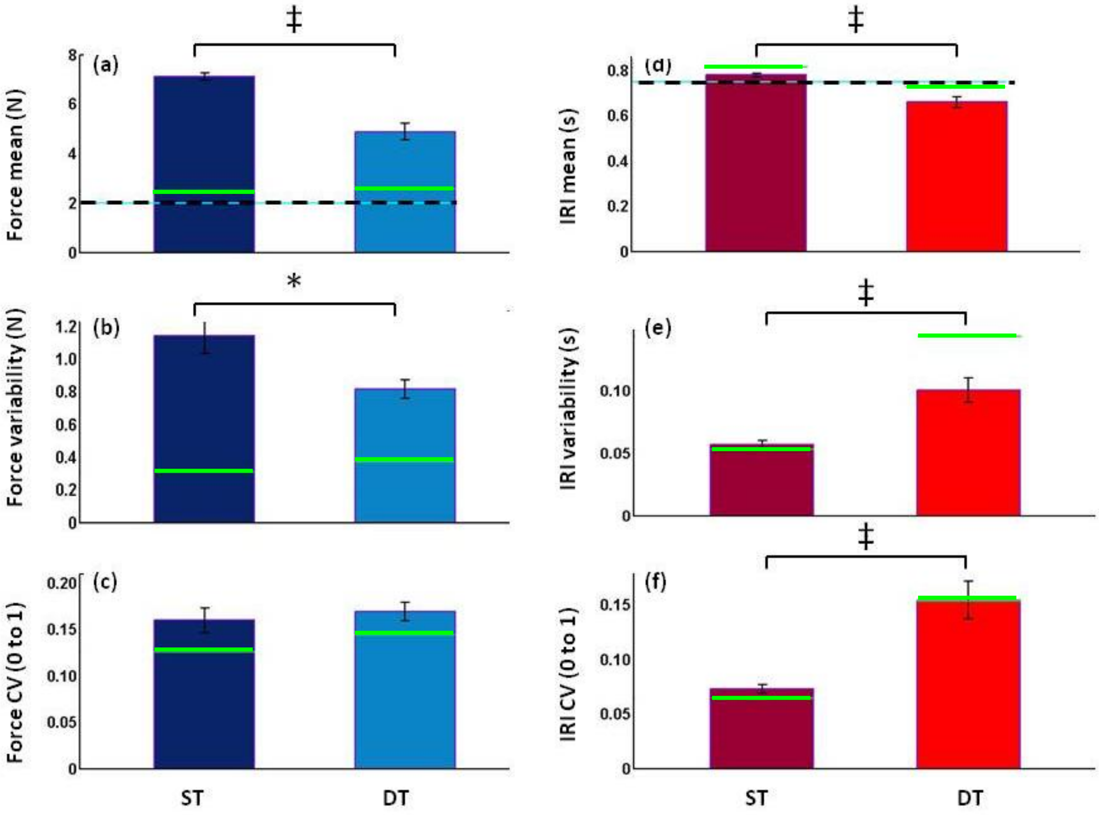

Figure 53: Mean and variability measures of patient SM for force **(a)-(c)** and IRIs **(d)-(f)** with healthy participant data depicted with green horizontal lines. Single task and dual-task performance are on the left and right respectively. In figures **(a)** and **(d)**, dashed horizontal lines denote the target force and target time interval levels. Error bars represent ±1 SE.

During the single task, correlations were negative at lag -1 [t(7) = -5.281, *p* <=.001] and positive at lag 0 [t(7) = 4.672, *p* = .001] (see Figure 54). Correlations were not significantly different from zero during dual-tasking.

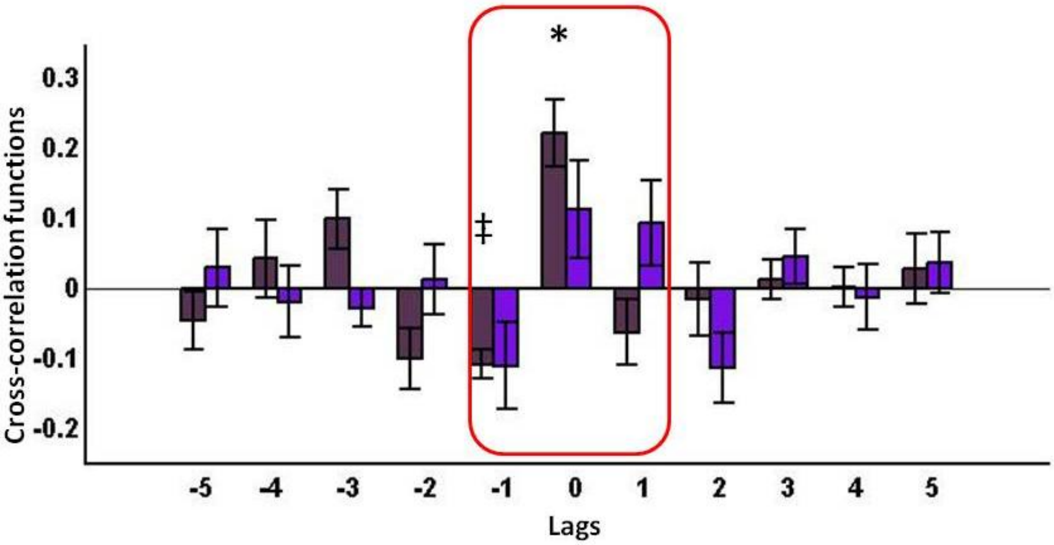

Figure 54: Patient SM's cross-correlation functions between IRIs and PFs between lags -5 and 5 for single task (darker purple) and dual-task conditions (lighter purple). Highlighted region (rectangle) indicates lags of interest, -1, 0 and 1. Error bars represent ±1 SE.

In summary, both SM's and MH's performance did not follow a consistent pattern (see Table 9). While SM's average force and force variability decreased from single task to dual task, MH's increased. Similarly, for average time intervals, SM was faster during the dual task, but MH slowed to more than twice the interval of the single task. However, both SM and MH had increased timing variability in the dual task. In the single task, they showed force-time dependence at lag 0. Correlations were also significant at lag -1 for SM and lag 1 for MH. Neither SM nor MH had significant correlations at any lags during the dual task.

		Force (N)	IRI (s)	Cross-correlations (lags)		
		M (SD) [CV]	M (SD) [CV]	-1	0	1
Single task	**SM**	7.121 (1.144) [0.161]	0.780 (0.057) [0.073]	Sig.	Sig.	Not sig.
	MH	2.528 (0.163) [0.064]	1.238 (0.079) [0.064]	Not sig.	Sig.	Sig.
Dual task	**SM**	4.880 (0.817) [0.167]	0.660 (0.100) [0.152]	Not sig.	Not sig.	Not sig.
	MH	7.650 (2.880) [0.376]	2.722 (0.942) [0.346]	Not sig.	Not sig.	Not sig.

Table 9: A comparison of results between SM and MH with similarities highlighted in blue.

6.5 Discussion

In the previous chapter, pulse-to-pulse dependence of force and timing was found to be present in healthy participants when cognitive resources were simultaneously engaged in more than one task. Furthermore, these patterns of dependence changed according to whether or not there was task prioritisation and, if there was, according to which task were prioritised. The influence of the availability of cognitive resources, in particular attention, suggested that the dependence between force and timing was a control strategy to free resources for engaging in a secondary task. Since controlling both parameters as one unit possibly utilises less resources than individual control of both, larger dependence between force and time with increasing cognitive limitations were expected. In this study a dual-tasking paradigm was used to investigate the force-time dependence in patients who experience praxis difficulties as a result of CVAs. The primary aim of the study was to examine if the patients have different force-time dependence patterns by applying the same cross-correlation analysis used with healthy participant datasets. Subsequently, the secondary aim was to investigate if the dependence (if present) tended towards reflecting a control strategy, or difficulty in control.

Patient MH performed as well as healthy participants in achieving and maintaining pulse production performance when it was a single task. However, there were significant force-time dependence at lags 0 and 1 which were absent in the healthy participants. This correlation pattern indicates that the current time interval is related to the current and preceding peak forces. Although mean and variability measures did not differ, cross-correlations revealed differences in the force-time interaction which implies that MH was utilising a different control strategy to achieve the pulse production task. During the dual-task, the dependence was absent and this could be due to the inability to perform both tasks simultaneously. MH's time interval lengthened considerably and variability, as measured by the CV, was three times as large as the single task. In addition, it was also observed that MH was unable to keep the response finger stationary during the dual-task as it was repeatedly sliding towards MH in between pulses. This is in comparison with the single task where MH had kept the placement of the response finger consistently at the same location of the response plate. This difference was attributed to the difficulty in controlling two attention demanding tasks resulting in the prioritising of the visual search task over pulse production. The selection of one task over the other is not uncommon in patients with CVA (Hyndman & Ashburn, 2004), and has been attributed to the increased use of central processing resources required by dual-tasks.

In contrast, although patient SM had a timing profile similar to that of healthy participants in both single and dual-tasks, force control differed. Unlike all healthy participants and other CVA patients, SM's force control was more accurate and less variable while dual-tasking. Variability decreased in proportion with mean peak force, leaving the CV unchanged in both conditions. SM's cross-correlations showed force-time dependence at lags 0 and -1 during the single task. The dependence describes a relationship between the current interval and the current peak force, as well as the subsequent peak force. A similar pattern was observed in healthy participants while dual-tasking without task prioritisation. However, the pattern was only present when the secondary visual search task was simple (1-digit). When the difficulty was increased (4-digits), the dependence was no longer present, as with SM when the secondary task was imposed. There seemed to be parallels with SM's single task performance with the healthy participants' simple dual-task, as well as SM's dual-task performance with the healthy participants' difficult dual-task. These comparable observations fit well with the idea that the force-time dependence reflects difficulty in control where more challenging tasks draw attentional resources away from pulse production, resulting in a decrease of dependence and a corresponding increase in task variability. If so, we would expect that intentionally directing attention towards pulse production would increase the dependence at the cost of poorer visual search task performance. However, this cannot be determined from the current study.

Both MH and SM's datasets were collected from a group study involving CVA patients. MH's performance was very similar to the group in general. MH's dataset was selected for discussion as he exhibited the largest difference between single and dual task conditions in both force and timing and therefore was most affected by the execution of the secondary task. In contrast, SM's performance was the most different from the rest. SM's dataset was chosen for further exploration as perfect scores were attained in the visual target search for all trials and therefore we assumed that SM was able to perform both tasks the most successfully. Large individual differences in the group were present and this limited the possibility of making group comparisons. Although all patients tested were assessed as experiencing difficulties in the praxis domain, many other factors could have contributed to the individual differences, for example, lesion location, years post-CVA, age, effectiveness of rehabilitation programmes attended post-CVA, post-CVA care and support, co-morbidity with other diseases, etc. Therefore, it would be important for future studies to consider these factors as inclusion or exclusion criteria. A further area of exploration along this line of study could be a comparison of differences as patients progress from the acute, to sub-acute, and chronic phases of the CVA. Reduction of force and timing variability, in either the central or peripheral processes, or perhaps both, could be useful indications of recovery which can be objectively measured using a simple and non-invasive pulse production task.

In summary, we showed that, overall, CVA patients are more variable in maintaining force and timing targets. However, individual differences in performance are noted, which are possibly related to the different ways each patient was affected by their CVA. Force-time dependence can be reliably present in a repetitive motor task when the availability of cognitive resources is limited. This relationship is elucidated using cross-correlation analysis as it provides the possibility of detecting a pattern of dependence over time. When a visual search task was performed concurrently with pulse production, the correlation at all lags were no different from zero. This pattern favours the hypothesis that the dependence reflects how well both tasks can be controlled simultaneously. The absence of correlations possibly indicates that the challenge to central processing was not met and as a result, performance of pulse production deteriorated. This is supported by the corresponding large increase in variability measures. By investigating force-time dependence in CVA patients with cognitive difficulties, we conclude that the results support the dependence as reflecting a loss of control which is dependent on pre-existing cognitive limitations.

6.6 Acknowledgement

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CHAPTER 7

GENERAL DISCUSSION

7.1 Introduction

The aim of this thesis was to study interactions between force and timing processes in voluntary repetitive motor responses. Two key assumptions provided the basis for the investigation. Firstly, both processes can be described from an information processing perspective and have a central origin which organises a motor execution plan implemented by a peripheral motor process. The second assumption is that variability is inherent within both timing and force production processes, resulting in moment-to-moment fluctuations in subsequent responses in a motor sequence. The presence of variability leads to the consideration of a third feedback process which operates in addition to the central and peripheral control mechanisms. Force and timing measures have been reported to co-vary in the literature, demonstrating a relationship whose nature can be further investigated. Thus, there is a potential for the development of a basic yet testable integrated timing and force control model to illustrate how these two processes interact in time. In order to develop an account of the interaction in simple repetitive behaviour, it is necessary to further understand the nature of both processes.

7.2 Summary of thesis

This thesis firstly discussed the current state of knowledge in a review of the literature (Chapter 2). The repetition of force and timing events over time introduced the need for a methodology which accounted for the time-varying nature of the responses, such as those applied in time series analysis. Subsequently, force-time interactions were examined in steady state sequences (Experiment 1 in Chapter 3), sequences with step changes (Experiment 2 in Chapter 4), and steady state sequences with a secondary visual search task as an attention load (Experiment 3 in Chapter 5). The account of control in normal healthy participants was then applied to describe behaviour of CVA patients in two case studies (Experiment 4 in Chapter 6). The present chapter summarises the empirical findings of each experiment and discusses how the findings contribute to the development of an integrative model where both force and timing processes can be described in parallel. Finally, limitations and strengths of the studies are detailed, along with suggestions of directions and opportunities for future research using these current studies as a foundation.

In the investigation of force-time interactions, various paradigms have been employed in the literature. As summarised in Chapter 2, these include self-paced, externally paced and synchronisation-continuation paradigms. Different tasks have also been used, and these include finger tapping, key presses, or grip pulses. Timing and force information have also been presented in both visual and auditory modalities, with and without feedback. Participants have responded in steady state sequences as well as accented sequences with a force change mid-sequence. To determine force-time relationship, many variables have been used for analysis, for example, peak force, peak rate of change of force, time to peak force, contact interval, non-contact interval, interresponse interval. Analysis methods applied have ranged from correlations to comparison of means, as well as time series analysis.

Interpretation of the findings becomes problematic as a result of the various methods, measures and analyses used. To allow a more controlled comparison between experiments, a force pulse production task was used throughout the investigation of force-time interaction in this thesis. Previous studies of force-time interactions using tapping have the complication of three phases of movement with quite different physical constraints, which are movement, collision and force production. Pulse production reduced if not removed any possible interactions with these factors which can affect timing (Piek et al., 1993). Therefore, the present approach allowed a more accurate attribution of performance outcomes specifically to force and timing behaviours.

In the first experiment of this thesis (Chapter 3), a novel paradigm was explored using three tasks from the literature where force-time dependence has been reported. Two of them involved steady state sequences, firstly, when both force and timing constraints were provided, and secondly, when either parameter is prioritised. The third utilised accented sequences with a force increase. The paradigm presented both force and timing information in the haptic modality during the paced phase of a pulse production task. The force pulses delivered consisted of waveforms recorded from a person’s pulse production performance as opposed to a computer generated signal. This method allowed a direct and novel way of presenting both force and timing information within a single modality. Such a presentation was in contrast with previous studies which tended to present force with visual representations and timing using auditory tones, which might favour timing. The outcome of force-time interaction concurred with previous literature when using the single modality paradigm, however, it was noted that the motor of the robotic haptic device overheated frequently, so for practical reasons the haptic input was changed to the visual modality in the remaining experiments. The use of the pulse production task was continued in subsequent experiments but was adapted with the use of load cells instead of a robotic haptic device.

From the steady state tasks tested above, there was no evidence of a force-time relationship in pulse production as characterised by cross-correlation analysis. In contrast, when participants' attention was directed at one parameter over the other, dependence was observed implying a change in control. Since only task instructions were manipulated, the dependence seemed to be associated with a higher level process affected by attention. In addition, corresponding changes were found in timing when a cyclic change in force was executed. The force change involved an increase of target force magnitude which was executed at every fifth pulse. This particular finding of timing being affected by a change in force within accented sequences has been linked with central clock adjustments in previous literature (Billon, Semjen & Stelmach, 1996). Here, the theoretical interest which links the findings in both steady state and accented sequences was the involvement of central processes in facilitating the relationship.

A detailed examination of the mean and variability measures of force and time parameters in Experiment 2 (Chapter 4) suggested that force and timing processes were independent but exhibited transient changes during a transition to increased or decreased force levels or time interval lengths. The transition involved step changes (increase and decrease) which were introduced halfway through a pulse production sequence to either force or timing parameters while the unchanged parameter was to be maintained. Overall, changes in force levels resulted in corresponding changes in timing, but not vice versa. This outcome suggested that force and timing processes involve a serial process where the determination of time intervals possibly precedes the scaling of force levels. An alternative view would be that force and timing processes run in parallel, but the integration process is serial, giving precedence to timing parameters. Thus, both parameters are autonomous but not independent.

The corresponding changes observed in both force and timing parameters during a change in force level or time interval reflected the presence of a dependency or a co-variation. In particular, the interaction with the phase of the transition (before or after) and the distance from the point of transition (one, three or six responses away) suggested that the relationship is transient. What then are the changes occurring at the transition which distinguishes it from the rest of the sequence and facilitates the relationship? It is possible that the transition necessitates a change to central processing, for example, a lengthening of the time interval means that new parameters need to be implemented. This implementation likely draws on cognitive resources and as a result, changes control behaviour in not only timing, but in force control. The cognitive involvement suggests that the force-time relationship would be open to dual-task interference.

In Experiment 3 (Chapter 5), a change of task was introduced by imposing a dual-task, so that cognitive resources were continuously engaged at a more demanding level. Cross-correlation analysis was applied to peak force and time interval time series. It was found that force-time dependence was not present during pulse production without the dual-task. However, with a concurrent visual search task, dependence was found between the current interval and the current peak force (terminating the current interval). Moreover, directing attention towards the primary or secondary tasks further affected control behaviour. When the primary task was given priority, the dependence was absent, whereas when the secondary task was prioritised, the dependence was present. The pattern of dependence indicated that larger timing variability would be associated with higher force variability. The presence of the dependence during dual-task suggested that the relationship is a strategy to accommodate the reduced availability of attention which had been directed to a different task. Therefore, it is reasonable to expect that increasing task difficulty would result in a larger magnitude of dependence. Surprisingly, there was less dependence. In this case, the dependence was more reflective of a loss of control where central processing is unable to meet the necessary requirements of the task. This possibility was supported by the increased variability in the primary task and corresponding reduced accuracy in the secondary task.

The presence of force-time dependence during dual-task performance reinforces the idea that attention is a factor which is related to the dependence, and that the interference occurs at the central level. It is assumed that the reduced availability of cognitive resources to execute two simultaneous tasks caused changes to control behaviour. These changes were reflected in the patterns of force-time dependence which differed under different prioritisation conditions.

Neuroimaging during timing tasks have implicated the left and right temporal lobes (Melgire et al., 2005; Vidalaki, Ho, Bradshaw, & Szabadi, 1999), the left parietal lobe (Coull & Nobre, 2008; Wiener, Turkeltaub, & Coslett, 2010), and temporoparietal region (Wilson et al., 2002). In tasks requiring the regulation of force control, activation is distributed bilaterally over the motor cortex and subcortical structures such as the basal ganglia (Stelmach et al., 1989; Stelmach & Worringham, 1988), and also the cerebellum (Charles, Okamura, & Bastian, 2013). If the integrity of any of these areas were compromised by a brain lesion, there might be more limitations on central processing which affect control behaviour in force-time tasks.

Experiment 4 (Chapter 6) explored if the account of normal control behaviour could explain behaviour in neurological patients who presented with cognitive deficits in the praxis domain. A similar force-time dependence pattern with larger correlation strength was expected to reflect the praxis deficits. Data from two CVA patients who sustained infarcts to the left hemisphere displayed larger force-time dependence in comparison with healthy participants. The increase in correlation magnitude reinforced the hypothesis that cognitive factors affect the regulation of force-time dependence. Interestingly, when a visual search task was performed concurrently with pulse production, no dependence was found. The absence of dependence as task difficulty increased was also observed in neurologically healthy participants. Therefore, the dependence could be related to how well both tasks were controlled simultaneously. As the task became progressively more difficult, the challenge to central processing was not met and, as a result, performance of pulse production deteriorated. This was supported by the corresponding large increase in variability measures. In terms of localisation of control in the brain, both force and timing processes are usually associated with the basal ganglia and cerebellum (O’Boyle, Freeman, & Cody, 1996; Pope et al., 2006; Spencer & Ivry, 2005). However, the findings in this study suggested that the integrity of cortical regions is necessary for maintaining performance, especially when multi-tasking occurs.

7.3 A proposed model

The outcomes from all four experiments inform the development of an integrative model where both force and timing processes can be described in parallel. It is pertinent to note that both force and timing variability are an important consideration in describing the relationship between force and timing control as the experimental findings suggest patterns of co-variation. In the literature, the Parallel Force Unit Model (Ulrich & Wing, 1991) is an example of a model describing how force units are recruited and their responses summed to produce a response force. The PFUM assumes that the activation of force units which contribute to an observed force pulse is centrally commanded. Although the force units are similar in their properties, their activation onset times are subject to variable delays and contribute to the variability observed during implementation of motor responses. This description highlights the relative contribution of two distinct sources to response variability. For timing production, Treisman's (1963) description of a timekeeping mechanism, as well as the W-K model (Wing & Kristofferson, 1973b), provide a parallel account of separable and independent sources of timing variance attributable to a central timekeeper and a peripheral implementation process. Assuming that a motor programme combines information from these two processes to produce repetitive motor responses in a sequence, it is then possible to hypothesise about the possible sources of force and timing interaction. Although feedback processes were not explicitly tested in this thesis, it is acknowledged as an important component and therefore has been included in the conceptual model proposed in Figure 55 below.

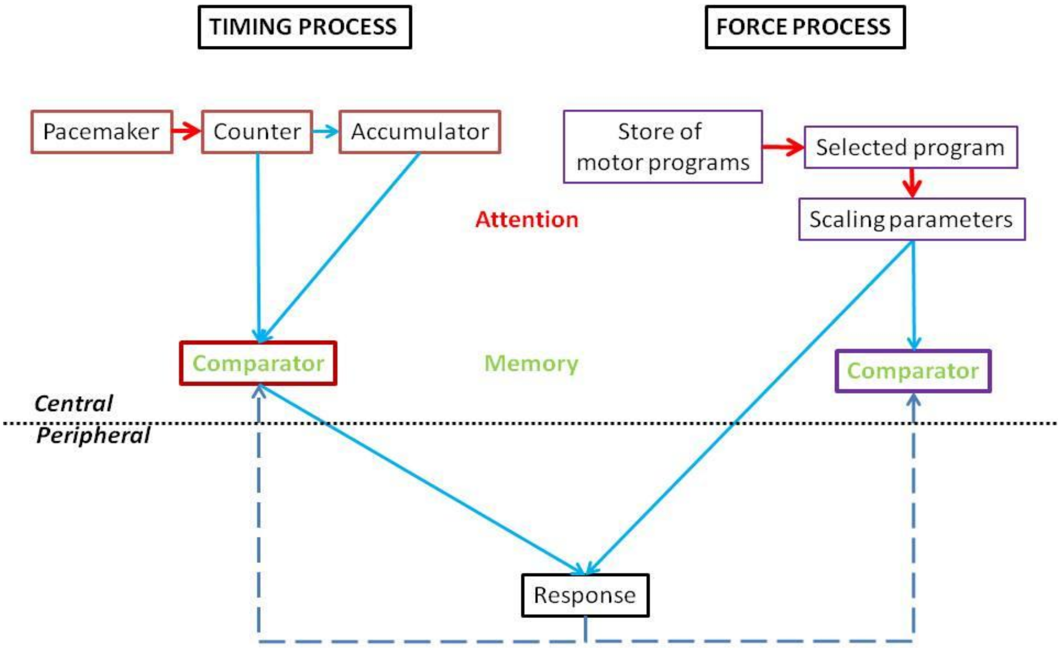

Figure 55: A conceptual model describing both timing (red boxes) and force processes (purple boxes). Arrows show flow of information (red arrows describe processes which are affected by attention, dashed arrows indicate feedback processes).

The model assumes that force-time dependence can be described from an information processing point of view as a two-level, central and peripheral process. At the central levels, attention and memory facilitate the different stages of both processes. In the timing mechanism, the workings of the internal clock can be seen as a continuous process. Attention modulates the count of regular neural pulses passed from the pacemaker to the accumulator. Working memory keeps track of and updates the number of pulses in the comparator. Comparisons are made between the target interval length held in reference memory and the number of pulses. When a match is found, the peripheral process is triggered to initiate a motor response. The timing of the motor response is also compared against the target and with any discrepancy being corrected for in the subsequent response.

In the force control mechanism, force production can be seen as a binary on/off process which either initiates or inhibits a response. Attention is involved in the selection of an appropriate motor program for a particular movement and the determination of its scaling factors. The peripheral process then converts and scales the signal triggered by the central controller at the appropriate force level by innervating target muscles. The required force level held in reference memory is then compared with and the outcome of the motor response. Adjustments would then be made to the subsequent responses correct for differences found between the response and the target.

In real-time, these two processes could run as follows: A target interval length (IRI_T) is stored as the central reference of the required timing outcome. This reference is used by the clock process to generate a timing event ($IRI_{n,\ n+1\ldots}$) (see Figure 56).

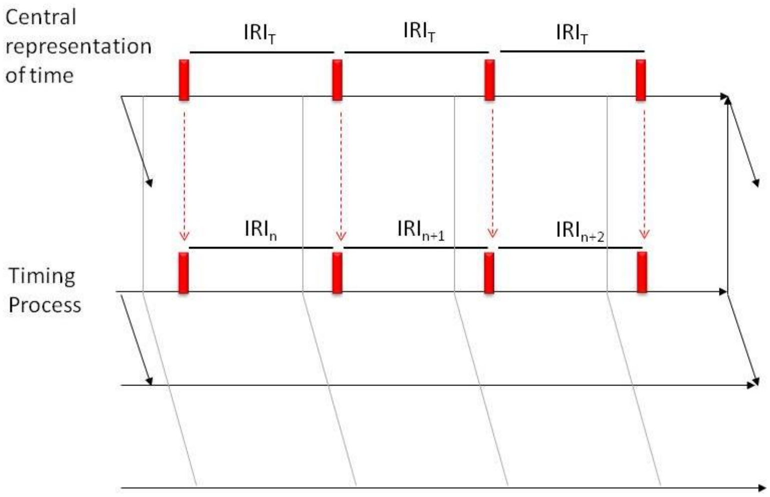

Figure 56: An interval is defined as the time which passes between two events (succeeding red bars) that denote the beginning and end of the interval.

A parallel process runs for force: A target force level (F_T) is stored as the central reference of a force outcome. The reference is used to scale the motor response ($F_{n, n+1...}$) at each timing event generated by the clock process (see Figure 57).

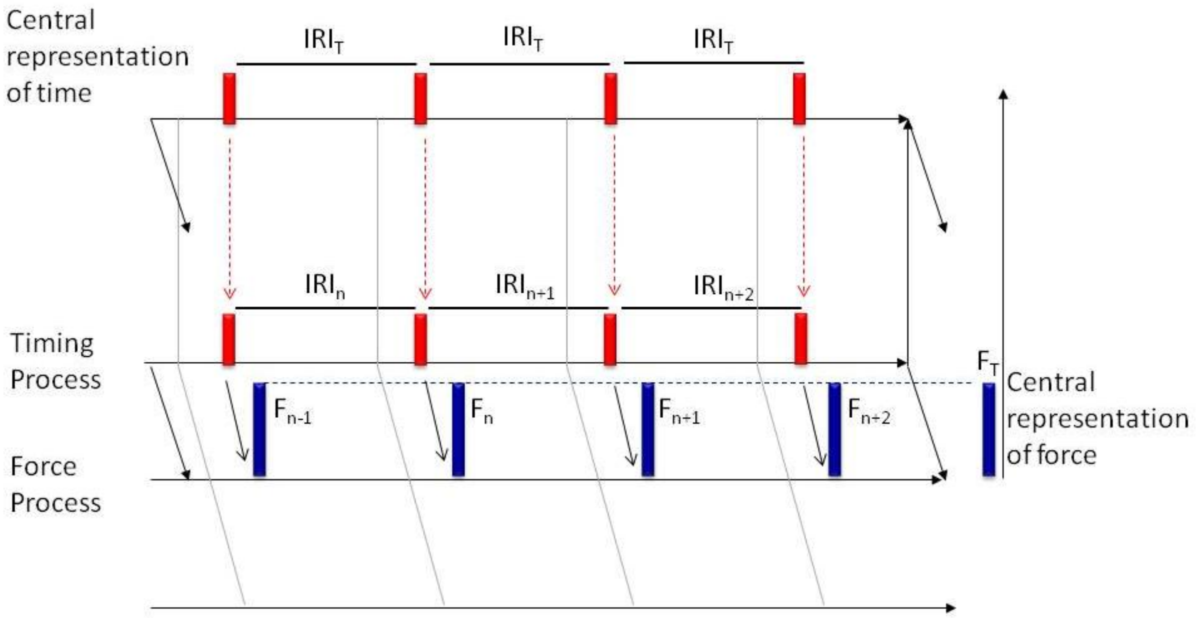

Figure 57: A force target is an *a priori* programme scaled to the required force level (blue bars) when the timing event requires a motor response.

Both force and timing information are then integrated and implemented as a behavioural response [(IRI_n, F_n); (IRI_{n+1}, F_{n+1}), ... (see Figure 58).

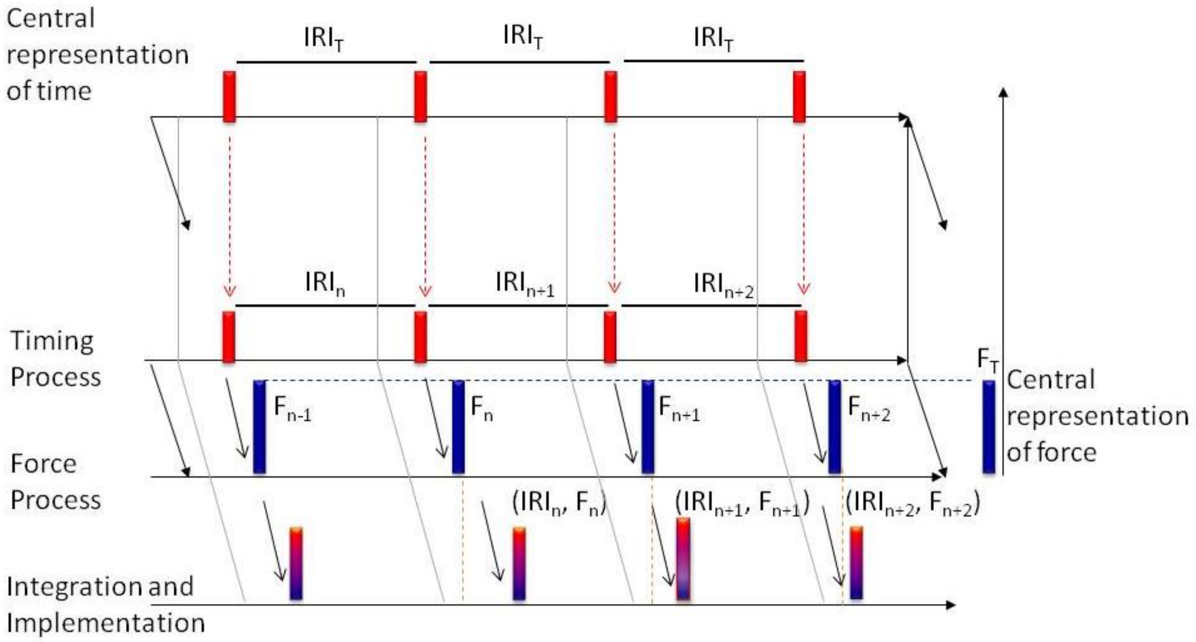

Figure 58: The red-blue bars represent the outcome of both timing and force processes, describing a motor response executed with a particular force magnitude after a particular interval has passed.

All three processes (timing, force, as well as integration and implementation) are open to interference which contributes to the variability of the actual motor response. To maintain a consistent performance, a feedback process identifies discrepancies and implements error-correction in subsequent responses (see Figure 59).

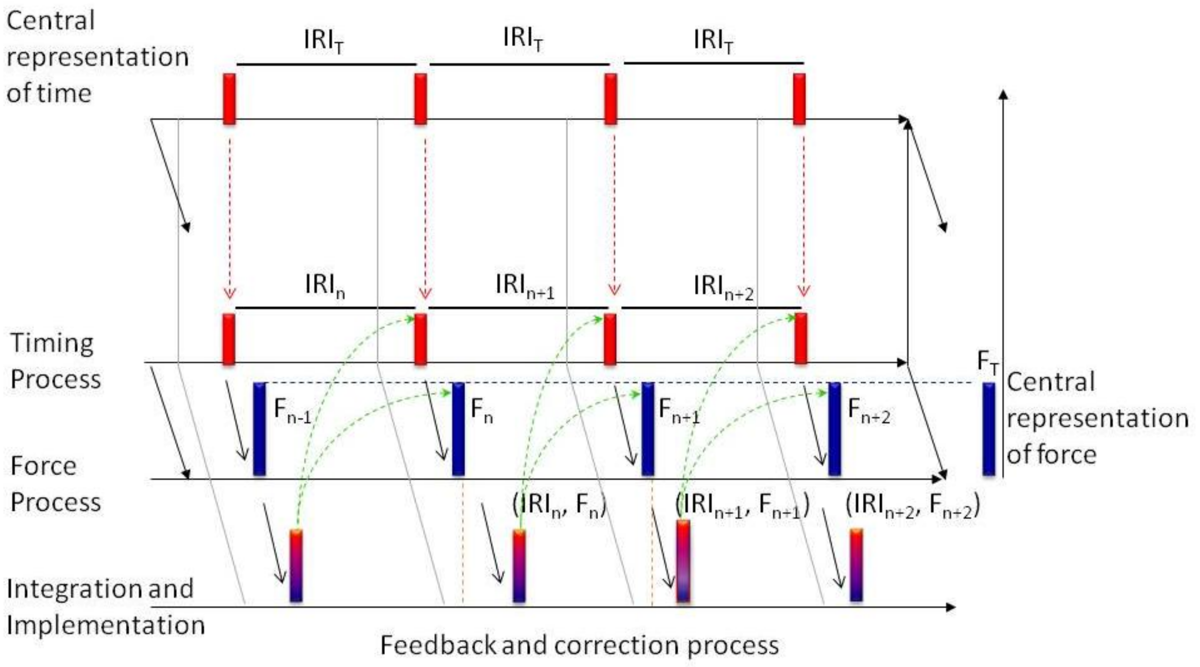

Figure 59: After implementation has occurred, a feedback process (green dotted lines) allows the comparison between the intended response and the actual outcome. Discrepancies would trigger adjustments to minimise the difference between target and response during the next implementation.

From the description of the model above, the variability of the timing and force processes is affected by the availability of attentional resources at the central processes. When a dual-task is implemented, both force and timing processes vary accordingly and result in dependence observed in cross-correlations.

One way of describing the dependence between force and timing is to consider the different components of a process that contribute towards a predicted outcome of each force-time response. The process then can be tested using computer simulation techniques. For example, a force control process can be described as (see Equation 7):

$$\dot{F}_n = F_T + \alpha(F_T - F_{n-1}) + \beta(IRI_T - IRI_n) + \varepsilon \tag{7}$$

where the predicted force at time n is the sum of the target force and a proportion of the discrepancy between the force target and the previous force, and a proportion of the discrepancy between the timing target and the previous interval, and an error term. A corresponding description for the timing process could be (see Equation 8):

$$I\dot{R}I_n = IRI_T + \gamma(IRI_T - IRI_{n-1}) + \delta(F_T - F_{n-1}) + \varepsilon \tag{8}$$

where the predicted interval at time n is the sum of the target interval and a proportion of the discrepancy between the timing target and the previous interval, and a proportion of the discrepancy between the force target and the previous force, and an error term.

The force target (F_T) and interval target (IRI_T) are representations of the information held in the comparators of the force and timing processes. This information is obtained from the paced phase in the synchronisation-continuation paradigm. The inclusion of the discrepancy between the targets and the previous responses represent a feedback mechanism where adjustments are made to bring the current response closer to the target. The error-correction parameters α, β, γ, and δ denote the strength of the correction which would be made, and these parameters are perhaps open to the effects of cognitive resource availability.

The description of the force-time dependence above is in its simplest form. Further consideration can be given to the following:

1) Error-correction for force control may span several time lags. Autocorrelation of peak force time series reveal positive correlations of up to five lags. The pattern suggests that each peak force is related to subsequent peak forces in decreasing magnitude.
2) The error-correction parameter may depend on the current availability of cognitive resources which can change according to task priority or task difficulty. Therefore, an additional ‘cognitive parameter’ which influences the error-correction parameter could describe this relationship.
3) Additional terms may be included to describe the motor implementation process. Two stage central-peripheral models characterise a motor response with a term describing a certain implementation delay which is independent of the central process.

The outcomes of the four experiments in this thesis provide considerations for the formalisation of a force-time model such as the one described above. Table 10 summarises the main results from each experiment and suggests how they might be taken into account in the model. Some considerations can be taken further with future experiments and these are also proposed below.

Experiment	Summary of Results	Implications for Force-Time model	Future Studies
1. Steady state and accented pulse production	- Interactions were present in variability measures - Increase in force level caused a change in timing measures	- Dependence is related to co-variation between force and timing - Timing decision process precedes force	- Including perturbations or delayed feedback in steady state pulse production to investigate nature of correction processes
2. Force and timing transitions	- Force transitions increased timing variability but not vice-versa - Transition effects are transient at the vicinity of the change	- Re-scaling of force levels affect timing variability - Force and timing are independent processes but can exhibit conditional co-variance	- Intentional linear increase or decrease instead of step changes to investigate effects of steady drift on force-time dependence

3. Cognitive effects of dual-tasking	- Force-time dependence absent in single task pulse production - Dependence present with secondary task but dependence patterns change when priority is passed between tasks	- Presence of co-variation is affected by availability of cognitive resources - The weight of attention given to the task changes co-variation patterns	- Pairing of reaction task response with different phases of pulse production cycles to investigate if force-time dependence is stronger or weaker when bimanual responses are coupled
4. CVA patient case study	- Force-time dependence present in single task pulse production - Dependence absent with secondary task	- The magnitude of co-variation increases with cognitive limitations - Task difficulty contributes to loss of either force or timing processes	- Pulse production with somatosensory deafferentation to investigate role of feedback processes

Table 10: A summary of experiment outcomes and their implications for the development of a force-time model.

Throughout the thesis, several adjustments were made after strengths and limitations to the methods applied were observed. Thus, each experiment's methodology contained modifications guided by previous literature as well as from the previous experiment. Here, the methodological points are summarised, together with suggestions which can be implemented for future studies. In Experiment 1 (Chapter 3), force and timing feedback was provided via the haptic modality. This method facilitated a more accurate perception of the task requirement of producing force pulses. It also removed the additional process of extracting force information from a visual presentation or auditory tone which could possibly result in higher performance variability. The use of different robotic haptic devices which can support task demands without overheating should be explored for future studies.

Experiment 2 (Chapter 4) utilised a visual presentation to indicate an upcoming change in force or timing which occurred halfway through a trial. It was challenging to visually represent the passing of time without providing timing information which might influence participants' timing performance. To overcome this, a bar which filled up continuously (as opposed to discrete signals) was designed to represent the length of time which passed during a trial. Future studies could incorporate this method of visualising time as an alternative to periodic flashes or clock-like presentations.

In Experiments 3 and 4 (Chapters 5 and 6), both force and timing information were presented in the visual modality in an attempt to control for any auditory bias towards timing as well as any possible performance differences attributable to modality specific effects if two types of pacing signal were used. Future studies could implement online feedback which would increase performance accuracy.

Experiment 3 (Chapter 5) involved a secondary visual search reaction-time task which required a motor response. It was effective in providing a constant working memory load and enabled the demonstration of the effect of attention on force-time dependence. Future studies could compare the differences in performance variability between left- and right-handed participants, or of pulse production using the dominant versus non-dominant hand. It would also be important to include a condition where participants performed the visual search task without a motor response to provide an objective quantification of the effects of the cognitive task.

In Experiment 4 (Chapter 6), pulse production was a simple yet effective task which differentiated neuropsychological patients with praxis deficits from normal healthy participants. A further area of exploration along this line of study could be a longitudinal observation as patients progress from the acute, to sub-acute, and chronic phases of the CVA. Changes in force or timing variability over time could be useful indications of recovery which can be objectively measured using a simple and non-invasive pulse production task.

Finally, as noted in Chapter 2, peak force events have been used to define the time intervals in all the experiments. Other possible measures can be explored in future studies, for example, force onset or peak velocity (rate of change of force). These are measures which have been used in previous literature to characterise force and timing parameters as they are features related to force-time profiles of force pulses. Such further exploration would contribute towards a more comprehensive description of force-time dependence.

7.4 Conclusion

Force and timing processes interact in subtle ways in the production of repetitive motor responses. The work in this thesis provided considerations supported by empirical findings for the development of an account of force-time interactions in the central nervous system. Adopting an information processing approach, the studies focused on variability measures of both processes. The most important finding in characterising this interaction was that force and timing processes co-vary in a sequence of repetitive responses. The pattern of co-variation was found to be affected by attention as control behaviour changed in response to additional cognitive load. This strategy of coping with cognitive challenges was also indicative of a loss of control when interaction disappeared while performing tasks requiring high attentional demand. Finally, a simple conceptual model illustrating how force and timing processes interact was proposed based on the findings, providing an opportunity for further testing directed towards developing a formal model for simulation studies in the future.

LIST OF REFERENCES

Alexander, N. B., & Hausdorff, J. M. (2008). Guest editorial: linking thinking, walking, and falling. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *63*(12), 1325–1328. http://doi.org/63/12/1325 [pii]

Allman, M. J., Teki, S., Griffiths, T. D., & Meck, W. H. (2014). Properties of the internal clock: first- and second-order principles of subjective time. *Annual Review of Psychology*, *65*(October 2013), 743–71. http://doi.org/10.1146/annurev-psych-010213-115117

Bangert, A. S., & Balota, D. A. (2012). Keep Up the Pace: Declines in Simple Repetitive Timing Differentiate Healthy Aging from the Earliest Stages of Alzheimer's Disease. *Journal of the International Neuropsychological Society*, *18*(6), 1–12. http://doi.org/10.1017/S1355617712000860

Bareš, M., Lungu, O. V., Husárová, I., & Gescheidt, T. (2010). Predictive motor timing performance dissociates between early diseases of the cerebellum and parkinson's disease. *Cerebellum*, *9*, 124–135. http://doi.org/10.1007/s12311-009-0133-5

Bathurst, K., & Kee, D. W. (1994). Finger-tapping interference as produced by concurrent verbal and nonverbal tasks: an analysis of individual differences in left-handers. *Brain and Cognition*. http://doi.org/10.1006/brcg.1994.1007

Bickerton, W.-L., Riddoch, M. J., Samson, D., Balani, A. B., Mistry, B., & Humphreys, G. W. (2012). Systematic assessment of apraxia and functional predictions from the Birmingham Cognitive Screen. *Journal of Neurology, Neurosurgery & Psychiatry*, *83*, 513–521. http://doi.org/10.1136/jnnp-2011-300968

Bieńkiewicz, M. M. N., Rodger, M. W. M., & Craig, C. M. (2012). Timekeeping strategies operate independently from spatial and accuracy demands in beat-interception movements. *Experimental Brain Research*, *222*, 241–253. http://doi.org/10.1007/s00221-012-3211-8

Billauer, E. (2012, Jul 20). *Peakdet: Peak detection using MATLAB*. Retrieved from http://www.billauer.co.il/peakdet.html

Billon, M., & Semjen, A. (1995). The timing effects of accent production in synchronization and continuation tasks performed by musicians and nonmusicians. *Psychological Research*, *58*, 206–217. http://doi.org/10.1007/BF00419635

Billon, M., Semjen, A., Cole, J., & Gauthier, G. (1996). The role of sensory information in the production of periodic finger-tapping sequences. *Experimental Brain Research*, *110*, 117–130. http://doi.org/10.1007/BF00241381

Bloem, B. R., Valkenburg, V. V., Slabbekoorn, M., & Van Dijk, J. G. (2001). The multiple tasks test. Strategies in Parkinson's disease. *Experimental Brain Research*, *137*, 478–486. http://doi.org/10.1007/s002210000672

Bond, J. M., & Morris, M. (2000). Goal-directed secondary motor tasks: Their effects on gait in subjects with Parkinson disease. *Archives of Physical Medicine and Rehabilitation*, *81*(January), 110–116. http://doi.org/10.1053/apmr.2000.0810110

Bowen, A., Wenman, R., Mickelborough, J., Foster, J., Hill, E., & Tallis, R. (2001). Dual-task effects of talking while walking on velocity and balance following a stroke. *Age and Ageing*, *30*(4), 319–323. http://doi.org/10.1093/ageing/30.4.319

Brown, S. W. (1997). Attentional resources in timing: interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & Psychophysics*, *59*(7), 1118–1140. http://doi.org/10.3758/BF03205526

Buhusi, C. V, & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews. Neuroscience*, *6*, 755–765. http://doi.org/10.1038/nrn1764

Buracchio, T., Dodge, H., Howieson, D., Wasserman, D., & Kaye, J. (2010). The trajectory of gait speed preceding mild cognitive impairment. *Archives of Neurology*, *67*(8), 980–986. http://doi.org/10.1001/archneurol.2010.159

Camicioli, R., Howieson, D., Oken, B., Sexton, G., & Kaye, J. (1998). Motor slowing precedes impaiment in the oldest old. *Neurology*, *50*(5), 1496–1498. http://doi.org/10.1212/WNL.50.5.1496

Cedervall, Y., Halvorsen, K., & Åberg, A. C. (2014). A longitudinal study of gait function and characteristics of gait disturbance in individuals with Alzheimer's disease. *Gait and Posture*, *39*, 1022–1027. http://doi.org/10.1016/j.gaitpost.2013.12.026

Charles, S. K., Okamura, A. M., & Bastian, A. J. (2013). Does a basic deficit in force control underlie cerebellar ataxia? *Journal of Neurophysiology*, *109*(November 2012), 1107–16. http://doi.org/10.1152/jn.00152.2012

Chen, Y., Repp, B. H., & Patel, A. D. (2002). Spectral decomposition of variability in synchronization and continuation tapping: Comparisons between auditory and visual pacing and feedback conditions. *Human Movement Science*, *21*(4), 515–532. http://doi.org/10.1016/S0167-9457(02)00138-0

Clamann, H. P. (1993). Motor unit recruitment and the gradation of muscle force. *Journal of the American Physical Therapy Association*, *73*, 830–843.

Coull, J. T., Cheng, R.-K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology*, *36*(1), 3–25. http://doi.org/10.1038/npp.2010.113

Coull, J. T., & Nobre, A. C. (2008). Dissociating explicit timing from temporal expectation with fMRI. *Current Opinion in Neurobiology*, *18*, 137–144. http://doi.org/10.1016/j.conb.2008.07.011

Daffertshofer, A. (1998). Effects of noise on the phase dynamics of nonlinear oscillators. *Physical Review E*, *58*(1), 327–338. http://doi.org/10.1103/PhysRevE.58.327

Dahl, S. (2004). Playing the accent - Comparing striking velocity and timing in an ostinato rhythm performed by four drummers. *Acta Acustica United with Acustica*, *90*, 762–776.

Dubost, V., Kressig, R. W., Gonthier, R., Herrmann, F. R., Aminian, K., Najafi, B., & Beauchet, O. (2006). Relationships between dual-task related changes in stride velocity and stride time variability in healthy older adults. *Human Movement Science*, *25*, 372–382. http://doi.org/10.1016/j.humov.2006.03.004

Elliott, M. T., Welchman, A. E., & Wing, A. M. (2009). Being discrete helps keep to the beat. *Experimental Brain Research*, *192*, 731–737. http://doi.org/10.1007/s00221-008-1646-8

Elliott, M. T., Wing, A. M., & Welchman, A. E. (2010). Multisensory cues improve sensorimotor synchronisation. *European Journal of Neuroscience*, *31*(October 2009), 1828–1835. http://doi.org/10.1111/j.1460-9568.2010.07205.x

Faisal, A. A., Selen, L. P. J., & Wolpert, D. M. (2008). Noise in the nervous system. *Nature Reviews. Neuroscience*, *9*(april), 292–303. http://doi.org/10.1038/nrn2258

Fraisse, P., & Oleron, G. (1954). La structuration intensive des rythmes. *L' Ann??e Psychologique*, *54*, 35–52. http://doi.org/10.3406/psy.1954.30157

François, M. (1927). Contribution à l ' étude du sens du Temps . La température interne comme facteur de variation de l ' appréciation subjective des durées, *28*, 186–204. http://doi.org/doi : 10.3406/psy.1927.6412

Gabrielsson, A. (1999). Council for Research in Music Education in Music Emotional Studying Expression Performance (pp. 47–53).

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*, 52–77. http://doi.org/10.1111/j.1749-6632.1984.tb23417.x

Glazier, P. S., Davids, K., & Bartlett, R. (2003). Dynamical systems theory: a relevant framework for performance-oriented sports biomechanics research. *Sportscience*, *7*(1997).

Goldenberg, G. (2003). Apraxia and beyond: life and work of Hugo Liepmann. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *39*, 509–524. http://doi.org/10.1016/S0010-9452(08)70261-2

Haggard, P., Cockburn, J., Cock, J., Fordham, C., & Wade, D. (2000). Interference between gait and cognitive tasks in a rehabilitating neurological population. *Journal of Neurology, Neurosurgery, and Psychiatry*, *69*, 479–486. http://doi.org/10.1136/jnnp.69.4.479

Harrington, D. L., Haaland, K. Y., & Hermanowicz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology*, *12*(1), 3–12.

Harrington, D. L., Haaland, K. Y., & Knight, R. T. (1998). Cortical networks underlying mechanisms of time perception. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *18*(3), 1085–1095.

Harrington, D. L., Lee, R. R., Boyd, L. A., Rapcsak, S. Z., & Knight, R. T. (2004). Does the representation of time depend on the cerebellum? Effect of cerebellar stroke. *Brain*, *127*(3), 561–574. http://doi.org/10.1093/brain/awh065

Hausdorff, J. M., Doniger, G. M., Springer, S., Yogev, G., Simon, E. S., & Giladi, N. (2006). A common cognitive profile in elderly fallers and in patients with Parkinson's disease: the prominence of impaired executive function and attention. *Experimental Aging Research*, *32*, 411–429. http://doi.org/10.1080/03610730600875817

Henneman, E. (1957). Relation between size of neuron and their susceptibility to discharge. *Science*, *126*(3287), 1345–1347.

Hoagland, H. (1933). The Physiological Control of Judgments of Duration: Evidence for a Chemical Clock. *The Journal of General Psychology*, *9*, 267–287. http://doi.org/10.1080/00221309.1933.9920937

Hove, M. J., Iversen, J. R., Zhang, A., & Repp, B. H. (2013). Synchronization with competing visual and auditory rhythms: Bouncing ball meets metronome. *Psychological Research*, *77*(4), 388–398. http://doi.org/10.1007/s00426-012-0441-0

Hyndman, D., & Ashburn, A. (2004). Stops walking when talking as a predictor of falls in people with stroke living in the community. *Journal of Neurology, Neurosurgery, and Psychiatry*, *75*, 994–997. http://doi.org/10.1136/jnnp.2003.016014

Inui, N., & Ichihara, T. (2001). Independence of timing and force control during finger-tapping sequences by pianists. *Perceptual and Motor Skills*. http://doi.org/10.2466/pms.2001.93.2.556

Inui, N., Ichihara, T., Minami, T., & Matsui, A. (1998). Interactions: Timing and force control of finger-tapping sequences. *Perception & Psychophysics*, *86*(1954), 1395–1401.

Ivry, R. B., & Richardson, T. C. (2002). Temporal control and coordination: the multiple timer model. *Brain and Cognition*, *48*, 117–132. http://doi.org/10.1006/brcg.2001.1308

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. *Annals of the New York Academy of Sciences*, *978*, 302–317. http://doi.org/10.1111/j.1525-1594.2008.00549.x

Jaillard, A., Naegele, B., Trabucco-Miguel, S., LeBas, J. F., & Hommel, M. (2009). Hidden dysfunctioning in subacute stroke. *Stroke*, *40*, 2473–2479. http://doi.org/10.1161/STROKEAHA.108.541144

Johannsen, L., Li, K. Z. H., Chechlacz, M., Bibi, A., Kourtzi, Z., & Wing, A. M. (2013). Functional neuroimaging of the interference between working memory and the control of periodic ankle movement timing. *Neuropsychologia*, *51*(11), 2142–2153. http://doi.org/10.1016/j.neuropsychologia.2013.07.009

Johnson, C. (2000). Effect of adding interpretive elements to a musical performance on the rhythmic and dynamic variations. *Bulletin of the Council for Research in Music Education*, (147). Retrieved from http://www.jstor.org/stable/40319394

Jones, K. E., Hamilton, A. F., & Wolpert, D. M. (2002). Sources of Signal-Dependent Noise During Isometric Force Production. *Journal of Neurophysiology*, *88*, 1533–1544.

Joundi, R. A., Brittain, J. S., Green, A. L., Aziz, T. Z., & Jenkinson, N. (2012). High-frequency stimulation of the subthalamic nucleus selectively decreases central variance of rhythmic finger tapping in Parkinson’s disease. *Neuropsychologia*, *50*(10), 2460–2466. http://doi.org/10.1016/j.neuropsychologia.2012.06.017

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, *70*(6), 257–272. http://doi.org/10.1037/h0021468

Keele, S. W., Ivry, R. B., & Pokorny, R. A. (1987). Force control and its relation to timing. *Journal of Motor Behaviour*, *19*(1), 96–114.

Keele, S. W., Pokorny, R. a, Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: a correctional analysis. *Acta Psychologica*, *60*, 173–191. http://doi.org/10.1016/0001-6918(85)90054-X

Keller, P. E. (2012). What movement force reveals about cognitive processes in music performance. In *Art in Motion II* (pp. 115–154).

Keller, P. E., Weber, A., & Engel, A. (2011). Practice makes too perfect: Fluctuations in loudness indicate spontaneity in musical improvisation. *Music Perception*, *29*(1), 109–114.

Koski, L., Iacoboni, M., & Mazziotta, J. C. (2002). Deconstructing apraxia: understanding disorders of intentional movement after stroke. *Current Opinion in Neurology*, *15*, 71–77. http://doi.org/10.1097/00019052-200202000-00011

Kugler, P. N., Kelso, S. J. A., & Turvey, M. T. (1982). On the control and coordination of naturally developing systems. *The Development of Movement Control and Coordination*.

Large, E. W. (2000). On synchronizing movements to music. *Human Movement Science*, *19*(4), 527–566. http://doi.org/10.1016/S0167-9457(00)00026-9

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychology and Aging*, *15*(3), 417–436. http://doi.org/10.1037/0882-7974.15.3.417

Lorist, M. M., Kernell, D., Meijman, T. F., & Zijdewind, I. (2002). Motor fatigue and cognitive task performance in humans. *The Journal of Physiology*, *545*, 313–319. http://doi.org/10.1113/jphysiol.2002.027938

Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience*, *27*, 307–340. http://doi.org/10.1146/annurev.neuro.27.070203.144247

McAngus Todd, N. P. (1992). The dynamics of dynamics: A model of musical expression. *The Journal of the Acoustical Society of America*, *91*, 3540. http://doi.org/10.1121/1.402843

McFarland, K., & Ashton, R. (1978). The lateralized effects of concurrent cognitive and motor performance. *Perception & Psychophysics*, *23*(4), 344–349. http://doi.org/10.3758/BF03199720

Meck, W. H. (1996). Neuropharmacology of timing and time perception. *Cognitive Brain Research*, *3*, 227–242. http://doi.org/10.1016/0926-6410(96)00009-2

Melgire, M., Ragot, R., Samson, S., Penney, T. B., Meck, W. H., & Pouthas, V. (2005). Auditory/visual duration bisection in patients with left or right medial-temporal lobe resection. *Brain and Cognition*, *58*, 119–124. http://doi.org/10.1016/j.bandc.2004.09.013

Mesulam, M. M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology*. http://doi.org/10.1002/ana.410280502

Morris, M. E., Summers, J. J., Matyas, T. A., & Iansek, R. (1994). Current status of the motor program. *Journal of the American Physical Therapy Association*, *74*, 738–748.

Newell, K. M. (1986). Constraints on the development of coordination. In *Motor development in children: Aspects of coordination and control* (pp. 341–360).

Newell, K. M. (2003). Schema theory (1975): retrospectives and prospectives. *Research Quarterly for Exercise and Sport*, *74*(March 2015), 383–388. http://doi.org/10.1080/02701367.2003.10609108

O'Boyle, D. J., Freeman, J. S., & Cody, F. W. J. (1996). The accuracy and precision of timing of self-paced, repetitive movements in subjects with Parkinson's disease. *Brain*, *119*, 51–70. http://doi.org/10.1093/brain/119.1.51

Parker, T. M., Osternig, L. R., Van Donkelaar, P., & Chou, L. S. (2006). Gait stability following concussion. *Medicine and Science in Sports and Exercise*, *38*(21), 1032–1040. http://doi.org/10.1249/01.mss.0000222828.56982.a4

Piek, J. P., Glencross, D. J., Barrett, N. C., & Love, G. L. (1993). The effect of temporal and force changes on the patterning of sequential movements. *Psychological Research*, *55*, 116–123. http://doi.org/10.1007/BF00419642

Pitcher, T. M., Piek, J. P., & Barrett, N. C. (2002). Timing and force control in boys with attention deficit hyperactivity disorder: Subtype differences and the effect of comorbid developmental coordination disorder. *Human Movement Science*, *21*, 919–945. http://doi.org/10.1016/S0167-9457(02)00167-7

Pope, P. A., Praamstra, P., & Wing, A. M. (2006). Force and time control in the production of rhythmic movement sequences in Parkinson's disease. *European Journal of Neuroscience*, *23*(December 2005), 1643–1650. http://doi.org/10.1111/j.1460-9568.2006.04677.x

Repp, B. H. (2000). Pattern typicality and dimensional interactions in pianists' imitation of expressive timing and dynamics. *Music Perception*, *18*(2), 173–211. Retrieved from http://www.ucpress.edu/journals/mp/\nhttp://www.jstor.org/stable/40285908

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, *12*(6), 969–992.

Repp, B. H., & Penel, A. (2002). Auditory dominance in temporal processing: new evidence from synchronization with simultaneous visual and auditory sequences. *Journal of Experimental Psychology. Human Perception and Performance*, *28*(5), 1085–1099. http://doi.org/10.1037/0096-1523.28.5.1085

Repp, B. H., & Penel, A. (2004). Rhythmic movement is attracted more strongly to auditory than to visual rhythms. *Psychological Research*, *68*, 252–270. http://doi.org/10.1007/s00426-003-0143-8

Roy, E. A., Clark, P., Aigbogun, S., & Square-Storer, P. A. (1992). Ipsilesional disruptions to reciprocal finger tapping. *Archives of Clinical Neuropsychology*, *7*, 213–219. http://doi.org/10.1016/0887-6177(92)90163-H

Salmon, V., & Thomson, D. (2007). Measurement of force production during concurrent performance of a memory task. *Physiotherapy*, *93*, 283–290. http://doi.org/10.1016/j.physio.2007.02.006

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning.

Schöner, G. (2002). Timing, clocks, and dynamical systems. *Brain and Cognition*, *48*, 31–51. http://doi.org/10.1006/brcg.2001.1302

Schulze, H.-H., Cordes, A., & Vorberg, D. (2005). Keeping Synchrony While Tempo Changes: Accelerando and Ritardando. *Music Perception*, *22*(3), 461–477. http://doi.org/10.1525/mp.2005.22.3.461

Semjen, A., Garcia-Colera, A., & Requin, J. (1984). On controlling force and time in rhythmic movement sequences: the effect of stress location. *Annals of the New York Academy of Sciences*, *423*, 168–182.

Shadmehr, R, Wise, S. P. (2004). A simple muscle model. *Computational Neurobiology of Reaching and Pointing*, Supplementary document.

Sheridan, P. L., Solomont, J., Kowall, N., & Hausdorff, J. M. (2003). Influence of Executive Function on Locomotor Function: Divided Attention Increases Gait Variability in Alzheimer's Disease. *Journal of the American Geriatrics Society*, *51*, 1633–1637. http://doi.org/10.1046/j.1532-5415.2003.51516.x

Sloboda, J. A. (1983). The communication of musical metre in piano performance. *The Quarterly Journal of Experimental Psychology Section A*, *35*(March 2015), 377–396. http://doi.org/10.1080/14640748308402140

Sloboda, J. A. (1985). Expressive skill in two pianists: Metrical communication in real and simulated performances. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, *39*(2), 273–293. http://doi.org/10.1037/h0080062

Spencer, R. M. C., & Ivry, R. B. (2005). Comparison of patients with Parkinson's disease or cerebellar lesions in the production of periodic movements involving event-based or emergent timing. *Brain and Cognition*, *58*, 84–93. http://doi.org/10.1016/j.bandc.2004.09.010

Stegemöller, E. L., Wilson, J. P., Hazamy, A., Shelley, M. C., Okun, M. S., Altmann, L. J. P., & Hass, C. J. (2014). Associations between cognitive and gait performance during single- and dual-task walking in people with Parkinson disease. *Physical Therapy*, *94*, 757–766. http://doi.org/10.2522/ptj.20130251

Stelmach, G. E., Teasdale, N., Phillips, J., & Worringham, C. J. (1989). Force production characteristics in Parkinson ' s disease. *Experimental Brain Research*, *165*(1), 165–172.

Stelmach, G. E., & Worringham, C. J. (1988). The preparation and production of isometric force in Parkinson's disease. *Neuropsychologia*, *26*, 93–103. http://doi.org/10.1016/0028-3932(88)90033-4

Sternad, D., Dean, W. J., & Newell, K. M. (2000). Force and Timing Variability in Rhythmic Unimanual Tapping. *Journal of Motor Behavior*, *32*(3), 249–267.

Stevens, L. T. (1886). Mind Association On The Time-Sense. *Mind*, *11*(43), 393–404.

Tan, H. Z., Durlach, N. I., Beauregard, G. L., & Srinivasan, M. a. (1995). Manual discrimination of compliance using active pinch grasp: the roles of force and work cues. *Perception & Psychophysics*, *57*(4), 495–510. http://doi.org/10.3758/BF03213075

Teki, S., Grube, M., Kumar, S., & Griffiths, T. D. (2011). Distinct neural substrates of duration-based and beat-based auditory timing. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *31*(10), 3805–3812. http://doi.org/10.1523/JNEUROSCI.5561-10.2011

Therrien, A. S., & Balasubramaniam, R. (2010). Timing and visual feedback constraints on repetitive finger force production. *Experimental Brain Research*, *201*, 673–679. http://doi.org/10.1007/s00221-009-2084-y

Treisman, M. (1963). Temporal discrimination and the indifference interval. Implications for a model of the "internal clock". *Psychological Monographs*, *77*(13), 1–31. http://doi.org/10.1037/h0093864

Ulrich, R., & Wing, A. M. (1991). A recruitment theory of force-time relations in the production of brief force pulses: the parallel force unit model. *Psychological Review*, *98*(2), 268–294. http://doi.org/10.1037/0033-295X.98.2.268

Verghese, J., Lipton, R. B., Hall, C. B., Kuslansky, G., Katz, M. J., & Buschke, H. (2002). Abnormality of Gait As a Predictor of Non-Alzheimer's Dementia. *The New England Journal of Medicine*, *347*(22), 1761–1768.

Vidalaki, V. N., Ho, M. Y., Bradshaw, C. M., & Szabadi, E. (1999). Interval timing performance in temporal lobe epilepsy: Differences between patients with left and right hemisphere foci. *Neuropsychologia*, *37*, 1061–1070. http://doi.org/10.1016/S0028-3932(98)00155-9

Vince, M. A., & Welford, A. T. (1967). Time taken to change the speed of a response. *Group*, *213*(5075), 532–533.

Voelcker-Rehage, C., Stronge, A. J., & Alberts, J. L. (2007). Age-related differences in working memory and force control under dual-task conditions. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *13*(March 2015), 366–384. http://doi.org/10.1080/138255890969339

Vorberg, D., & Schulze, H.-H. (2002). Linear Phase-Correction in Synchronization: Predictions, Parameter Estimation, and Simulations. *Journal of Mathematical Psychology*, *46*(1), 56–87. http://doi.org/10.1006/jmps.2001.1375

Vorberg, D., & Wing, A. M. (1996). *Chapter 4 Modeling variability and dependence in timing*. *Handbook of Perception and Action* (Vol. 2). http://doi.org/10.1016/S1874-5822(06)80007-1

Wearden, J. H. (2004). Decision processes in models of timing. *Acta Neurobiologiae Experimentalis*, *64*, 303–317.

Wencil, E. B., Coslett, H. B., Aguirre, G. K., & Chatterjee, A. (2010). Carving the clock at its component joints: neural bases for interval timing. *Journal of Neurophysiology*, *104*(March 2010), 160–168. http://doi.org/10.1152/jn.00029.2009

Wiener, M., Turkeltaub, P. E., & Coslett, H. B. (2010). Implicit timing activates the left inferior parietal cortex. *Neuropsychologia*, *48*(13), 3967–3971. http://doi.org/10.1016/j.neuropsychologia.2010.09.014

Wilson, S. J., Pressing, J. L., & Wales, R. J. (2002). Modelling rhythmic function in a musician post-stroke. *Neuropsychologia*, *40*, 1494–1505. http://doi.org/10.1016/S0028-3932(01)00198-1

Wing, A. M. (2002). Voluntary timing and brain function: an information processing approach. *Brain and Cognition*, *48*, 7–30. http://doi.org/10.1006/brcg.2001.1301

Wing, A. M., & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*(1), 5–12. http://doi.org/10.3758/BF03198607

Wing, A. M., & Kristofferson, A. B. (1973b). The timing of interresponse intervals. *Perception & Psychophysics*, *13*, 455–460. http://doi.org/10.3758/BF03205802

Yamanishi, J., Kawato, M. & Suzuki, R. (1980). Two coupled oscillators as a model for the coordinated finger tapping by both hands. *Biological Cybernetics,37*(4), 219-25.

Yang, Y. R., Chen, Y. C., Lee, C. S., Cheng, S. J., & Wang, R. Y. (2007). Dual-task-related gait changes in individuals with stroke. *Gait and Posture*, *25*, 185–190. http://doi.org/10.1016/j.gaitpost.2006.03.007

Yogev, G., Giladi, N., Peretz, C., Springer, S., Simon, E. S., & Hausdorff, J. M. (2005). Dual tasking, gait rhythmicity, and Parkinson's disease: Which aspects of gait are attention demanding? *European Journal of Neuroscience*, *22*(April), 1248–1256. http://doi.org/10.1111/j.1460-9568.2005.04298.x

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders*, *23*(3), 329–342. http://doi.org/10.1002/mds.21720

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders*, *27*(6), 765–770. http://doi.org/10.1002/mds.24963

Zelaznik, H. N., Spencer, R. M. C., & Ivry, R. B. (2002). Dissociation of explicit and implicit timing in repetitive tapping and drawing movements. *Journal of Experimental Psychology. Human Perception and Performance*, *28*(3), 575–588. http://doi.org/10.1037/0096-1523.28.3.575

Appendix

Comparisons from Figure 10	
Comparison	**T-test**
0.6 s_1.5 N and 0.8 s_1.5 N	t(46) = -9.588, *p*<.001
0.6 s_1.5 N and 1.0 s_1.5 N	t(40) = -13.121, *p*<.001
0.8 s_1.5 N and 1.0 s_1.5 N	t(40) = -6.535, *p*<.001
0.6 s_2.0 N and 0.8 s_2.0 N	t(46) = -17.728, *p*<.001
0.6 s_2.0 N and 1.0 s_2.0 N	t(46) = -23.962, *p*<.001
0.8 s_2.0 N and 1.0 s_2.0 N	t(47) = -10.562, *p*<.001
0.6 s_2.5 N and 0.8 s_2.5 N	t(42) = -9.443, *p*<.001
0.6 s_2.5 N and 1.0 s_2.5 N	t(41) = -17.653, *p*<.001
0.8 s_2.5 N and 1.0 s_2.5 N	t(41) = -6.600, *p*<.001

Comparisons from Figure 11	
Comparison	**T-test**
0.6 s_1.5 N and 1.0 s_1.5 N	t(41) = -5.132, *p*<.001
0.8 s_1.5 N and 1.0 s_1.5 N	t(41) = -4.416, *p*<.001
0.6 s_2.0 N and 0.8 s_2.0 N	t(46) = -4.639, *p*<.001
0.6 s_2.0 N and 1.0 s_2.0 N	t(46) = -7.036, *p*<.001
0.8 s_2.0 N and 1.0 s_2.0 N	t(47) = -4.850, *p*<.001
0.6 s_2.5 N and 1.0 s_2.5 N	t(41) = -4.748, *p*<.001
0.8 s_2.5 N and 1.0 s_2.5 N	t(41) = -3.808, *p*<.001

Comparisons from Figure 12	
Comparison	**T-test**
0.8 s_1.5 N and 1.0 s_1.5 N	t(41)=-2.425, *p*=.020
0.8 s_2.5 N and 1.0 s_2.5 N	t(41)=-2.450, *p*=.019

Comparisons from Figure 13	
Comparison	**T-test**
0.6 s_1.5 N and 0.6 s_2.0 N	t(46) = -6.599, *p*<.001
0.6 s_1.5 N and 0.6 s_2.5 N	t(42) = -7.553, *p*<.001
0.6 s_2.0 N and 0.6 s_2.5 N	t(42) = -2.961, *p*=.005
0.8 s_1.5 N and 0.8 s_2.0 N	t(47) = -9.199, *p*<.001
0.8 s_1.5 N and 0.8 s_2.5 N	t(47) = -7.020, *p*<.001
1.0 s_1.5 N and 1.0 s_2.0 N	t(41) = -6.029, *p*<.001
1.0 s_1.5 N and 1.0 s_2.5 N	t(41) = -7.027, *p*<.001

Comparisons from Figure 14	
Comparison	**T-test**
0.6 s_1.5 N and 0.6 s_2.0 N	t(46) = -4.889, *p*<.001
0.6 s_1.5 N and 0.6 s_2.5 N	t(42) = -6.311, *p*<.001
0.6 s_2.0 N and 0.6 s_2.5 N	t(42) = -3.037, *p*=.005
0.8 s_1.5 N and 0.8 s_2.0 N	t(47) = -4.910, *p*<.001
0.8 s_1.5 N and 0.8 s_2.5 N	t(47) = -3.797, *p*<.001
1.0 s_1.5 N and 1.0 s_2.0 N	t(41) = -4.143, *p*<.001
1.0 s_1.5 N and 1.0 s_2.5 N	t(41) = -3.385, *p*=.002

Comparisons from Figure 15	
Comparison	**T-test**
0.8 s_1.5 N and 1.0 s_1.5 N	t(41) = -2.625, *p*=.012

Comparisons from Figure 18	
Comparison	**T-test**
Lag -5	t(16) = 0.012, *p*=.991
Lag -4	t(16) = -1.111, *p*=.283
Lag -3	t(16) = -0.858, *p*=.403
Lag -2	t(16) = -0.538, *p*=.598
Lag -1	t(16) = 0.435, *p*=.669
Lag 0	t(16) = -0.168, *p*=.868
Lag 1	t(16) = 1.377, *p*=.188
Lag 2	t(16) = -0.658, *p*=.520
Lag 3	t(16) = -1.137, *p*=.272
Lag 4	t(16) = -0.310, *p*=.760
Lag 5	t(16) = 0.005, *p*=.996

~---~ End of thesis. ~---~