The Cognitive Context of Sensorimotor Synchronisation

Marek Sinason

A thesis submitted to

The University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

Jan 14th 2013 School of Psychology

The University of Birmingham

Acknowledgements

The change from a Newtonian conception of Universal time to the relational concept of Time that Einstein introduced had a profound impact on science, and culture. The relativity of the Time of a PhD also has a profound impact on relationships, at home and at work, just as they in turn, did on it. I would like to thank all those at the SyMoN lab (past and present) who maintained such pleasant and humorous working relationships at even at stressful times, and for contributing to the hardworking but friendly atmosphere that Alan Wing seems to have encultured.

I extend a special thanks to everyone who took part in the weekly Beats meetings (namely Alan Wing, Andrew Welchman, Juliane Honische, Mark Elliott Dagmar Fraser with new additions of Trudy Pelton and Winnie Chua) along with notable visitors from near and far that took part. Joining these meetings at the start of the PhD proved to be a most formative and enjoyable introduction to the ongoing timing research community and conferences that I was about to contribute to. I would also like to thank Nick Roach who made time to build me a photoreceptor to calibrate my equipment between many other supportive jobs for other members of the department while studying for his own PhD.

Finally, I would like to thank my family; my neice, who has kept me in mind despite the long gaps between visits in her early years, my sister for her support and contribution of band members for participation in some studies, and both my parents for their maintained interest and support for my endeavours....and to Katherine Dandridge for shared times past and shared times to come.

ABSTRACT

The cognitive context of sensorimotor synchronisation (SMS) starts with the assumption that performance of relatively simple behaviour emerges through the background noise of a psychological context. The need to acknowledge this assumption becomes more apparent when clear definitions are sought. For example SMS has been defined as the "coordination of a rhythmic action with a rhythmic event sequence" . This definition draws on the notion of measurement, (via coordination), the ability to produce repeated actions (rhythmic action) and the ability to perceive a repetition of events (event sequence). Each of these component notions when investigated empirically draws our attention to variability. Our understanding of variability in measurement, variability in the (re)production of action, and variability in perception has a long history in psychology and more broadly in science. The empirical findings of research on sensorimotor synchronisation outlined in the literature review (Chapter 1) indicate the progress that has been made in many lines over the last 100 years in understanding the nature of the component sources of variability. Despite this progress, and despite the growth in understanding the component sources of variability in cognition, perception and action, the role of more executive cognitive processes have not yet been well integrated to successful models of sensorimotor synchronisation.

This thesis presents a series of studies investigating more precisely the role of executive control functions on the variability of repetitive production of movements. If executive functions are involved in such timing, then timing should be impaired in a dual task situation where the concurrent task also recruits executive functions. A simple dual task paradigm is introduced to a sensorimotor task (in ChapterChapter 2)

to explore this assumption with some additional analysis based on the level of musical experience of the participants. A follow up study using a similar paradigm further explores the nature of the interference effect of a dual task on motor variability by varying the mode of the stimulus and responses to the secondary task. Findings from these experiments draw from competing information processing theories of cognitive sources of variability to account for the findings. Chapter 4 introduces a perturbation paradigm which had previously been identified as a way to measure more automated rhythmic movement production and online control that was considered more insulated from executive functions. A dual task probed the assumption that higher level executive processes would not interfere in perturbation recovery. A follow-up study using the perturbation paradigm was used with professional musicians to better understand the role of skill and musical training on both cognitive and motor sources of variability. Chapter 6 introduces a novel paradigm for assessing the variability of memory processes involved in rhythmic movement production by introducing different length gaps between synchronisation and continuation tapping movements. Two classes of behaviour were identified. Firstly, the introduction of the gap reduced the speeding up that was associated with initiating continuation tapping. Secondly, the introduction of the gap increased the amount of drift away from the target interval.

The findings of the 5 experiments presented here are discussed (Chapter 7) in relation to existent theories and ongoing debates in the field of sensorimotor synchronisation. The contribution of this research highlights the importance of executive processes often overlooked when assessing the nature of variability in rhythmic movement production and opens some clear pathways for future research, adjustments to current models used, and novel paradigms.

ACKNOWLDEGEMENTS

ABSTRACT

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION AND OVERVIEW OF THESIS

.

CHAPTER 2: ADDITIVE FACTORS, ATTENTION AND TIMING VARIABILITY

CHAPTER 3: ADDITIVE FACTORS II - STIMULUS AND RESPONSE MODALITY

CHAPTER 4: PERTURBATION RECOVERY

CHAPTER 5: PERTURBATION RECOVERY II - SKILL

CHAPTER 6: GAP TAPPING - MOTOR SYNCHRONISATION MAINTENANCE

CHAPTER 7: CONCLUSION

APPENDIX

CHAPTER 1

1.1 INTRODUCTION

Richard Feynman, a Professor of Theoretical Physics, recounts to his friend and drumming colleague Ralph Leighton (Feynman 1988) a number of basic questions about timing that he tried to investigate as a young student: what *does* determine the "time sense"? When you're trying to count at an even rate, what does that rate depend on? And what could you do to yourself to change it?

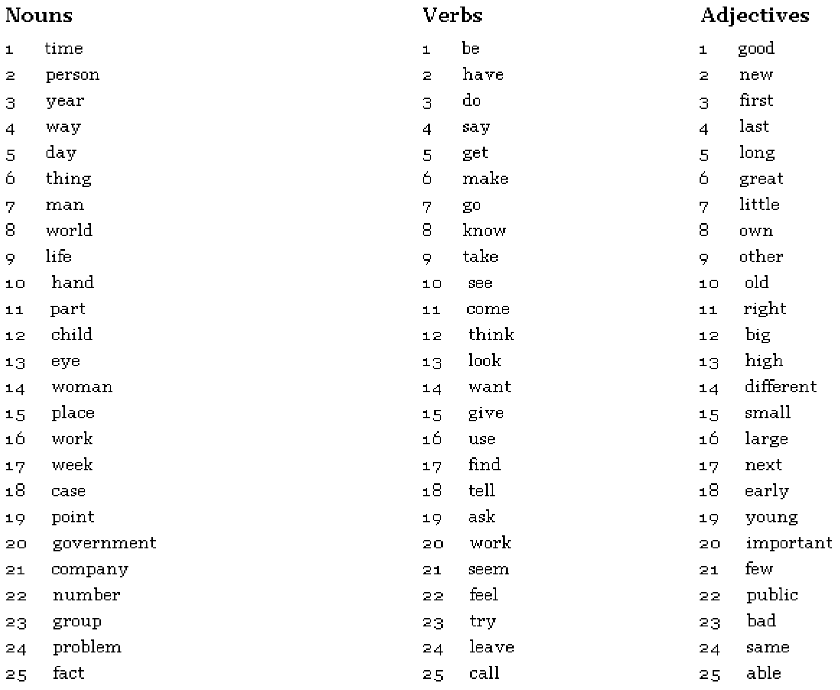
He started by counting to 60 in a slow, steady rhythm: 1, 2, 3, 4, 5 .... and when he got to 60, he found only 48 seconds had gone by. The next time, 48. Then 47, 48, 49, 48, 48 .... So he found he could count at a fairly standard rate, certainly more reliably than when attempting to guess the passing of a minute without counting. Having established a fairly reliable standard he wondered what would influence that rate. He considered heart rate may affect the rate of his count, so tried again after running up and down stairs, and after lying on a bed and found this made little difference to his reliability. He then tried other tasks, such as putting away the laundry, counting socks, arranging socks in different geometrical patterns, counting lines of newspaper text and even reading newspaper articles. He found some counting tasks interfered with his timing, but nothing interfered more than speaking aloud. When telling his friends of his discoveries, one disputed the idea that speaking would interfere, and after subjecting himself to a similar test, proved he could speak nonsense or read aloud and keep a much more reliable counting rate than Feynman when speaking whilst counting internally. After some discussion it emerged that his friend was counting in a different way, by visualizing a passing tape with numbers on, so he was internally watching, rather than internally speaking the numbers.

He states “We discovered that you can externally and objectively test how the brain works: you don't have to ask a person how he counts and rely on his own observations of himself; instead, you observe what he can and can't do while he counts.” This personal account of Fenyman, traverses the logic of many paradigms investigated thoroughly by psychologists in the last 100 years of timing research, and many themes explicitly researched in this thesis, particularly the notions of interference effects, dual tasks or divided attention and individual differences explored directly in Chapters 2-5.

1.2 Background of Temporal Terminology in science and philosophy

Before reviewing any aspect of timing in psychological research, we are confronted by a need to differentiate the particular aspect we are interested in from the wealth of themes that have been investigated. This is not only due to the importance of temporal measurements in almost all aspects of science, but also the wealth of associations and temporal assumptions that the singular word Time evokes. Time is infact the commonest noun used in the English language, shortly followed by *year* (number 3*)*, *day(*number 5*) and month* (ranked 40th) (see Table 1). The frequent use of the word Time is not doubt in part due to its inclusion in common phrases and its idiomatic use in adverbial phrases like *on time, in time, last time, next time, this time,* etc. Nevertheless the Oxford English dictionary defines 26 different specific meanings of Time as a noun, 4 different definitions as an adjective, and 7 different definitions as a verb (OED 2012).

This breadth of multiple meanings and associations with the word Time seriously reduces its utility as a search term in the literature. For example when using PyscINFO database to search the psychological literature for studies on the topic of time in December 1999 using the dating parameters 1887-present, Rockelein (Roeckelein 2000)found a total of 138,397 studies containing the keyword time. In Feb 2012, using the same search criteria returns 325,028 studies. Showing in the last 13 years more publications used the term as a key word than in the previous 100 years combined.



	Nouns		Verbs		Adjectives
1	time	1	be	1	good
2	person	2	have	2	new
3	year	3	do	3	first
4	way	4	say	4	last
5	day	5	get	5	long
6	thing	6	make	6	great
7	man	7	go	7	little
8	world	8	know	8	own
9	life	9	take	9	other
10	hand	10	see	10	old
11	part	11	come	11	right
12	child	12	think	12	big
13	eye	13	look	13	high
14	woman	14	want	14	different
15	place	15	give	15	small
16	work	16	use	16	large
17	week	17	find	17	next
18	case	18	tell	18	early
19	point	19	ask	19	young
20	government	20	work	20	important
21	company	21	seem	21	few
22	number	22	feel	22	public
23	group	23	try	23	bad
24	problem	24	leave	24	same
25	fact	25	call	25	able

Table 1: List of the most commonly used words in the English language based on analysis of the Oxford Corpus texts of over 2 billion words used in literature, journals and web-blogs

However the frequency of talk about ‘Time’, is also due to the ongoing discussions, measurements, and disputes and definitions that have accompanied its conception throughout scientific and philosophical history. While the challenge of Einstein’s General and Special Relativity made a huge impact to physicists that had previously used a Newtonian uniform and absolute time dimension for calculations, the adoptions of different calendars, and even the coordination of transport timetables, had long since provided a backdrop for the fights between local and universally accepted standards(Landes 1983). Even more ancient Greek debates about the ontological status of Time, whether it was discrete or a continuum, whether it was an illusion or a sense, continue to ripple through to conceptual and empirical disputes today (Treisman 1963; Lewis and Miall 2006; Torre and Balasubramaniam 2009; Bruno H 2011; Rodger and Craig 2011; Repp, Keller et al. 2012)

An example of the difficulties raised by standards and measurements in science made the news in September 2012 the OPERA team at CERN had announced the surprising results that sub-atomic particles (neutrinos) had travelled some six kilometres per second faster than the velocity of light. A disconcerting finding as distance in meters is officially defined by the distance light travels in a portion of a second: In 1983 the 17th CGPM (BIPM 2012)specified the current definition, as follows:

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

However in February 2012 a 60 nanoseconds discrepancy was tracked to a bad connection between a fibre optic cable that connects a GPS receiver and an electronic card in a computer. This glitch may infact explain the apparent faster than light travel of neutrinos. (News 2012). An oscillator designed to synchronise the timing of each neutrino at their points of departure and landing was also reported as needing to be verified by the OPERA team.

This news item highlights the need to separate issues of time definition, time variability in the measurement process from the timing of the thing being measured. The unit of time internationally recognized by definition is the second. It was defined originally as the fraction 1/86 400 of the mean solar day. (NIST 2012) However, variability in the rotation of the Earth required the definition of the unit of time to be more precise. Accordingly the 11th CGPM (1960) adopted a definition given by the International Astronomical Union which was based on the tropical year. Experimental work had, however, already shown that an atomic standard of time-interval, based on a transition between two energy levels of an atom or a molecule, could be realised and reproduced much more precisely than astronomical observation. This led the 13th CGPM (1967) to replace the definition of the second by the following (affirmed by the CIPM in 1997 that this definition refers to a cesium atom in its ground state at a temperature of 0 K):

> **The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.**

While changes in definitions and measurements are contended with in all sciences, they are perhaps particularly acute to those investigating aspects of timing where the changing definition, scale and measurement can all add to the inherent variability that needs to be understood. In psychology this issue becomes explicit in that Time can, and has been investigated as both a Dependent and Independent variable (see Fig 1).

DEPENDENT VARIABLE		**INDEPENDENT VARIABLE**	
TIME ORDER ERROR	(Stott 1935) (Woodrow 1936)(Woodrow 1936)	FILLED /EMPTY	(Spencer 1921) (Triplett 1931) Weber (1933)
TIME DISCRIMINATION	(Dunlap 1915) (Woodrow 1928a)	SENSORY MODALITIES	(Gridley 1932) (Goodfellow 1934)
TIME ESTIMATION	(Spencer 1921) (Swift 1925) (Hoagland 1933)	STIMULUS DURATION	(Curtis 1916; Harton 1939c)
TIME PERSPECTIVE	(Guilford 1926) (Farber 1944)	INDIVIDUAL DIFFERENCES	Weber (1933), (Woodrow 1933; Woodrow 1934) (Nitardy 1943)
TIME PERCEPTION	(Weber 1927) Scott (1948)	PHYSIOLOGICAL FACTORS	(Carrel 1931; Hoagland 1933; Hoagland 1934)
DURATION ESTIMATION	(Curtis 1916) Sturt (1923)	INTERSTIMULUS INTERVAL	(Lifshitz 1933; Needham 1935)
TEMPORAL EXPERIENCE	(Carrel 1931) (Lewis 1931-1932)	TEMPORAL ORDER	(Postman 1944) (Hammer 1949)
TIME ORIENTATION	(Macleod 1935) (Davidson 1941)	STIMULUS CHARACTERISTICS	(Ford 1937)
TIME CONCEPT	(Oakden 1922) (Bradley 1948) (Ames 1946) (Schneider 1948)	KINESTHETIC FORCE FIELDS	(Weber 1927)
TEMPORAL INDIFFERENCE INTERVAL	(Woodrow 1934)		
TIME DISTORTION	Cooper (1948)		

Fig (1) Example of early psychology of time references drawn from Doob (1971) and Roeckelein (1973, 2000)

Historically, the notion or variable of time may have been treated as either an independent variable or a dependent variable depending on the particular hypothesis and research goals of a given study. For example, the DV of ‘time estimation expressed as seconds’ may be measured as a function of the IV (stimulus) of the “delay between two intervals to be discriminated”. (Roeckelein 2000). This capacity for temporal conceptions to represent both the figure and the ground, exposes the empirical need to assess variability in both. For example, attempting to measure the shortest duration of a sound that can be perceived is different from the measurement of the duration of the sounds perception.

Psychological investigations using different temporal frameworks have resulted in a number of important distinctions and approaches to experimentation (fig 1). Studies of time as a stimulus attribute were historically regarded as investigations of temporal perception, whereas studies of time as a response attribute are often referred to as aspects of temporal performance. In studies of time as a IV, the response measure has often been a categorical one such as left or right lever response; whereas in studies of time as a DV the measure is a quantitative one on the temporal dimension.

In the hundred years since, the need for more specific terminology in different fields (tempo, accelerando etc in musicology, distinctions such as short term and long term memory, rates of stimulus decay or extinction, even the notion of evolution and development) all draw on the many meanings and uses of often ancient temporal terminology to define perspectives, durations, relations or points on abstract dimensions.

1.3 Quantifying Regular Motions

One very ancient theme that can be traced to Aristotle is to link time with motion “the Number of motion”(Roeckelein 2008), while for Descartes, many centuries later, it was a relation derived “from a comparison of the durations of regular motions”. For Plato rhythm was defined as “order in movement(Roeckelein 2000), Paul Fraisse defined it as “order in succession”(Fraisse 1984). The link of founding time in regular movements finds its way to both the development of accurate clocks(Landes 1983) and modern international standards of the second based on the most reliable regular oscillations, and to some of the earliest experimental research by Vierordt in 1868 on the ability to produce regular movements by tapping rhythms (Lejeune 2009).

Mach in 1865 made an important contribution to theories of rhythm production by emphasizing the predominantly motor nature of the phenomenon. Building on this Bolton made a stronger claim in 1896 (Roeckelein 2008) that rhythm is a universal phenomenon in nature and in involuntary physiological activity (such as the pulse, heartbeat, and respiration) and the cycles of night and day and seasons. This theme of exploring relations of regular motions to other regular motions, has led to great advances in the precision of time-keeping devices such as Huygens pendulum clock, and the development of modern standardised units of time. These tools have in turn aided the precision of measurement in science and our understanding of movement timing variability on many different scales(Landes 1983). For example the rotation of the earth producing regularities of night and day, and yearly rhythms had been a standard used to measure variability such as rate of growth per year, or yield per calendar month, or physiological activity and circadian rhythms. Mirroring the ability to use time as dependent or independent variable, the invention of the pendulum clock made it possible to mark time with less than a minute variability over the course of the day and become a standard to measure the variability of seasonal daylight. For smaller time-divisions, chronographs and stopwatches divided the minutes and seconds into ever smaller divisions from the 1/5th second standard in 1864 to the 1/10th of a second used to record athletic records in the 1932 Olympics. By the Olympics of 1962, what would have been considered a dead heat between two runners, first place could now be separated from second place by 100th of a second. (Quercetani 1964) The ability to quantify with increasing precision the regularity of movements to ever more reliable faster oscillations in time-keeping devices, has led to a number of quantitive models of movement timing to which we will now turn.

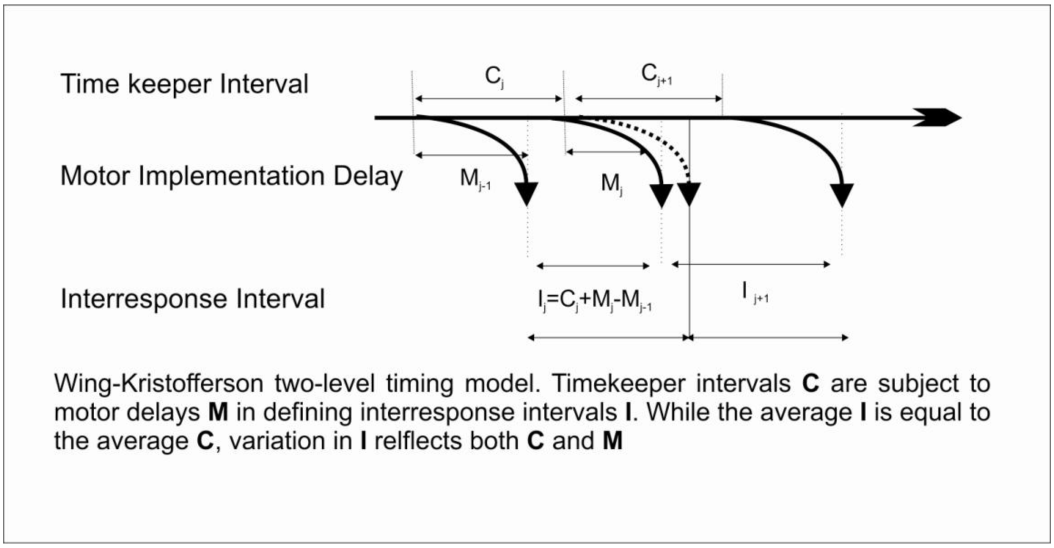
1.3 Modern Models of Timing

1.3.1 Regular Movements

Studying the synchronisation of repetitive finger taps with a stream of regular external events has, as we have seen illustrated in Fig 1,a long history in experimental psychology(Stevens 1886; Dunlap 1910; Aschersleben 2002; Zelaznik 2005). Synchronisation requires the ability to control motor output based on the prediction of external events (Harry 1985; Harry 1987a; Harry 1987a). It is the combination of an external signal (such as a metronome) and the requirement of a controlled coordinated movement that separates sensory motor synchronisation (SMS) research from other types of timing research. While someone listening to music or a metronome may find their attention starts to entrain or synchronise to the beats of the sounds and may include imagined movements, this would not be SMS as there is no overt movement. Similarly, although there may be movements and synchronisation required while playing a musical instrument this is not considered SMS as there is no external stimulus beat to act as a referent.

This specific delineated field of timing investigation has produced some well replicated findings that do not apply to other types of timing research. For example, one of the oldest findings in SMS research is that when tapping a finger to a metronome, the taps tend to preceded the tones by a number of milliseconds (Miyake 1902). This anticipation tendency or mean negative asynchrony (MNA) is widely replicated in SMS research and yet participants are generally unaware of this tendency of timed movements to be produced ahead of the sound to be synchronised with. Many explanations have been offered to account for this asymmetric finding sometimes attempting to explain it on the side of sensation (neural transmission times for sensory information (Fraisse 1980), or perception at the level of central represenation(Aschersleben 1995; Aschersleben 2002). Alternative theories posit it asa consequence of attempting to minimise variance (Vorberg 1996). Empirical support has been found for each theory by comparing nerve conduction delays of different effectors and comparing the level of negative asynchrony, or by delaying the feedback of the tap from the perception of the tap, nevertheless no single theory yet accounts for all the findings.(Repp 2005). The importance of MNA in the literature lies in the assumption that it reveals systematic effects of variability in both perception and action. Moreover MNA suggests that some aspect of the external interval has been internalised to initiate movements to synchronise rather than simply react to regular sounds. It is to these sources of movement variability and their models that we now turn.

SMS involves coordinating inherently variable movements with the variable perception of external signals. Even a perfect metronome will be subject to perceptual variability due to natural variability arising in the neural circuitry. Building on the research of Stevens (1886) who investigated the accuracy and inherent variability of maintaining tapping with a metronome set pace, Wing and Kristofferson offered a quantitative 2 level model (Wing & Kristofferson 1973a, 1973b); here referred to as the WK model which distinguished a central timer and a motor implementation process (see adapted fig 2). This model was able to develop the contrast of two sources of variance that Stevens' research picked up, a short term variance around the mean target interval which corresponds to the variance produced by motor delays, and a longer term drift which corresponds to the standard of a central timer or remembered (internalised) metronome interval duration. Under this model, short term fluctuations around the mean of the produced intervals are attributed to peripheral noise associated with motor implementation. Whereas a second source of variability is related to the length of the interval to be timed and is independently attributed to central (clock) timing processes. The independence of these two sources of variance implies that producing longer intervals increases the variability of the central timing processes but not the variability of the peripheral motor implementation. Indeed when investigating tapping behaviour at a range of different tempo’s between 290ms and 540ms, the decomposed variance of the central timing processes were found to increase linearly with the mean target interval whereas the peripheral motor delay variance was found to be relatively constant in accord with the Wing-Kristofferson (WK) model predictions (Wing 1980).



Wing-Kristofferson two-level timing model. Timekeeper intervals **C** are subject to motor delays **M** in defining interresponse intervals **I**. While the average **I** is equal to the average **C**, variation in **I** relflects both **C** and **M**

Fig 2. The Wing-Kristofferson two-level timing model.

1.3.2 Perception of regularity

While able to partition the variability of central timekeeping from motor variability by using the WK model, other lines of research have attempted to understand and model the variability at the level of perception. Numerous studies of time as a stimulus attribute combined with reliable performance knowledge about timing from classical conditioning and animal studies indicate that the standard deviation of the temporal measure is proportional to its mean. This is termed scalar or Weber law timing (Gibbon 1977; Gibbon 1984; Staddon 1996).A further lawful finding is that the relation between perceived time and a linear metric of time can be described by a power function (e.g. (Eisler 1975; Eisler 1976; Eisler 2008). Eisler (1976) compiled power function exponents from 111 time perception studies published between 1868 and 1975, and found that the average exponent (slope value) across studies was 0.9. These results mean that temporal judgements follow changes in clock-time duration in a nearly veridical fashion. Although nether Weber law timing nor the associated power function holds for every temporal schedule or every duration of dependent measure (Staddon 1996; Staddon 1999) nevertheless for many common situations these two properties have been reliably found.

On the theoretical side, several quantitative models have been advanced to explain such data, including scalar expectancy theory (SET) model, an information-processing model developed by Gibbon (Gibbon 1977; Gibbon 1991; Gibbon 1992; Penney 2008), the learning-to-time (LeT) model, a behavioral model developed by Machado (1997), the multiple-oscillator model (Church & Broadbent 1990) the spectral theory of timing, Packet Theory (Guilhardi & Church, 2005) the multiples-time-scale model of time (Staddon 1996) and real-time models of conditioning. They differ in their perceptual representations of time, in their memory representations, and their decision processes. An important implication of these theoretical assumptions is how varied the internal representation of time is for each of these models. For example, from an interval model perspective, the indifference interval (where subjects neither overestimate nor underestimate a time period) is a memory trace of a single discrete interval, whereas from multiple time scale models the representation of time is a relatively deteriorating memory trace, whereas from an entrainment perspective a global context could be said to induce one or more internal periodicities that contribute to an overall sense of pace that may be expressed as a reverberating circuit or emergent internal period (e.g., McAuley & Jones, 2003).

1.3.3 *Information Processing*

Alternative clock models come from information processing perspectives that emphasise memory components. Most theories that incorporate explicit memory for time involve three independent components: an internal clock used to estimate duration, a reference memory used to store information about duration, and a comparison mechanism used to make judgments about how much time has elapsed relative to a remembered (expected) standard duration (Church and Broadbent, 1991). The traditional heuristic used to describe interval timing is an based on a model first proposed by (Treisman 1963).

The model entails three distinct stages in which temporal information about an event is abstracted, encoded, and acted upon. Building on this framework, scalar expectancy theory (SET) has been particularly influential because it has been successfully applied to both human and animal data (Gibbon 1977; Gibbon 1984; Gibbon 1991; Penney 2000; Penney 2008). SET posits a neural pacemaker that emits a continuous stream of pulses. Stimulus events marking the beginning and ending of event durations trigger the closing and opening of a switch that gate pulses into an accumulator. The count of the pulses accumulated over the target event duration represents a subjective duration code that is stored in reference memory. Successive time intervals are estimated independently, with relative duration judgments about time intervals involving a comparison between a working memory representation of the accumulator and a criterion time sampled from reference memory. A schematic of the various components of SET is shown in Fig.3

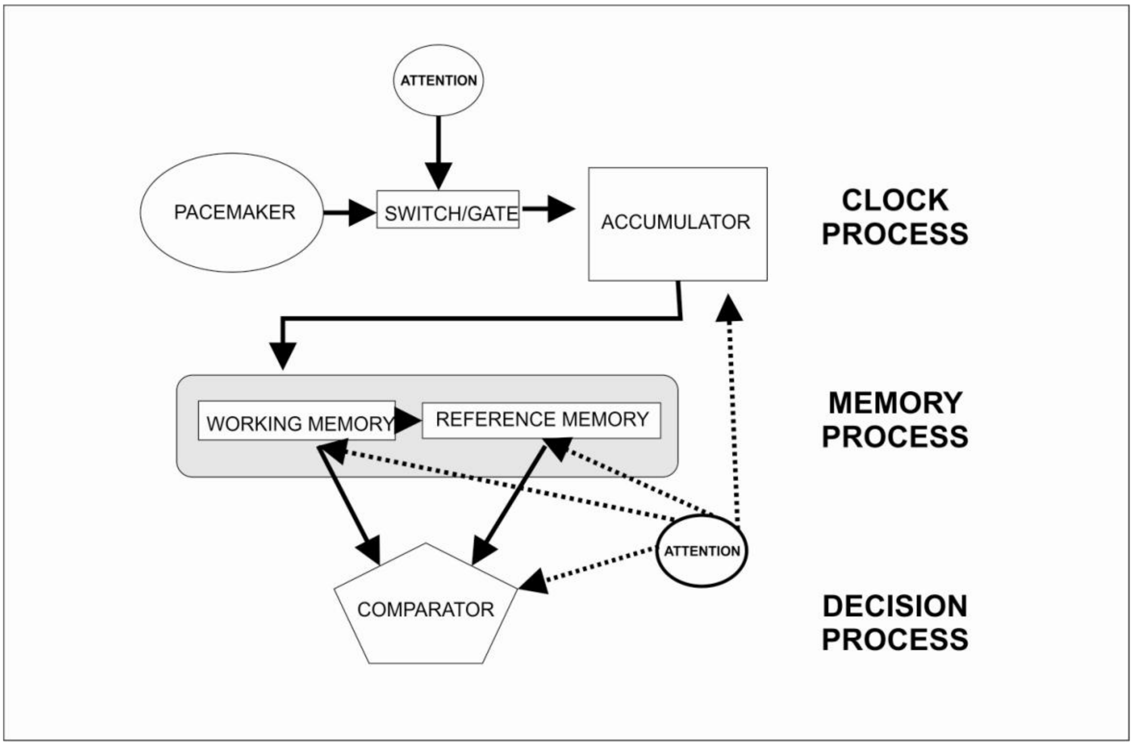
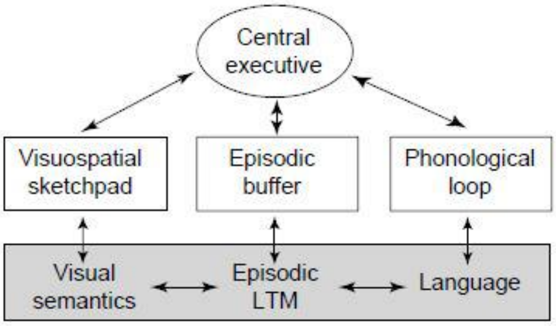


Fig 3 An information processing model of internal clock processes.

Notwithstanding the success of the WK model and the SET model, the assumption that a unitary ‘internal clock’ underpins movement timing control is perhaps overly simple. For example, different forms of internal clocks or pacemakers have been proposed (Gibbon 1984; Treisman 1990; Wearden 1995) and the outputs of these different internal clocks might interact in various ways with other processes such as sensory feedback, memory and decision mechanisms. Fig 4 illustrates a number of conceptual models that allow for separate model timers, multiple oscillators, shared or independent accumulators. These alternate models can account for slightly different empirical findings and lend themselves to different predictions for where resources may be shared or bottlenecked. For example it has been proposed that accumulators, could underlie the estimation of both time and number or counting processes (Meck & Church, 1983). An accumulator could then represent the duration or the numerosity of objects or events through different operative modes, by summing the impulses produced by a generator either at a given frequency for duration processing or each time an event or an object was encountered for numerosity processing (Meck, 1997; Meck & hurch, 1983; Meck, Church & Gibbon, 1985). This would explain some of the bidirectional interference often found when doing mathematical calculations and regular movements. (Brown 1990; Brown 1997). However, if a separate accumulator was available for each mode, interference during counting or timing of visual and auditory stimuli would be predicted to interfere less than if a single amodal accumulator was assumed. (see fig 4)

While the stages and components of the information processing models mimic many of the executive processes of models of working memory or short term memory such as those proposed by The Atkinson–Shiffrin model in 1968, or the Badley & Hitch model of working memory (1986), these tend not to be used or referenced in SMS research as they offer no specific timing module or clock component see Fig 3a.



.

Fig 3a Badley & Hitch 2000 model of working memory

While some researchers in the fields of music and memory have argued that rhythm may be a component part of the phonological loop (Saito 1977; Saito 1994; Saito 2001) most researchers take it to represent the short term store of auditory linguistic information. The absence of an explicit temporal module or patterns of temporal features found in metronomic rhythm have tended to see limited use of these more traditional models of executive functions and memory in the timing domains for the SET models. (Fig 4)

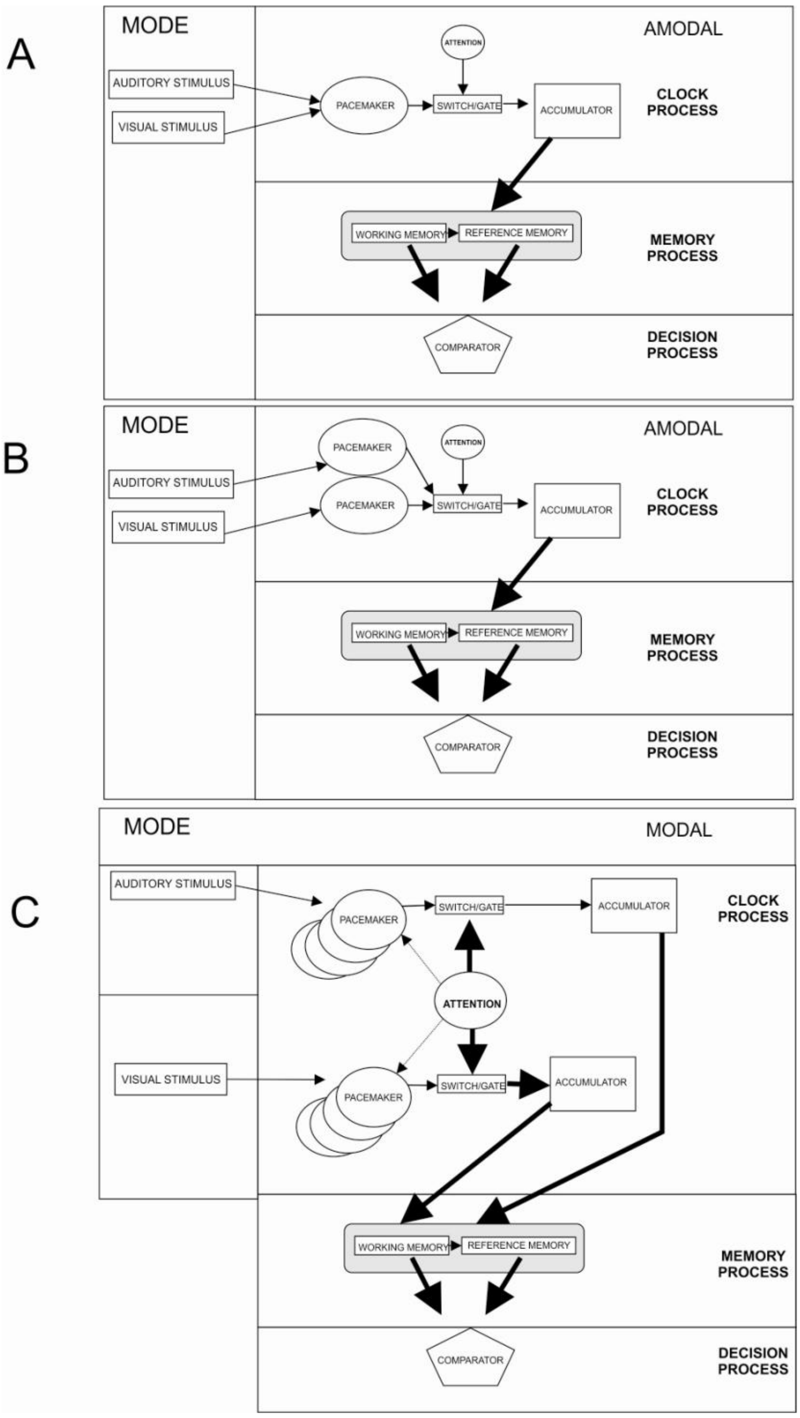


Fig 4. Illustration of 3 different information processing models of timing accommodating theories of single or multiple pacemakers, accumulators and modal interactions. Different roles for attention are identified in each, switching on one or more pacemakers, or time-sharing between them.

There have been several proposals about how attention might influence timing performance within the information processing or scalar expectancy framework. One proposal is that attention influences the probability that participants' behaviour is controlled by stimulus timing on a given trial (Church and Gibbon, 1982; (Gibbon 1992; Macar 1994; Meck 2002; Coull 2004). In this view, divided attention decreases the probability that attention is focused on any single stimulus, resulting in an increased asymmetry of the response distributions for each stimulus. An alternative proposal is the attentional switch hypothesis.

The attentional switch hypothesis proposes that attention operates as a switch at the clock stage. The attentional switch influences timing by altering the efficiency with which pulses from the pacemaker are transferred to the accumulator (Allan, 1992; Lejeune, 1998; Macar et al., 1994; (Meck 2002). Under focused attention conditions, pulses accumulate as a function of time, and the subjective experience of duration is directly proportional to the count of the number of pulses that occur over the temporal extent of the stimulus. However, when attention is divided between two tasks (e.g., a temporal and a nontemporal task or two timing tasks), the assumption is that some pulses may be "lost," with the proportion of lost pulses inversely related to the amount of attention allocated to the timing task.

Alternative models (Block 1978; Block 1980; Block 1982; Jones 1989; Block 1990; Block 1992; Block 1997; Barnes 2000; Barnes and Jones 2000; Jones 2004; Block 2010; Ogden, Salominaite et al. 2011) posit even greater roles for memory and attention processes dispensing with a general purpose amodal pacemaker altogether. These models, like the information processing models have developed to explain different types of timing variability than rhythmical movements, such as perceptual judgements, retrospective judgements, and time estimation and anticipation. The contextual change model (Block 1978, 1985, 1989, 1990) proposes that judged duration is monotonically increasing function of the number of contextual changes which are encoded into memory during a time period. These contextual changes include both those taking place in the external environment and those occurring in the internal events, such as in meaning, cognitive strategies, and mood states.

The contextual change model uses this attentional and memory based explanation for why ‘empty’ durations are often perceived and estimated to be shorter than filled durations. Ordinarily, fewer contextual changes will occur during an ‘empty’ duration than a duration filled with an information processing task. Accordingly, empty durations are characteristically underestimated compared with durations filled with information processing tasks.

Error correction

A major characteristic to emerge as fundamental to research on SMS is that it cannot be maintained without error correction. Once again variability is a central issue as the variability even in a periodic movement like finger tapping will produce ever accumulating descrepancies from subsequent taps if attempting to match a precise periodic signal such as a metronome. The perception of growing asynchrony between tapping and a metronome beat offers a chance to correct the phase or the period of the tap to return to a more synchronised rhythm. The significant issue at stake with these two options of error correction (phase vs period) is that both assume some sort of internal time-keeper but a phase correction leaves the internal timekeeper period unchanged and adjusts the phase of the movement onset. This is considered a relatively peripheral and automated process of online control. Whereas a period correction refers to a change to the period of the internal timer while keeping the peripheral movement initiation the same. (Bruno H 2001; Repp 2001; Repp 2001; Repp 2002; Repp 2002a; Keller and Repp 2004; Repp and Penel 2004; Thaut and Kenyon 2004; Repp 2008; Repp and Keller 2008; Delignières and Torre 2011; Repp and Moseley 2012).

Perturbation studies have typically been used to probe the SMS error correction models. By inserting a phase shift in an otherwise isochronous sequence of metronome beats, it forces the tapping participant to produce a large synchronisation error which they need to correct to return to synchronised tapping. While noticing the error in phase between the tap and the metronome, ‘perceiving’ the error might be considered the clearest candidate for requiring an important role for attention and executive processes in SMS models. However in series of studies conducted by Repp, Repp showed the recovery pattern following a perturbation (roughly exponential in asynchrony reduction as predicted by linear first order phase correction models) even when below the perceptual detection threshold. This surprising result has provided strong support for quantitative models of timing in SMS without needing any recourse to explicit roles for memory and attention that dominate time in time judgement and time perception research.

Two studies of note seem to buck this trend. The first being Sergent (Sergent 1993) who explored the variability of tapping when conducting a dual task of anagram solving while looking at the influence of handedness. Using the WK model to partition the variance they were able to show increased variability of central timing processes but not motor implementation when solving anagrams. The second was an experiment by Miyake et al (Takano and Miyake 2007)who explored tapping variability while conducting a word memory task. Miyake concluded that tapping to an interstimulus onset interval (ISI less than 1500ms is mainly based on automatic processes which are not influenced by the secondary task. These two studies found contrary findings and used different methods to assess tapping variability and different secondary tasks. Neither have been replicated nor explored for different measures of tapping variability, different effectors or different secondary tasks. While Sergent considered a number of structural limitations of shared neural circuitry for the nature of the interference found, Miyake was looking more at capacity limitations of attention and working memory as indicated by changes in MNA. Both approaches nevertheless assume an amodal general purpose internal timekeeper capable of both peripheral automatic error correction and more central executive control.

1.4 **Summary**

The analysis of regular motions and repetitive actions have lent themselves to a variety of quantitive models of timing and made use of precision instruments with more frequent regular oscillations to measure their variability. However the focus on regular motions has perhaps come at a price of removing consideration to other fields exploring different ways of looking and defining temporal relationships. For example Church notes that Psychologists interested in temporal aspects of action and cognition do not typically attend to research on classical conditioning or schedules of reinforcement. One reason for this is that conditioned responses reside in the domain of ‘learning’ not ‘cognition or ‘perception’. Similarly (Church 2003) highlights that studies of the temporal dimension by psychophysics, biological rhythms and animal learning paradigms progressed independently. Church elaborates that “articles based on studies in these three fields typically were published in different journals and they rarely cited each other. The secondary literature also typically treated these three fields as separate topics”. A similar concern is highlighted by (Boltz 1995) in the relative independence of clinical and cognitive literatures on time estimation with the result that "each has often ignored certain theoretical ideas or empirical findings that might be useful for the development of the other".

It is a central theme of this thesis, that having established a very good understanding of the variability of movements to a range of variable regular stimuli over the last hundred years (see Fig 1), that it is through linking back with developments in other fields of timing research such as memory, learning, perception and attention, that more elusive aspects of movement timing variability will be better contextualised.

Nevertheless, in contrast to the success of many quantitive models of movement timing, those models that already give a greater role to processes of memory and attention such as the contextual change model of Block assume that time judgements are inferred from the amount of some nontemporal parameter (the number of chunks in memory or the number of contextual changes, or degree of segmentation respectively). Although these attributes may be important aspects of an event they do not specify the intrinsic timing of information within an interval or the total time span itself.

Thus while some models can explain the variability of time estimations and time perception well with a clear role for attention and and memory processes, how they interact with very precise, often automatic, motor control is not clear. It is toward a better understanding of this interplay of low level sensorimotor control and higher level cognitive factors that the experiments in ChapterChapter 2-6 are directed.If executive functions are involved in such timing, then timing should be impaired in a dual task situation where the concurrent task also recruits executive functions. A simple dual task paradigm is introduced to a sensorimotor task (in Chapter 2) to explore this assumption. A follow up study in Chpater 3 using a similar paradigm further explores the nature of the interference effect of a dual task on motor variability by varying the mode of the stimulus and responses to the secondary task. Findings from these experiments draw from competing information processing theories of cognitive sources of variability to account for the findings. Chapter 4 introduces a perturbation paradigm which had previously been identified as a way to measure more automated rhythmic movement production and online control that was considered more insulated from executive functions. A dual task probed the assumption that higher level executive processes would not interfere in perturbation recovery. A follow-up study Chapter 5 using the perturbation paradigm was used with professional musicians to better understand the role of skill and musical training on both cognitive and motor sources of variability. Chapter 6 introduces a novel paradigm for assessing the variability of memory processes involved in rhythmic movement production by introducing different length gaps between synchronisation and continuation tapping movements. Two classes of behaviour were identified. Firstly, the introduction of the gap reduced the speeding up that was associated with initiating continuation tapping. Secondly, the introduction of the gap increased the amount of drift away from the target interval.

The findings of the 5 experiments presented here are discussed (Chapter 7) in relation to existent theories and ongoing debates in the field of sensorimotor synchronisation. The contribution of this research highlights the importance of executive processes often overlooked when assessing the nature of variability in rhythmic movement production and opens some clear pathways for future research, adjustments to current models used, and novel paradigms.

CHAPTER 2:

ADDITIVE FACTORS, ATTENTION AND TIMING

2.1 ABSTRACT

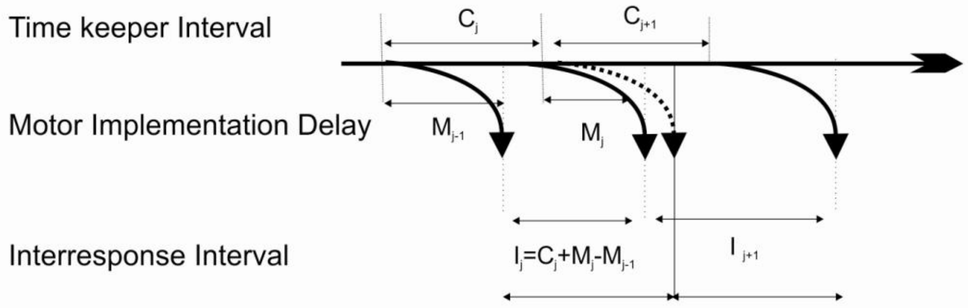
When performing simple or complex tasks we may expect to see a performance cost during distractions or if attention is divided with another task. When the task requires evenly timed movements, the cost of divided attention may be an increase in the variability of the movements. In this study we explored the cost of divided attention (single task vs counting backwards in threes) on the variability of repetitive finger tapping movements in 42 healthy participants. We used a 3-factor counterbalanced within-subjects design to explore the cost of divided attention in the interactions with 2 different movement types (index finger vs little finger) and 2 different intervals (400 vs 650ms). According to the Wing-Kristofferson (WK) timing model, motor variance is independent from the variance of central clock processes. Therefore we expected greater variability when participants tapped with the little finger compared to the index finger due to additional motor control variance. Whereas, we expected greater variability of tapping responses at the longer interval duration due to variability in central clock processes. Importantly, according to the (WK) model, we would expect no interactions of movement type with either interval duration or divided attention. In contrast we expect a strong interaction between divided attention and interval duration both due to variability of central clock processes. In Line with the WK model we found a significant interaction with interval duration and divided attention and no interactions with movement type in line with WK model. However further analysis revealed that the degree of prior musical experience heavily moderated the cost of

divided attention on timing variability, particularly at longer intervals and with the more unusual movements.

2.2 INTRODUCTION

Timing Variability

“Repeated movements are rarely, if ever, exactly the same but are subject to variation” (Wing 2004). Although some variation may be intentional, or contextual, some may reflect the difficulty of the movement, or inherent noise in the component processes(Van Beers 2004), or indeed the timescale or speed of the movement investigated (Repp 2003b). Stevens (Stevens 1886) noted that even with a simple repetitive movement such as a finger tap along to a metronome-set rhythm, that the continued taps, with the metronome turned off, seem to vary more with the length of the target interval aimed at. Additionally he observed that this subsequent behavioural variability had two components, a short term fluctuation around the mean of the interval and a longer term drift. The two level timing model of Wing and Kristofferson (Wing 1973) could account the trends found by Stevens in the way it partitioned the variance. The model assumes that variability of interresponse intervals is a product of central timekeeping variability on the one hand, and the independent variability of motor implementation delays on the other. Wing and Kristofferson (Wing 1973) assumed that, in self- paced tapping, a succession of command pulses is generated by an internal timekeeper. Each pulse initiates a motor implementation process which leads, after some delay (motor implementation delay), to an observable response. The intervals marked off by the timekeeper as well as the motor delays are assumed to be subject to independent chance fluctuations. If these assumptions hold, then the intervals between responses (IRI) are decomposable into contributions of the timekeeper and of the motor system. Wing and Kristofferson (1973) assumed that timekeeper intervals and motor delays are independent random variables. They also assumed mutual independence between the timekeeper intervals and the motor delays. These assumptions imply that the variance of the observable interresponse intervals equals the timekeeper variance plus twice the motor delay variance (see Fig5). On this basis, an empirical finding (Wing 1980) that variability increases along with an increase in the mean of the set interval, is thought to reflect the increase of variability in the central timekeeping processes with the relatively unchanged additional variability of motor implementation. Indeed when investigating tapping behaviour at a range of different tempo’s between 290ms and 540ms, the decomposed variance of the central timing processes were found to increase linearly with the mean target interval whereas the peripheral motor delay variance were found to be relatively constant in accord with WK model predictions (Wing 1980). Further empirical tests of the model have been reviewed by Vorberg and Wing (1994, 1996).



Wing-Kristofferson two-level timing model. Timekeeper intervals **C** are subject to motor delays **M** in defining interresponse intervals **I**. While the average **I** is equal to the average **C**, variation in **I** relflects both **C** and **M**

Fig 5. The Wing-Kristofferson two-level timing model.

Additional support for the independence of these two sources of variance comes from Sergent, Hellige, and Cherry (1993) who analysed the effects of concurrent anagram solving on timing in terms of the two-level timing model and found the secondary task increased the variance of the central timekeeper leaving the variance of the motor implementation relatively unchanged.

The resulting interference of the concurrent task could be a consequence of the intrinsic anatomical and functional properties of the brain centres involved in the tasks and limiting their processing capabilities. This interference is usually referred to as "structural interference" similar to the "functional cerebral distance principle" posed by Hiscock (1996). This posits that two concurrent activities interfere with each other to the extent that they share the same functional cortical space .

In other cases an interference of a secondary task takes place although the concurrent activities do not share any obvious common perceptual or motor mechanism. This has been explained by postulating that attentional mechanisms of the human operator have a limited capacity.Therefore, when the attentional demand exceeds its limited capacity, performance deteriorates even though there is no competition for any specific brain area. This second type of interference has been called "capacity interference". Reasons why there may be selective central interference of a concurrent task comes from an information processing perspective, whereby oscillations or pacemaker components interact with memory and attentional resources before passing timing information for use in movement. A theoretical account of these cognitive processes in central timing was provided by Gibbon, Church, and Meck (1984), based on the work of Creelman (1962) and Treisman (1963). Gibbon et al. assumed that timekeeping is based on pacemaker pulses gated into an accumulator with a count being compared against a target value maintained in a reference memory to determine when a response should be made (see Fig. 6).

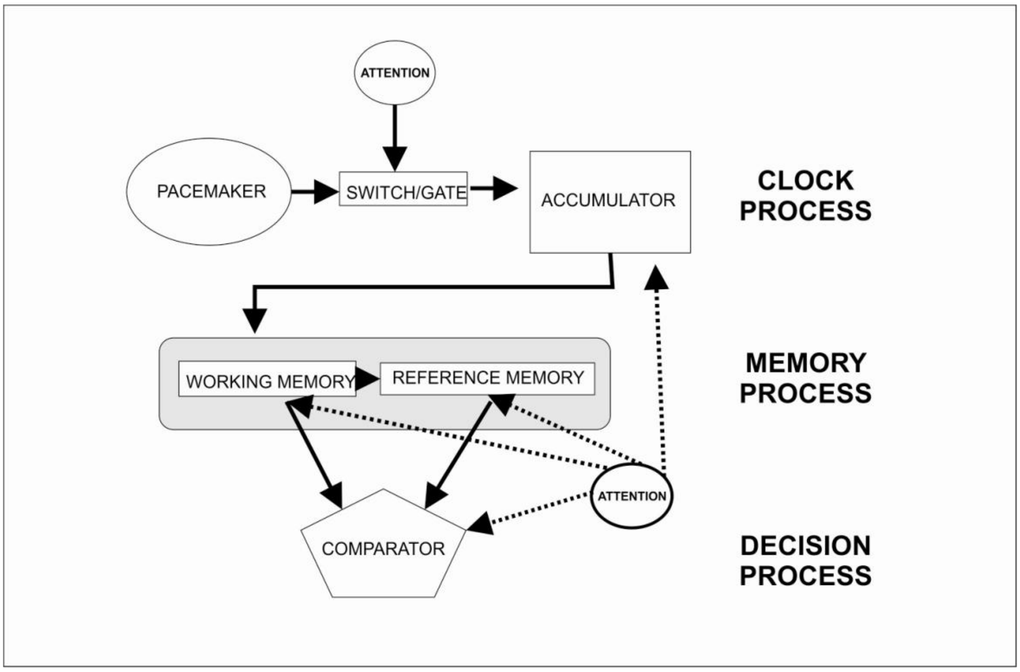


Fig 6 Information processing model of timing. Clock, memory and decision processes each require resources that could be compromised with a secondary task. Dotted lines represent potential costs of divided attention at specific stages in addition to the explicit role attention is given in models with gating or switches.

From this perspective impaired timing during simultaneous performance of another task might result from disturbances to decision processes, memory processes or disruption of the attentional gating process (Zakay & Bloch, 1996)

Dual tasks were initially developed to study divided attention. When performing a dual task, the requirements of each task have to be held concurrently in working memory with sufficient resources being allocated to each task performed. The limited capacity of the attention explains why the performance of concurrent tasks leads to increased cognitive demands. Since coordination of the tasks requires additional resources, the amount of resources allocated to the performance of each task decreases.

It has been shown, for instance, that the presence of a concurrent task during a timing task decreases the accuracy of time estimations when compared with a single-task (temporal) condition (Brown, 2006, 2008; Brown & Merchant, 2007; Field & Groeger, 2004; Zakay, 1998). According to Brown (2008), the interference caused by competing tasks on timing is “the most well-replicated finding in all the time perception literature”.

The attentional gate or switch (see fig 6) is the part of the clock process that is directly associated with the mechanisms of attention (Meck, 1984). When the switch is closed, the pulses that are emitted by the pacemaker are accumulated in the counter/accumulator. It is the amount of attention paid to time that determines the accumulation of pulses in the counter. When full attention is dedicated to time, the switch is closed and the accumulation is at its maximum. Some authors also refer to the existence of a gate that determines the flow of pulses when attending to time, the switch being associated with attending to a duration-onset signal (Block & Zakay, 2008). Therefore a concurrent task might change the flow of pulses to the accumulator, resulting in more variable counts in the accumulator, interfere with memory processes or decision processes as comparisons are made with reference intervals.

Both the nature of dual task interference and the independence of two sources of variance in the WK model makes applicable Sternberg’s additive factor method (Sterberg 1969) whereby experimental factors that influence distinct processes can have selective additive effects. Although originally formulated to explore independent stages of processesing with reaction time studies, the logic of Sterberg’s additive factor method is simply that if processes *a* and *b* can be influenced independently, then an appropriately targeted experimental factor A influences *a* but not *b*, whereas a appropriately targeted experimental factor B influences process *b* but not *a*.

While previous research has indicated factors that may target specific processes involving timing variability in either perception or action, little is known about how these factors may interact. By selecting different factors that both target central timing processes alongside a 3rd factor that targets peripheral motor implementation variability, we aim to expose more about the role of attention through these interactions (Fig 7). The role of attention as indicated by information processing models (Fig 3) is combined with the assumptions of the WK model in Fig 8.

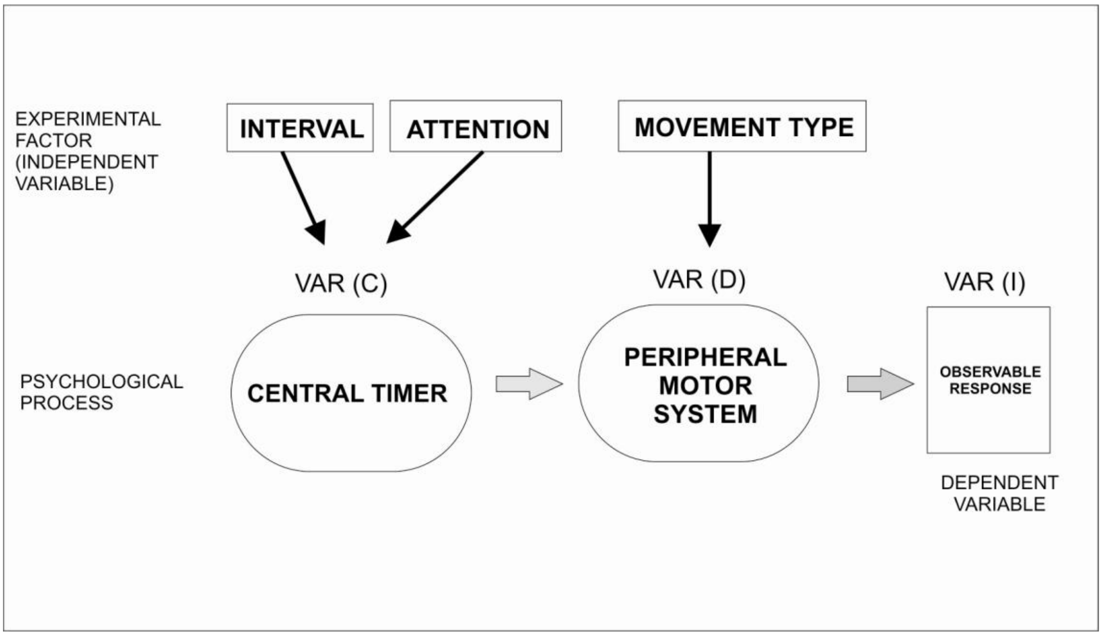


Fig 7. Experimental Factors. According to the WK model, a longer interval increases VAR (C) but not VAR (D) if the two sources of variability are independent. An unusual movement might increase VAR (D) but would not effect the VAR (C). If divided attention also interferes with central timing processes, variability should be additive, resulting in maximal VAR (I) in dual task conditions at longer intervals.

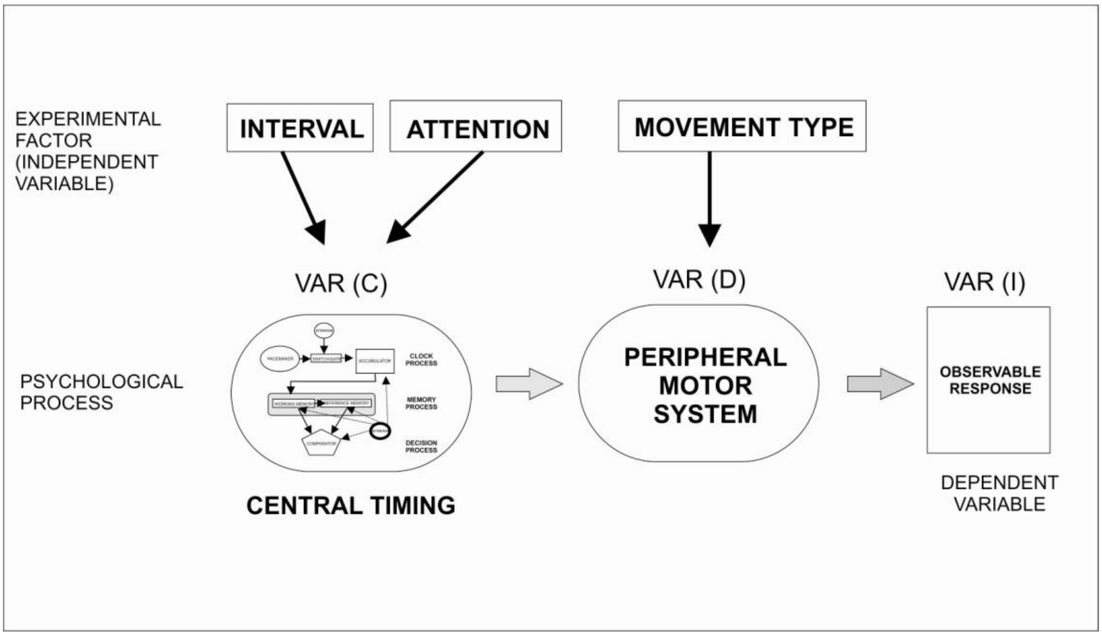


Fig 8. Combination of WK models independence of two factors affecting variability and Information Processing model of Timing.

In this study we explore the effects of divided attention through the interactions between 3 different factors known to individually effect timing variability using the additive factor approach pioneered by Sternberg. We used 2 different movement types (index finger vs little finger) and 2 different intervals (400 vs 650ms) with and without a secondary task. We expected greater variability when participants tapped with the little finger compared to the index finger due to additional motor control variance. Whereas, we expected greater variability of tapping responses at the longer interval duration due to variability in central clock processes. Importantly, according to the (WK) model, we would expect no interactions of movement type with either interval duration or divided attention. In contrast we expect a strong interaction between divided attention and interval duration both due to variability of central clock processes (as indicated in fig 4). This paradigm also offers a strong test of the logic of additive factors and the independent sources of variability assumed in the WK model.

2.3 **METHOD**

An opportunity sample of 41 undergraduate participants (mean age 20) were tested. They were right handed, had normal or corrected vision and gave informed consent before taking part in the experiment. Each participant completed a background questionnaire and then completed 8 blocks of experimental conditions comprising 1 practice trial then 3 experimental trials in each condition.

2.3.1Apparatus

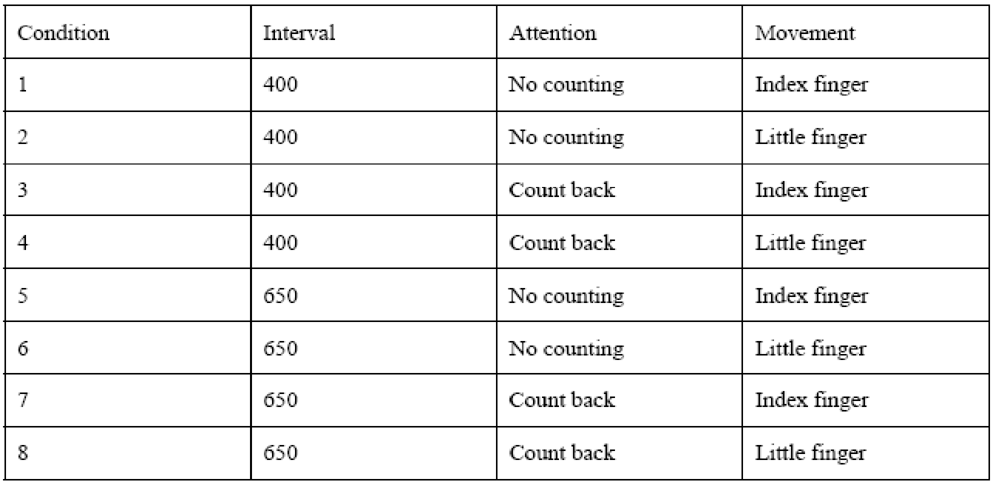
Subjects were seated comfortably on a chair facing a 19inch computer monitor with their hand on the mouse which was used as the response manipulandum. The stimulus presentation and collection of the behavioral responses were controlled by a customised program (LV-APP) written in labview (version 6.5). The LV-APP displayed a visual metronome at a fixed pace, and recorded the interresponse intervals of the participants synchronized mouse clicks to an accuracy of +/-1 ms. See Appendix for calibration issues.

2.32 Experimental Task

Subjects were trained to produce tapping movements by clicking the mouse button to synchronise with a sensory stimulus and then to continue tapping with the same interval without sensory stimulus. At the beginning of the trial, the stimuli were presented with a preset interstimulus interval (ISI) appropriate for that block (either 400ms or 650ms). Subjects were required to tap the mouse button each time a stimulus was presented, which resulted in a stimulus–movement synchronisation. After 10 consecutive synchronized movements the pacing stimulus was eliminated, and the subjects continued tapping at the same interval for 30 additional intervals per trial. During the practice trial feedback was displayed graphically on the screen, indicating the participantsmean intertap interval, to ensure subjects were adjusting to the appropriate ISI for that block of trials. No feedback was displayed during experimental trials and 3 experimental trials would follow with an intertrial interval of 3s.

Participants would complete the task using either their index finger or their little finger to click the mouse button, either as a single task condition or alongside a secondary task according to the counterbalanced block design. The secondary task required participants to silently count backwards in 3's from a random whole number (greater than 30 and less than 100) provided by the experimenter. At the end of the trial the participant would reveal the number they had reached.

The pacing stimuli were in the form of an orange circle (4-cm side) presented in the center of a computer screen for 33 ms and was fully detectable. Means and standard deviations of the interesponse intervals were recorded for analysis along with the results of the secondary task and the written questionnaire. Data values above or below 3 SD from the mean were removed, corresponding to either accidental doubleclicks, or missed clicks of the mouse (This excluded only 3 values from experimental trials). The reported *P* values in the repeated-measures ANOVAs correspond to the Greenhouse–Geisser test, which corrects for possible deviations in sphericity. The level of statistical significance to reject the null hypothesis was 0.05. SPSS statistical package(version 12 2003, SPSS, Chicago, IL) were used for the statistical analyses.



Condition	Interval	Attention	Movement
1	400	No counting	Index finger
2	400	No counting	Little finger
3	400	Count back	Index finger
4	400	Count back	Little finger
5	650	No counting	Index finger
6	650	No counting	Little finger
7	650	Count back	Index finger
8	650	Count back	Little finger

Fig 9. Indicates the block design of all conditions completed by participants.

2.4 **RESULTS**

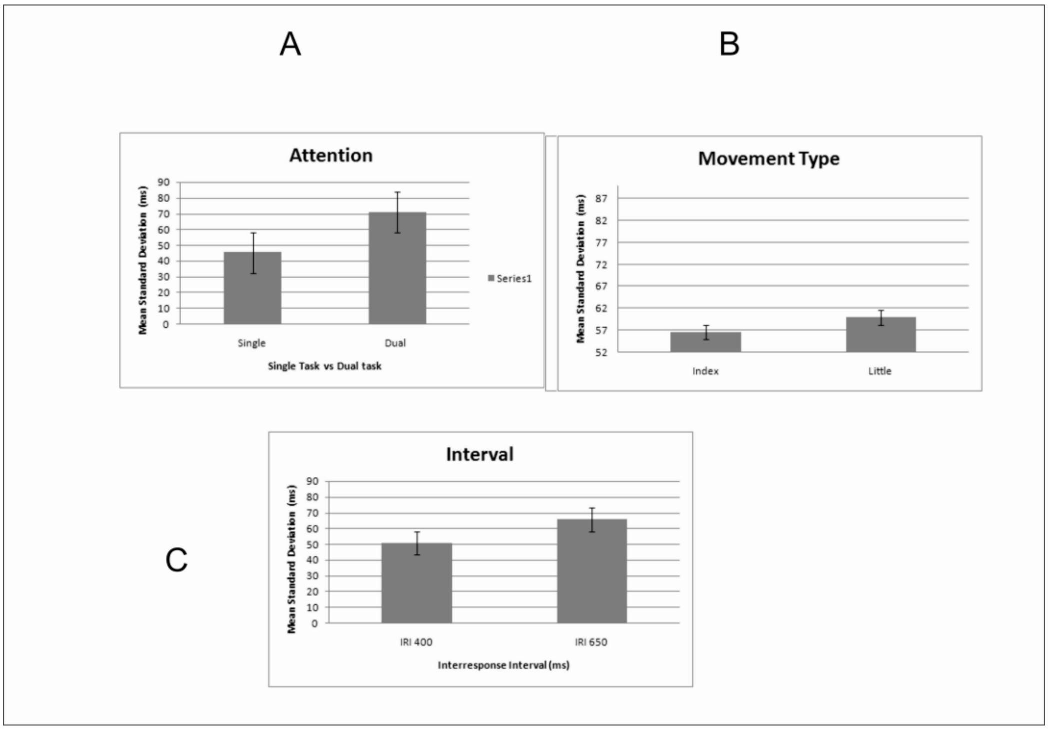


Fig 10. Average Standard deviation plotted against all trials conducted with conducted with single task or counting task (plot A); all trials conducted with movement type 1 or 2 (index or little finger, plot B); all trials conducted with IRI of 400 or 650 ms (plot c). Error bars indicate +/- 1 Standard error

MAIN EFFECTS

DUAL TASK:

The results of the ANOVA (fig 10A) reveal significant effects of dual task [*F*(1, 40) = 28.48, $p < .001$] confirming that divided attention (couting backwards in 3’s) significantly interfered with the ability to maintain the lower tapping variability of single task conditions.

MOVEMENT:

While variability was greater in each condition when using the little finger compared to the index finger (fig 10B), the increase was slight and did not reach a level of significance [*F*(1, 40) = 3.21, *p* 0.081]

INTERVAL:

The results of the ANOVA show the longer interval of 650ms (fig 10C)contributed significantly more variability than the shorter interval of 400 ms [*F*(1, 40) = 51.44, $p < .001$]

INTERACTIONS:

The resultant interactions were central to the logic of this experimental paradigm, that is, confirmation of each hypothesis regarding the expected outcomes relied not only on some results being significant, but importantly that others were not. The results of the ANOVA revealed a significant interaction between Dual Task * Interval [*F*(1, 40) = 6.10, $p < .05$] and importantly, no significant interaction between Dual Task *movement [F(1,40)=5.74, p .87] and no interaction between Interval * movement [F(1,40)=0.96, p .75]. Lastly the ANOVA found no 3 way interaction between Dual Task*Interval*Movement [F(1,40)=1.04, p .31]. The lack of interaction between movement and interval is visible in the almost parallel slope of the plotted standard deviation (fig 13). By comparison, the significant interaction between Dual task and Interval shows the steeper slope at the longest interval (650ms) as predicted.

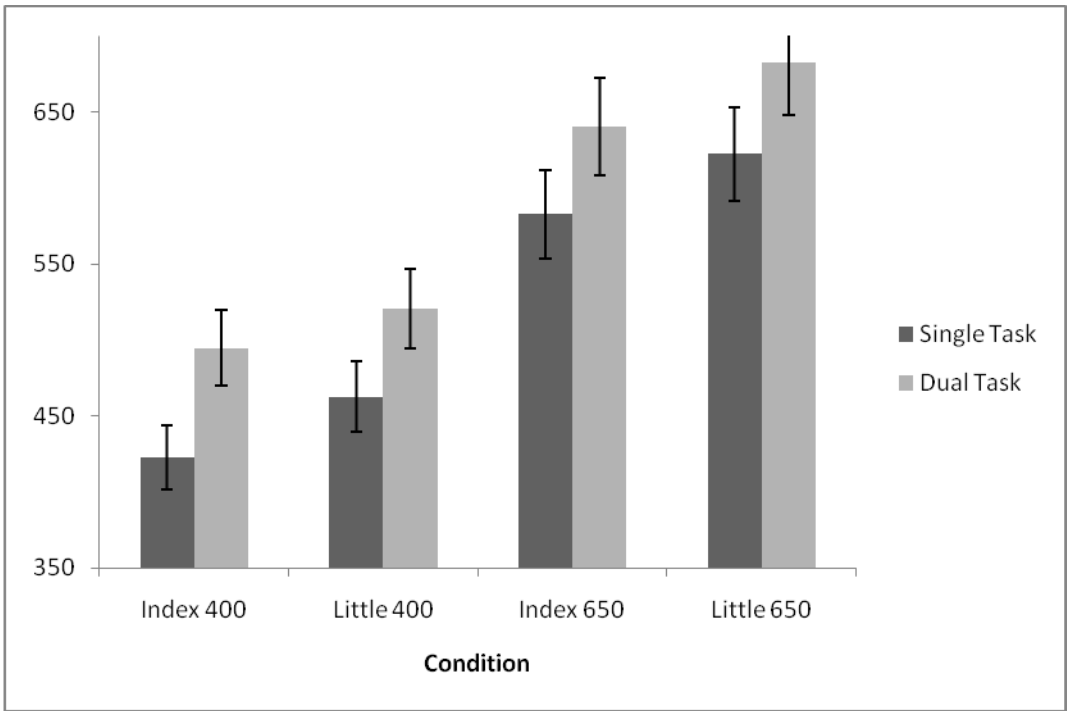


Fig 11. A comparison of single task and dual task effects on the mean Interresponse intervals (ms) for tasks completed in each condition and with each movement type. Error bars represent standard error.

INTERESPONSE INTERVALS:

Fig 11 allows a comparison of the cost of divided attention on the mean interresponse intervals. Although the primary interest of this study was variability, it is worthy to note that the dual task cost lengthened the mean interesponse interval in every condition. The single task mean IRI is longer than might be expected at 400 ms and shorter than might be expected at 650ms. This is consistent with findings in time perception and retrospective time estimation studies that short intervals are lengthened and long intervals shortened, but less common in rhythmic timing research. The effect of using a more unusual movement was also to lengthen the mean IRI. When looking at the results of condition on variability (fig 12) the effect of the unusual movement (little finger) had a more moderate outcome indicating a comparable stability with slightly more variance than usual movement (index finger) at the cost of accuracy (slightly longer IRI).

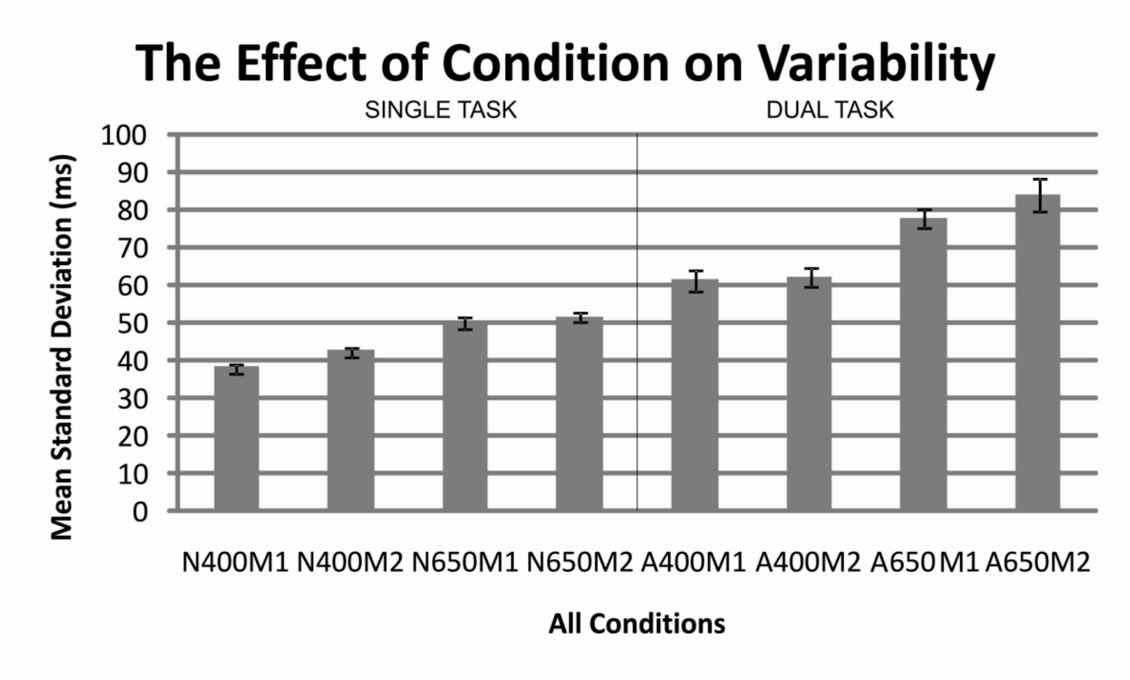


Fig 12 Plots the effect of condition on the mean standard deviation for both single tasks and dual tasks.

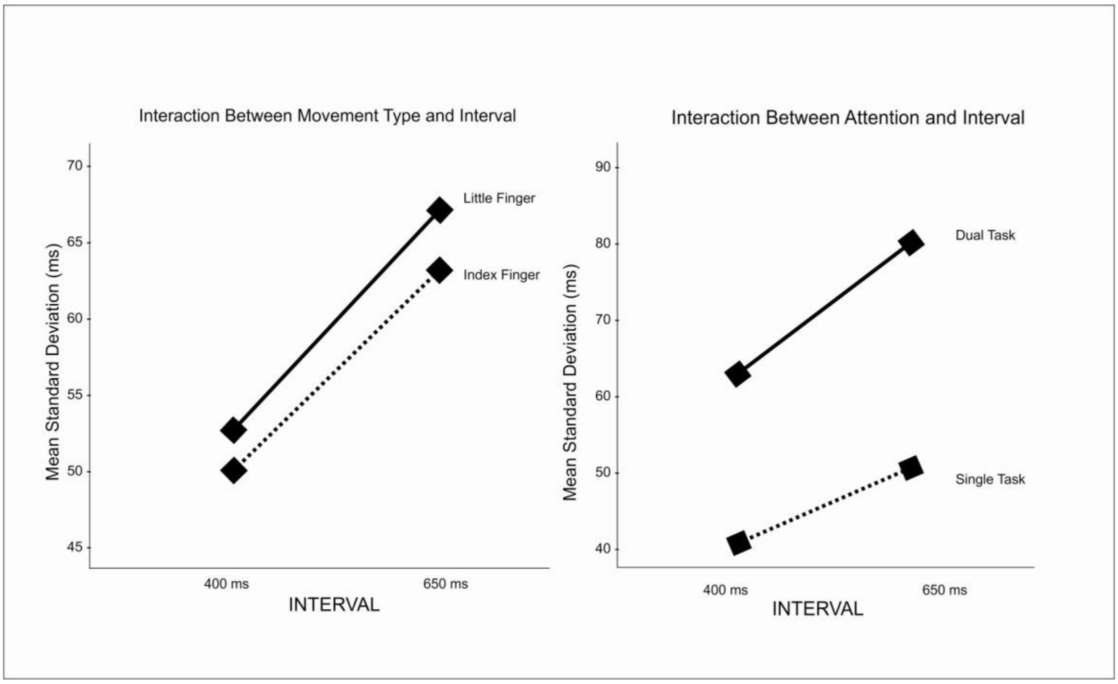


Fig 13. 2 way Interactions illustrated with slope of the average standard deviation of movement type (little finger or index finger) against interval (400 x 650ms) left, and right the average standard deviation of trials conducted with different attentional demand (single task or dual task) against interval (400 x 650 ms).

SKILL:

Using the answers from the background questionnaire participants were coded by the level of prior music training and regularity of performance (more than once a week practice for more than a year). This divided the group almost into equal halves, with 19 coded as musicians, and 21 as non-musicians. The mean standard deviation of the interresponse intervals were grouped according to the level of musical experience in figure 14. Although musical expertise has been shown to lower movement variability however it is clear that any advantage conferred by musical experience only showed in this study in relation to the dual task conditions where the musical group scored significantly less variability (M=53.93, SD=10.42) than non-musicians (M=63.13, SD=20.36) conditions; t (4)=2.44, p = 0.02 but were indistinguishable in single task conditions.

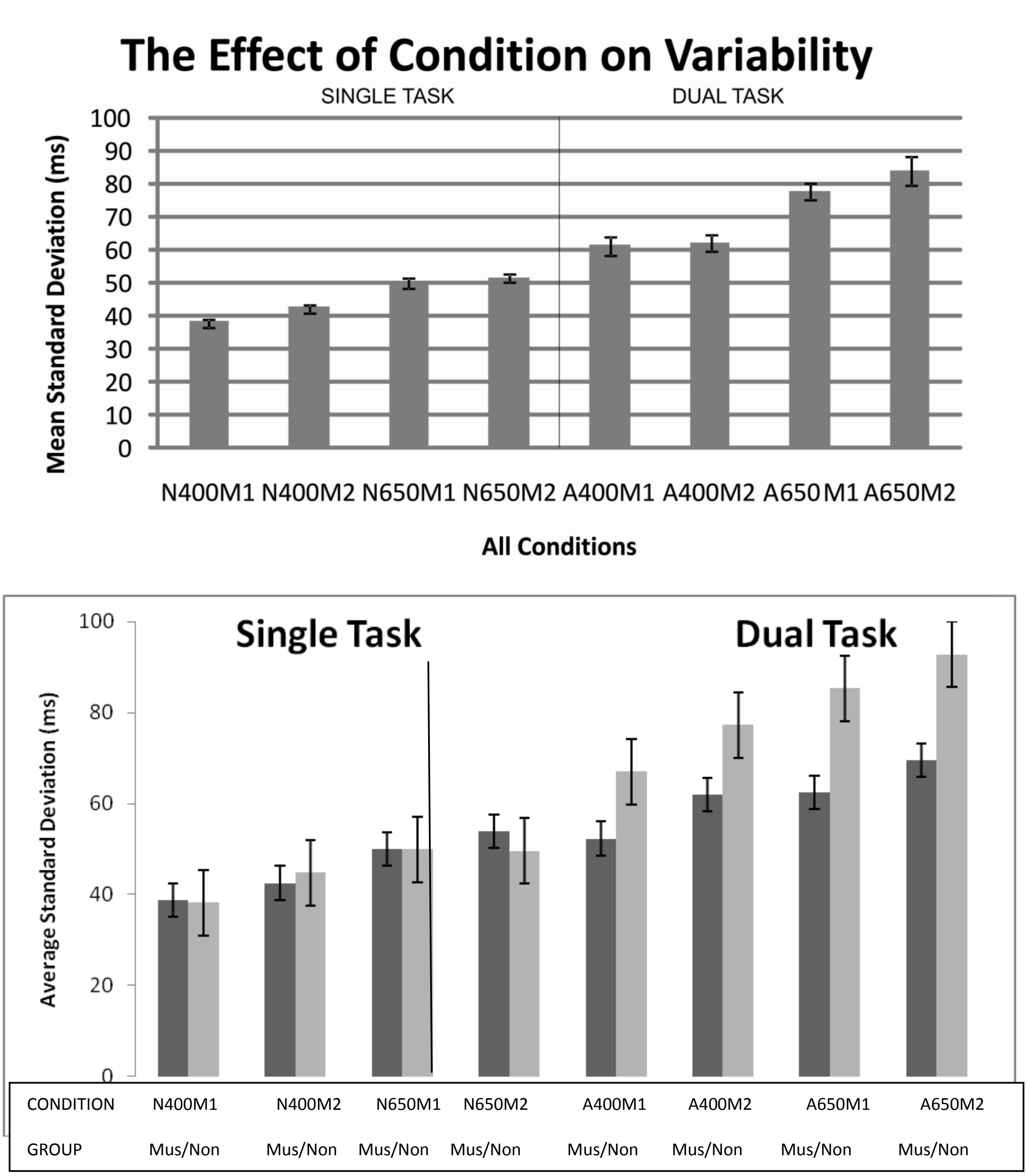


Fig 14 Mean Standard Deviation of musicians and non-musicians plotted for each of the 8 conditions

2.5 **DISCUSSION**

The results from this study support the main assumptions behind the hypothesis and experimental design. Due to the independence of central timing processes and peripheral motor implementation processes assumed in the WK model, support was gleaned from both a significant interaction between factors acting on central timing processes (interval length and attention demanding task) and a lack of significant interaction on the factor targeted to influence peripheral motor processes (use of index finger or little finger). Therefore the results found offer strong support for the the logic of additive factors as introduced by Sternberg, and the independent sources of variability assumed in the WK two-level timing model. In addition, the combination of factors allow us to see the relative contribution that each factor plays in the variability of rhythmic tapping. For example in this study, as indicated in Fig 10, the interference of an attention demanding task such as counting backwards in 3's increased variability more than either the longer interval or the unusual movement type, as the dual task cost clearly resulted in greater variability in every condition.

However a number of factors may have additionally contributed to the main effects that raise further questions. For example, the strong increase in interference of the secondary task, could be due to the use of visual pacing stimulus rather than auditory pacing signal requiring more attention and memory resources to maintain the interval in mind than if an auditory stimulus had been used. This question arises due to the powerful effect of auditory distractors that lead Repp to suggest this reflects "a basic attraction of rhythmic movement to auditory rhythms"(Repp 2006). Furthermore when Repp put auditory and visual pacing target stimulus in direct comparison with cross modal distracters participants taps were found to track the timing pattern of auditory distractor sequences when slightly in phase with targeted visual sequences but not the reverse (Repp 2004). Although prior research has shown visual pacing was generally more variable than than tapping with an auditory stimuli (Jäncke, Loose et al. 2000), the relative increase in variability that a secondary task induces raises some questions about the structural and capacity explanations of this interference. The Jancke et al 2000 study used imaging while comparing continuation tapping with both visual and auditory pacing stimulus. This study trevealed that paced finger tapping in the context of auditory pacing stimuli relies more on brain structures subserving internal motor control while paced finger-tapping in the context of visual pacing stimuli relies on brain structures relying on the subserving processing or imagination of visual pacing stimuli(Jäncke, Loose et al. 2000). Thus a structural explanation of the interference found in this study would suggest any use of imagery in the secondary task (visualizing the running total) might interfere more with the timing of longer intervals that also rely on similar brain structures (contributing to this significant main effect of interaction) while avoiding interaction with the movement type.

An alternative explanation of the significant interaction comes from the possibility that individuals covertly verbalised (rather than visualised) the running total in the secondary task. Speaking has been found to reduce the rate of tapping and to increase its variability (particularly in younger children) and that this has been shown to effect the right hand more than the left (Hiscock, Kinsbourne et al. 1985). This asymmetric effect of handedness has also been given a structural explanation of interference, attributed to the fact that speaking and right-hand movements are both controlled by the left cerebral hemisphere of right-handers. (Kinsboume & Hicks, 1978).

This structural interference has been used to explain why concurrent reading of paragraphs reduced unimanual tapping rates more for the right hand than the left even when reading silently (Hellige and Longstreth 1981). Participants in this study were all right handed and both movement types were conducted with the right hand, the additional variability of this structural interference would be equal with both movement types. While structural interference may have played a part in the overall variability, the pattern of the interactions cannot be explained by structural limitations alone. For example, although dual task mean IRI was shown to be longer than mean IRI with single task tapping, the mean single task tapping was already longer than the target interval for short intervals, and shorter than the target interval for longer intervals, a finding which is more compatible with perceptual distortions (Nakajima 2004; Grondin 2005). It is also possible that the strategy used to avoid a capacity limitation induced by the dual task resulted in slowing the timing of movements to adjust to the rate or speed of mental calculation. This possibility cannot be ruled out as the rate of calculation was left to the participants to control. Thus although the mode of the stimulus and the possibility for structural sources of interference might have contributed additional sources of variability, and strategy could be used to compensate for capacity limitations during dual tasks, the pattern of interaction, between dual task and interval (but not between dual task and movement type, and not between interval and movement type) are still best explained by the independence of the two-level WK model.

Just as there may be individual difference in the style and strategy used for mental arithmetic, there may also be background differences in the experience and skill of timed movements through musical practice. Although musical expertise has been shown to lower movement variability which might confer an advantage at shorter intervals, or when using more unusual movements (Franek 1991) (for example piano players may have more experience initiating timed movements with their little finger). It is clear that any advantage conferred by musical experience only showed in this study in relation to the dual task conditions where the musical group scored significantly less variability than non-musicians conditions but were indistinguishable in single task conditions. This advantage could be from experience in changing focal attention between a number of different temporal patterns as suggested by the dynamic attending theory (Jones 1976, 1987, 1990; Jones and Boltz 1989). This theory suggests that experience of music containing periodicity at more than one level, such as tracking both melodic and harmonic changes, is explained by the listener making use of multiple oscillators rather than a single oscillator or pacemaker, and so gives experience in directing attention between multiple temporal patterns. It is also possible that musical experience might give more of an advantage of protecting movement timings from irrelevant or distracting interference, a role attributed to the central executive(Krampe, Mayr et al. 2005; Brown 2006).

However even though the participants with greater musical experience exhibited less variability during the dual task trials than non-musicians, they still showed greater variability than when conducting single task trials, and greater variability at the longer interval as predicted by the additive factors. Thus although musical experience can moderate the nature of these interactions, it cannot eliminate the same trends found by less musically experienced participants.

2.6 **SUMMARY**

The effect of divided attention was explored through a pattern of interactions between 2 other factors, interval and movement type, each targeting variability of an independent process in the WK model. Using the logic of additive factors, that factors operating on the same processes will interact and add to the exhibited variability, an attention demanding task was found to interact with the interval but not movement inline with the predictions and assumptions of the WK model. The results implicate capacity limitations of attention, but do not rule out contributions of stimulus mode and structural limitations in the pattern of variability which are addressed directly in the following Chapter.

CHAPTER 3:

ADDITIVE FACTORS II – Modal Effects

3.1 INTRODUCTION

The results of the previous experiment implicate capacity limitations of attention as a major source of variability in continuation tapping, but do not rule out contributions of individual differences in strategy and skill or more subtle interference with stimulus and response modalities. Some improvements to the paradigm to further explore these modal interactions involve controlling the rate at which participants proceed with calculations, and comparing mixed modes to assess any greater tendency for secondary task entrainment. In addition, a 700 ms interval was used as this was the interval resulting in least over or underestimations in the literature.(Fraisse 1957; Glover SR 2001).

3.2 METHODS:

An opportunity sample of 11 undergraduate participants (mean age 19) were tested. They were right handed, had normal or corrected vision and gave informed consent before taking part in the experiment. Each participant completed a background questionnaire and then completed 8 blocks of experimental conditions comprising 1 practice trial then 3 experimental trials in each condition. Prior to the experimental conditions, participants first attempted an example of the secondary task by itself (without tapping). Only if they scored 80% pass (2 missed identifications out of possible 10) could they initiate the experimental blocks otherwise they had to repeat the secondary task until they reached the 80% inclusion criterion. No participants were eliminated at this stage.

3.21 Apparatus

Subjects were seated comfortably on a chair facing a 19inch computer monitor with their hand on the mouse which was used as the response manipulandum. Participants were asked to wear headphones throughout the experiment even though sounds would only be heard on some of the trials according to the block design. The stimulus presentation, secondary task display, and collection of the behavioral responses were controlled by a customised program (LV-APP) written in labview (version 6.5). The LV-APP displayed a visual metronome at a fixed pace, and recorded the interresponse intervals of the participants synchronized mouse clicks to an accuracy of +/-1 ms. See Appendix for calibration issues.

3.22 Experimental Task

Subjects were trained to produce tapping movements by clicking the mouse button to synchronize with a pacing stimulus and then to continue tapping with the same interval without pacing stimulus. At the beginning of the trial, the pacing stimuli were presented with a preset interstimulus interval (ISI) appropriate for that block (either 400ms or 700ms). Subjects were required to tap the mouse button each time a stimulus was presented, which resulted in a stimulus–movement synchronisation. After 10 consecutive synchronized movements the pacing stimulus was eliminated, and the subjects continued tapping at the same interval for 30 additional intervals per trial. During the practice trial feedback was displayed graphically on the screen, indicating the participant’s mean intertap interval, to ensure adjustments were being made to the appropriate ISI for that block of trials. No feedback was displayed during experimental trials and 3 experimental trials would follow with an intertrial interval of 3s.

3.33 Secondary Task:

A major difference from the previous experiment was the automated initiation of the stimulus for the secondary task from within the application. The LV-App would launch an executable macromedia flash file which would initially display a white background beside the lvapp display at the start of the trial. After 5 seconds of continuation tapping (where the pacing signal has been switched off) one of two different stimulus conditions would be displayed through the flash file window. In the visual condition, a series of randomised low numbers (1-9) would appear at 1450ms intervals (each onscreen for 66ms) until the end of the trial. In the auditory condition a cross hairs would appear with the same onset times as the visual stimulus but with embedded wav files of each equivalent number being "spoken" that played through participants headphones every 1450ms. Each digitised voiced number was also normalised to 66ms and was clearly comprehensible to all participants. In both conditions (auditory and visual presentation of the numbers) the task of the participants was the same. Participants were asked to track the total number of switches from odd to even or even to odd numbers. Thus in the sequence:

2 4 1 7 9 3 5 8 6

there would only be a total of 2 changes from odd to even or even to odd numbers see Fig 15.

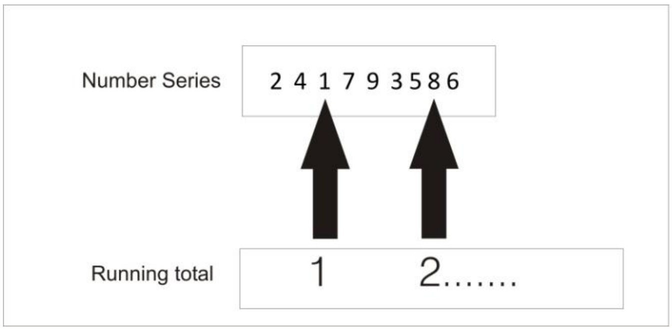
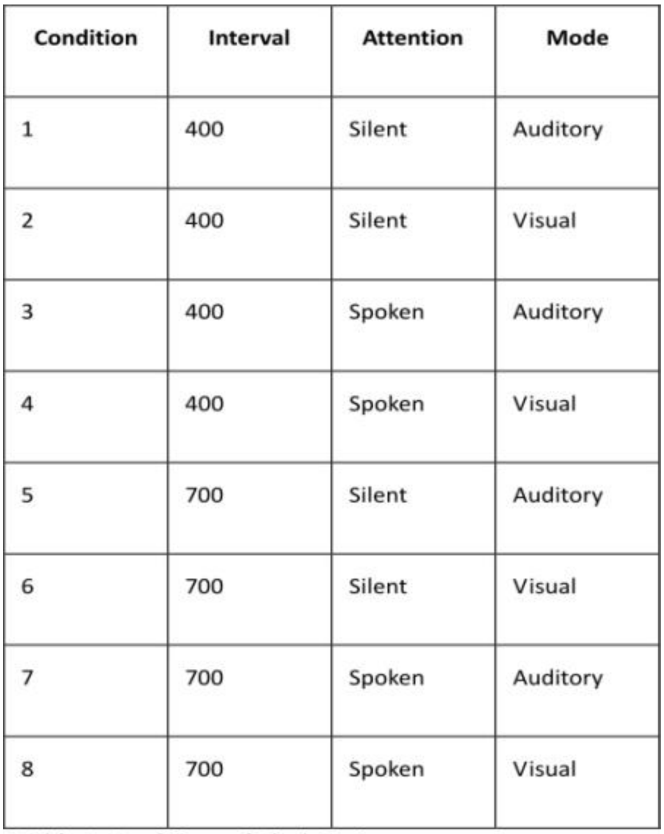


Fig 15. Secondary task. Number series appears sequentially (in either visual or auditory mode) Participants pay attention to any instance the number sequence changes from odd to even number or the reverse (arrows). Participants update the running total either silently or out loud.

Each trial had the same mean number of changes (6) to attend to and would vary by no more than + or – 2 changes per stimulus set. According to the block design participants were instructed to either a) silently add the number of changes and keep a running total and then verbally give the total to the experimenter at the end of the trial, or b) say outloud the running total as each change was noticed.

The pacing stimuli were in the form of an orange circle (4-cm side) presented in the center of a computer screen for 33 ms and was fully detectable. Means and standard deviations of the interesponse intervals were recorded for analysis along with the results of the secondary task and the written questionnaire. Data values above or below 3 SD from the mean were removed, corresponding to either accidental doubleclicks, or missed clicks of the mouse (This excluded only 8 values from experimental trials). The reported *P* values in the repeated-measures ANOVAs correspond to the Greenhouse–Geisser test, which corrects for possible deviations in sphericity. The level of statistical significance to reject the null hypothesis was 0.05. SPSS statistical package(version 12 2003, SPSS, Chicago, IL) were used for the statistical analyses. Total Errors in the secondary task were averaged and itemised according to errors of omission (missing a change that was present) or errors of addition (counting a change when there was none).

A three-factor experiment was run in a randomised block design with participants tapping at each of two intervals (400 x 700ms) with a concurrent attention-demanding task (counting the number of switches from odd to even numbers either silently or outloud) using two different modes of presentation (visual or auditory). This resulted in the following 8 conditions.



Condition	Interval	Attention	Mode
1	400	Silent	Auditory
2	400	Silent	Visual
3	400	Spoken	Auditory
4	400	Spoken	Visual
5	700	Silent	Auditory
6	700	Silent	Visual
7	700	Spoken	Auditory
8	700	Spoken	Visual

Table 1: Conditions of Block Design

3.3 **RESULTS**

The results of the ANOVA reveal significant main effects for Tempo [$F(1, 10) = 16.61$, $p < .01$] confirming that the longer interval of 700ms added significantly more variability than the shorter interval of 400ms.

STIMULUS MODE:

While the average variability was greater in each condition when the stimulus mode was auditory rather than visual, the increase was of no statistical significance [$F(1, 10) = 2.170$ p *.175*] The added variability of the auditory stimulus conditions is visible in Fig (17) .

RESPONSE MODE:

The results of the ANOVA show marginally significant effect when the response mode was speaking outloud compared to silent calculation the secondary task [$F(1, 10) = 3.645$, p .089]

INTERACTIONS:

The resultant interactions were central to the logic of this experimental paradigm, that is, it is through how these factors interact that we may better understand their shared resources or independent sources of variability. The results of the ANOVA revealed a significant interaction between the Response mode * Interval [$F(1,10) = 5.290$, $p < .05$] indicating that at slow speeds, speaking outloud significantly increased the variability beyond the increase of tempo or speaking alone. No interaction was found between Stimulus mode * Interval nor for the 3 way interaction between Stimulus mode * Response mode * Interval. The lack of interaction between stimulus mode and interval is visible in the almost parallel slope of the plotted standard deviation (fig 16). By comparison, the significant interaction between response mode and Interval shows the steeper slope at the longest interval (700ms) as predicted.

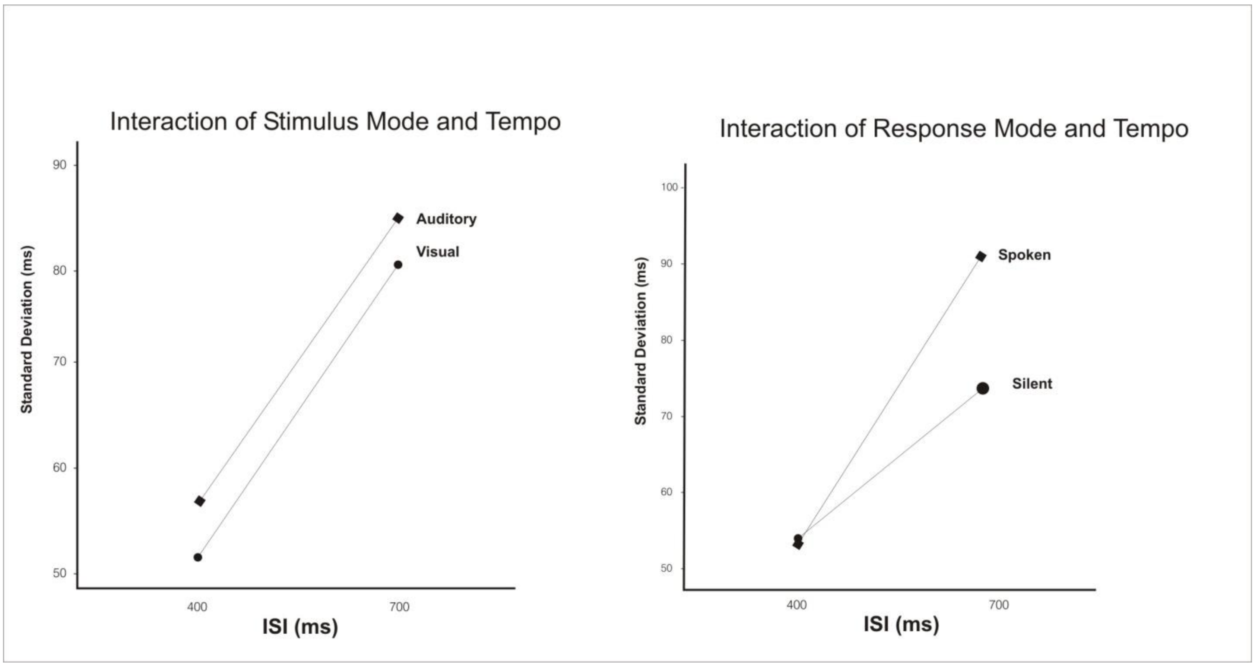


Fig 16. Interactions. Left shows small additive variability (SD) for auditory stimulus presentation at each ISI but no interaction. Right shows significant interaction with greater variability (SD) of speaking outloud at a longer ISI.

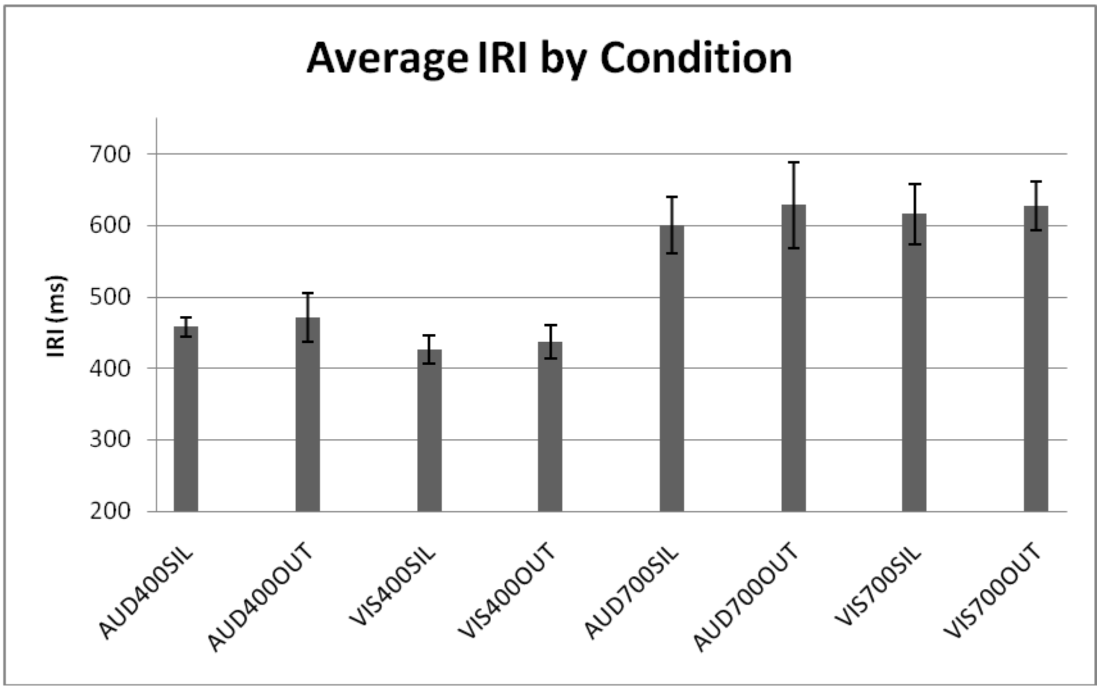


Fig 17. Shows the average IRI for each of the 8 conditions. Error bars represent standard deviation.

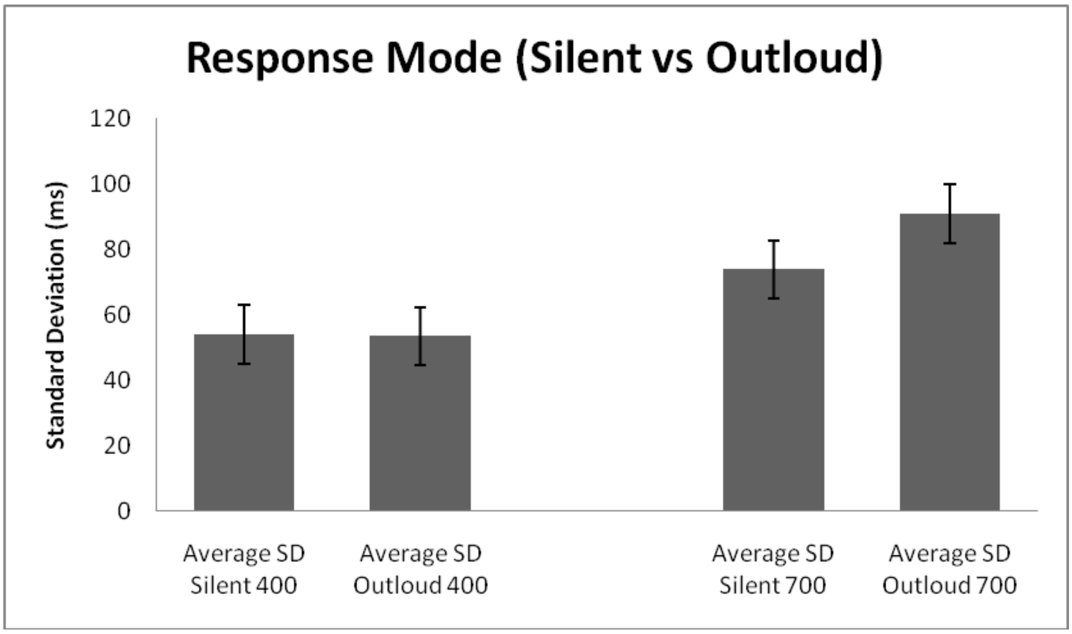
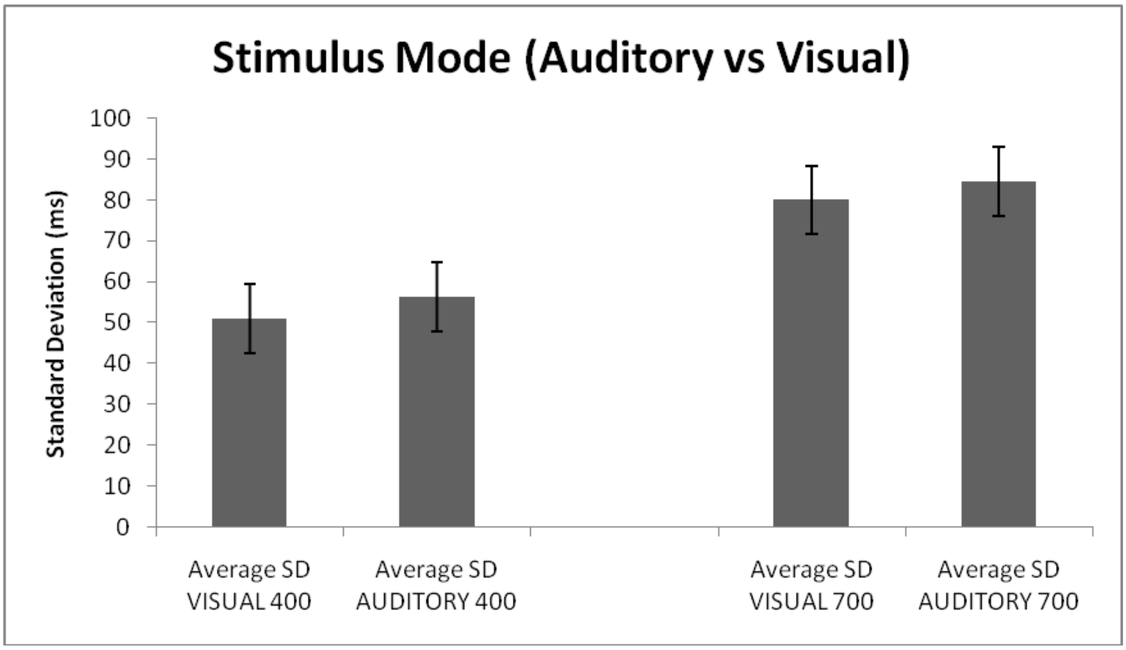


Fig 18A (Above). Variability (average standard deviation ms) of responding as a function of silently or out loud versions of the secondary task (collapsed across stimulus mode) Fig 18B (Below) Compares the variability (Average Standard deviation ms) of tapping to either an auditory or visual stimulus in the secondary task (collapsed across response mode)



.

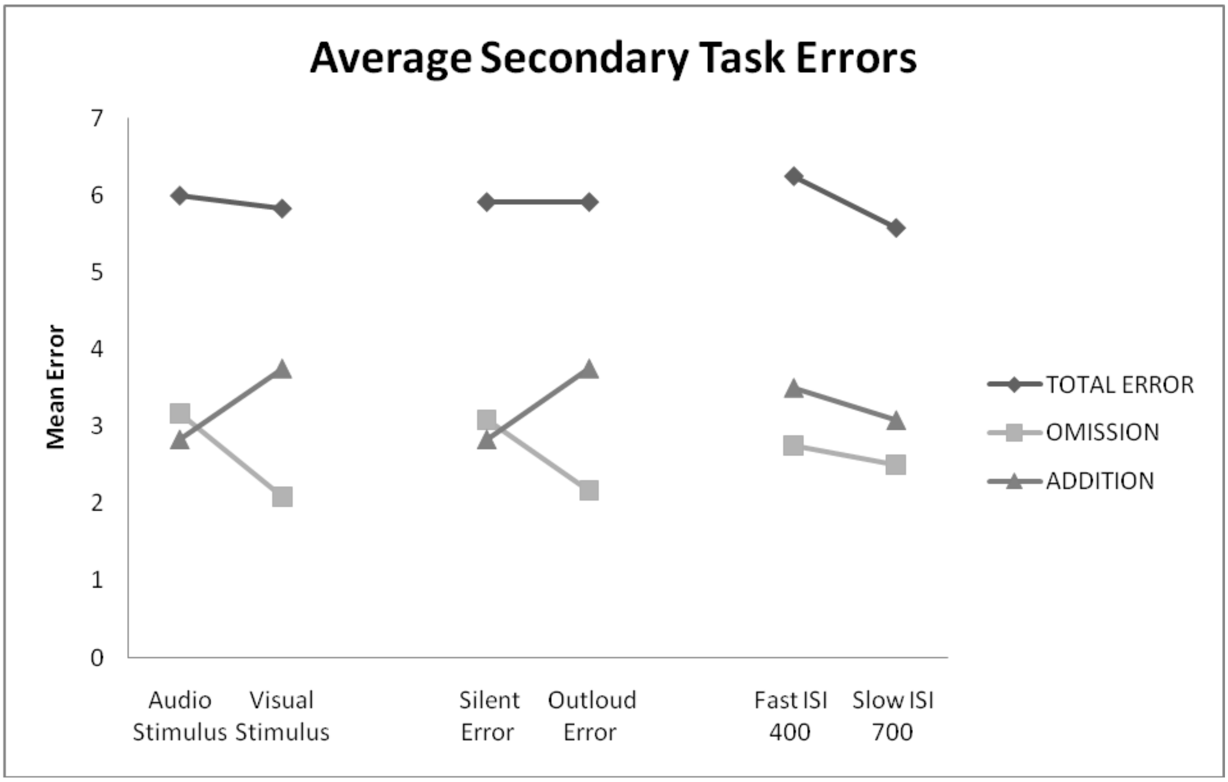


Fig 19. Illustrates the average pattern of secondary task errors. The total error (top) is broken down into an error of omission (where a change was missed) or addition (where a non-existent change was perceived or counted). These errors are presented for comparison of Audi vs visual Stimulus (left), Silent or Outloud Responses (middle), and Fast or slow ISI (right)

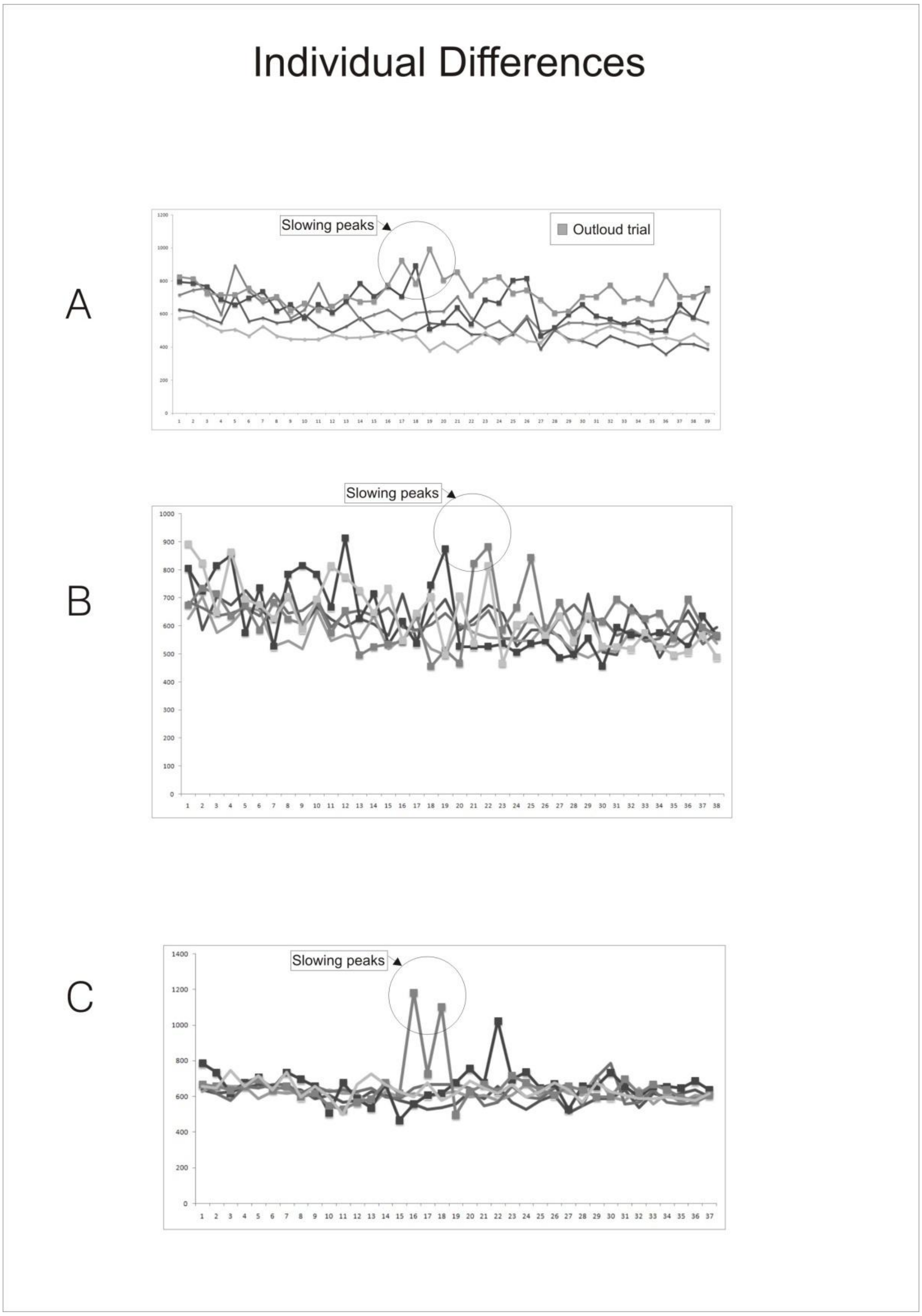


Fig 20. Examples of trials from the 3 individuals. All trials are taken from the slower ISI 700. A) Illustrates a participant with wider intertrial variability and a general trend toward speeding as the for both speaking and silent trials. Despite this trend the slowing peaks common in speaking trials are highlighted. B) Illustrates a participant with less intertrial variability yet also illustrating a tendency to speed up as the trial progresses and slowing peaks for speaking trials. C) Illustrates a participant with low intertrial variability and less trend of speeding up, yet slowing peaks are clearly visible for speaking trials.

3.4 **DISCUSSION**:

As expected from the previous experiment (CChapter 2) and from extant research (Repp 2003b; Flach 2005; Repp 2005; Repp and Doggett 2007) the results of the ANOVA confirm that the longer interval of 700ms adds significantly more variability than the shorter interval of 400ms. This can be explained by the added variability accumulated by the clock processes of information processing models discussed in the previous Chapter. That no main effect was found for the stimulus mode (auditory or visual) of the secondary task is more interesting. We expected that the distraction of a regular auditory sound in the secondary task might interfere with the continuation timing of responses much more than a visual distraction (Kato and Konishi 2006; Repp 2006). We also considered that the English language of the auditory stimulus might interfere with the subvocal language mediating participants self-direction(Baddeley 2003), and also interfered with the language based running totals that would also require resources from the articulatory loop of Baddeley's model of working memory. Lastly we considered that as language is predominately left sided, that more language and auditory processing might increase structural interference with right hand movements (Hiscock, Kinsbourne et al. 1985; Keefe 1985; Hiscock, Kinsbourne et al. 1987). The fact that no such differences were found supports the idea that both the visual and auditory stimulus were treated in much the same way, either by conversion via accumulators to an amodal count, or via the phonological loop whereby visual images of numbers can be transferred to equivalent verbal representation rendering little difference to the mode of the stimulus(Baddeley 1986; Alan 2000). Another possibility is that timing is reliant on the currently employed neural networks (Jantzen 2007) and as the visual pacing signal employed visuo-motor networks rather than auditory ones, they may be of lower temporal resolution contributing to more equal variability despite the secondary stimulus mode. Another alternative explanation is that participants used a different executive strategy to give higher priority of shared attentional resources to maintain tapping at a cost to the attention given to the secondary task(Brown 1990; Brown 2002; Brown 2006). Some support for this possibility comes from the pattern of errors in the secondary task (Fig 19) which were higher overall for auditory vs visual stimulus trials and more errors of omission occurred in trials with an auditory stimulus. This bidirectional interference might therefore have lessened the cost on timing variability.

The marginal main effect of response mode is also quite surprising. Given the strong support in the literature for the interference effects of speaking on movement timing (Thornton and Peters 1982; Hiscock, Kinsbourne et al. 1985; Keefe 1985; Hiscock, Kinsbourne et al. 1987). However the nature of this interference was much clearer when looking at the pattern of interactions.

INTERACTIONS:

The resultant interactions were central to the logic of this experimental paradigm, that is, it is through how these factors interact that we may better understand their shared resources or independent sources of variability. The significant interaction between the Response mode * Interval indicating that at slow speeds, speaking outloud significantly increased the variability suggests that speaking outloud shares some resource (structural or capacity) with timing processes. If the increase in variance was due for example to the fact that speaking is itself a motor act, we would expect additive interference at both 400ms interval and 700ms. The greater inference exhibited at 700ms suggests there is an increase in complexity not reducible to either tempo, additional motor planning or difficulty in calculation by themselves. One explanation of the additional difficulty comes from considering the extra demands of sustained coordination of the tasks. For example, (Engle 1999; Engle 2004; Oberauer, Lange et al. 2004) proposed that working memory capacity is the ability to temporarily maintain representations activated in the face of distraction. Their view can be summarized by the equation ‘‘complex span=simple span + controlled attention. This characterization of a difficulty of attentional control over a longer span would explain why attentional resources might be stretched by both a longer interval and an additional goal to keep the running total + keeping the running goal to remember to say it outloud each time it increases. A traditional information processing model supports this view (Fortin 2000) suggesting that shifting from one task to another or simply to interrupting time estimation could lead to loss of temporal information in the accumulation process. A consequence of this timesharing with other information-processing loads is that time is lost! More specifically the time-sharing assumption (Buhusi 2009) is that when subjects attend to a second task, estimated durations are shorter, due to resources being taken away from timing. Support for this can be seen in the shorter IRI for all intended 700ms intervals (fig 17). Buhusi (2009) conclude on the basis of their own evidence that the brain circuits engaged by timekeeping comprise not only those primarily involved in time accumulation, but also those involved in the maintenance of attentional and memory resources for timing, and in the monitoring and reallocation of those resources among tasks. This view is supported by findings in this and the last study and suggestive of a useful combination of the Church 1984/Baddeley2000 timing model developed in the last Chapter (Fig 21) whereby attention when drawn to the memory processes and information management of complex secondary tasks, attention is withdrawn from the switch to accumulators resulting in shorter time estimations/productions.

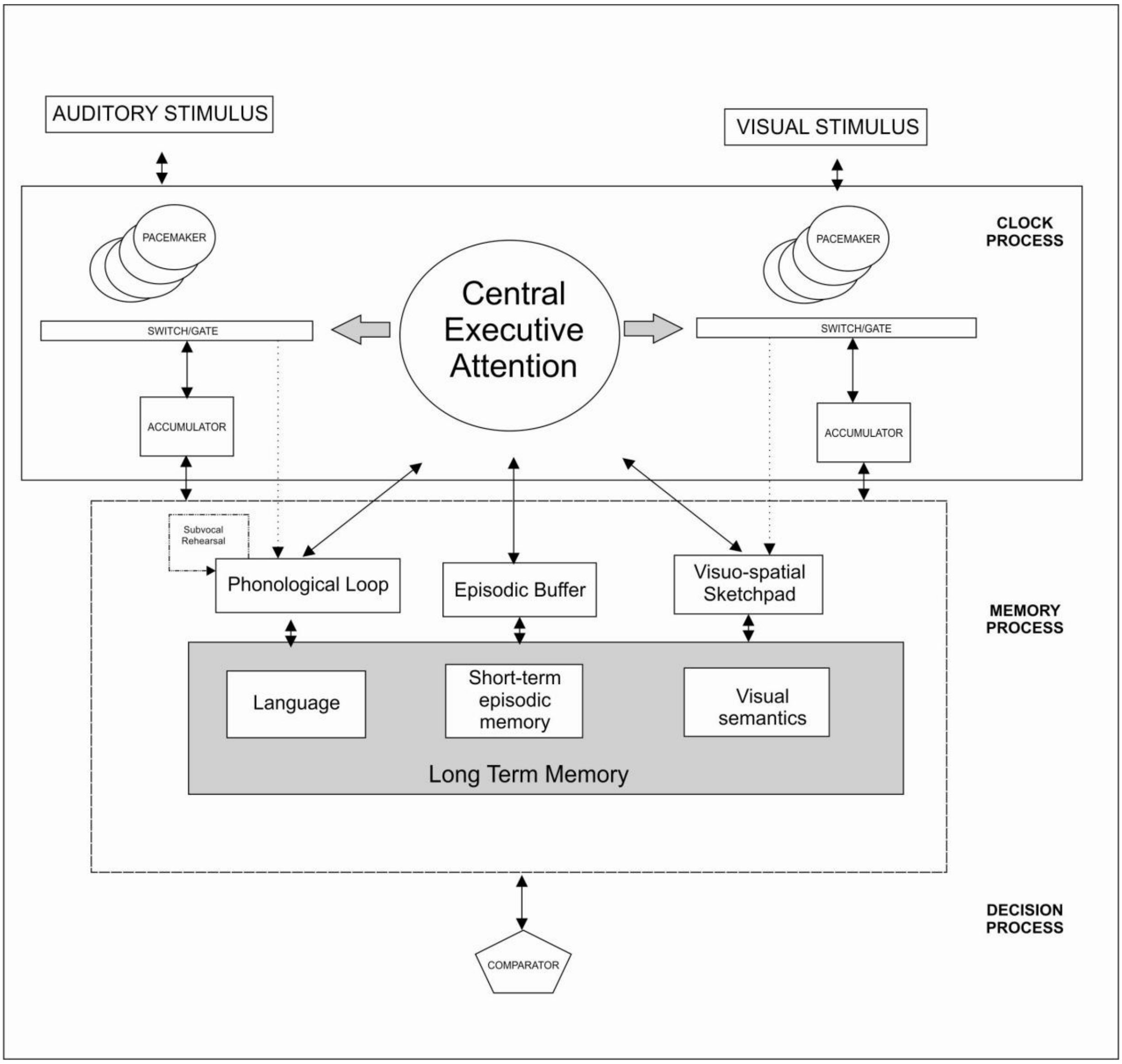


Fig 21. Combination Church/Baddeley Information Processing Model

An additional benefit of mixing the Baddeley 2000 model with the current information processing models of timing is it brings the interplay of language use in memory and in vocalisation into the range of factors known to add to timing variability. It also helps to consider more directly the use of language used by participants to coordinate actions, strategise with secondary tasks demands and remember task instructions. The inclusion of the episodic buffer as distinct from the central executive is suggested (Baddeley 2003) to be capable of binding together information from a number of sources and modalities into a single multifaceted code. This distinct addition may support a different sort of timing mirroring the distinction between more automatic aspects of timing and action from the more deliberate. This distinction has proved necessary to account for the ability to synchronise with regular stimulus that include perturbations below the conscious threshold yet seem to produce rapid automatic responses. This distinction will be investigated in Chapter 4 and 5.

Finally a closer look at individual differences illustrated in Fig 20 raises 2 additional points. On the one hand the slowing peaks visible above the intertrial variance are characteristic slowing of movements on speaking outloud tasks commonly mentioned in the literature (Thornton and Peters 1982; Hiscock, Kinsbourne et al. 1985; Keefe 1985; Hiscock, Kinsbourne et al. 1987). These slowing of movements increase the variability of speaking costs at slower intervals, but seem to be in one direction (i.e. they do not include downpeaks below the intertrial variability. On the other hand a general drift toward speeding up in the continuation stage may be due to the increasing clock time since the pacing signal was last refreshed. This last point is investigated more directly in Chapter 6.

CHAPTER 4:

PERTURBATION RECOVERY

4.1 ABSTRACT

As discussed in the introduction, models of movement timing do not typically consider a critical role for attention, working memory processes or executive control when correcting asynchronies in simple, repetitive movements. However these processes have been strongly implicated in studies with duration perception, and duration performance judgements. This study offers an appraisal of the assumption that automatic error correction in sensorimotor synchronisation has limited involvement of higher cognitive processes. In contrast to a common assumption of automaticity of error correction in SMS research, attention demanding dual task conditions were found to broadly increase asynchrony and slow error corrections directly after a perturbation. Interpretations are offered for this finding in the context of current models and measures used in SMS research.

4.2 **INTRODUCTION**

Sensorimotor synchronisation (SMS) has been defined as the rhythmic coordination of perception and action (Repp 2005). Linear models of sensorimotor synchronisation account well for much of the variance during paced repetitive movements within certain parameter ranges (Vorberg & Wing 1996). Linear models can also account for patterns of error corrections required to maintain synchronicity with regular and perturbed metronomes without explicit recourse to higher level cognitive functions (Schulze & Vorberg 2002, 2005). As a result, support has grown for the assumption that error corrections are largely automatic and independent of higher level functions such as awareness, and attention.

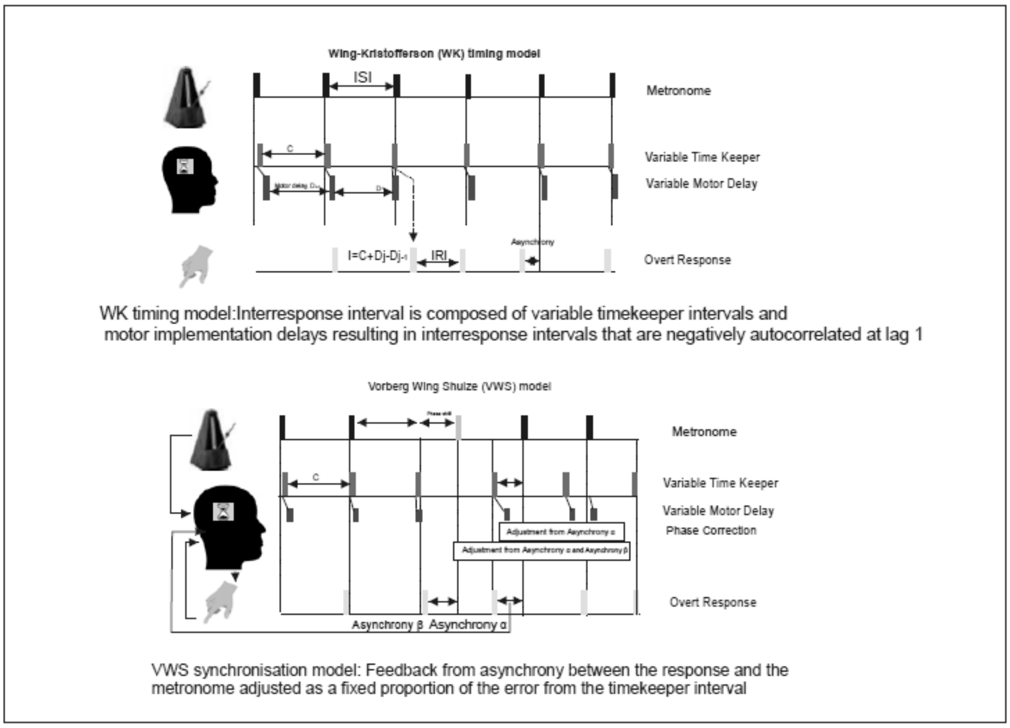
Extant research into the role of awareness, attention, intention, and working memory in repetitive movement synchronisation, has tended to confirm a dissociation between a low level peripheral automatic corrective process and a central timekeeping process more influenced by higher level factors (Sergent, Hellige, Cherry 1993; Repp 2001a, 2002c, 2002d, Repp & Keller 2004, 2008). Specifically, performed error corrections required to maintain synchrony following a perturbed stimulus, have been found to be as accurate below as above perceptual thresholds suggesting no benefit of conscious attention (Vorberg and Wing 1996; Repp 2002a,c; Ivry & Hazeltine 1995; Semjen, Vorberg & Schulze 1998; Semjen, Schulze & Vorberg 2000).

However the ability to automatically adjust phase of repetitive movements has itself recently been found to be influenced by higher level contextual factors such as the way instructions are framed to participants and the perceived difficulty of a task at hand (Repp 2002b, Repp & Keller 2008). This suggests that a phase correction process may be more influenced directly by higher level factors than previously thought, or that the behavioural expression of phase correction is mediated or overlapped by different processes which are responsive to higher level factors.

The following sections of this Chapter recount some of the main approaches and models used to explain the timing variance of simple finger tapping followed by the extensions required to model synchronisation and error corrections. Finally, issues will be highlighted which are directly explored in the research reported here which further explores the role of attention in sensorimotor synchronisation and error correction.

Sensorimotor Synchronisation

Building on the research of Stevens (1886) who investigated the accuracy of maintaining tapping with a metronome set pace, Wing and Kristofferson offered a quantitative 2 level model (Wing & Kristofferson 1973a, 1973b); which distinguished a central timer and a motor implementation process (see Fig 22). This model was able to develop the contrast of two sources of variance that Stevens' research picked up, a short term variance around the mean target interval which corresponds to the variance produced by motor delays, and a longer term drift which corresponds to the standard of a central timer or remembered metronome interval duration.



WK timing model:Interresponse interval is composed of variable timekeeper intervals and motor implementation delays resulting in interresponse intervals that are negatively autocorrelated at lag 1

VWS synchronisation model: Feedback from asynchrony between the response and the metronome adjusted as a fixed proportion of the error from the timekeeper interval

Fig 22. (WK) Model of Timing and extended (VWS) Model of Synchronisation

The WK model provides estimates of two sources of variance that contribute differentially to the statistics derived from a series of observable interresponse intervals (IRI). Extending this model to account for re-synchronisation with a metronome after a perturbation or asynchrony to an isochronous pattern requires feedback to account for any asynchronies between the variable taps and the external metronome standard. Error corrections can be accounted for with a relatively simple phase correction strategy which compensate for phase differences between the response and the metronome in a fixed proportion of the synchronisation error from the timekeeper interval α. Moreover, the next-to last asynchronycan be brought in to the calculation, as well. Then, the underlying timekeeper will be additionally corrected by a proportion of the previous error with error correction parameter β, (Vorberg & Schulze 2002; Vorberg & Wing 1996) here referred to as VWS model.

The WK model contrast between central/cognitive timer and peripheral/automated motor components shares with VWS model an assumption that during action there is a progression from awareness and planning which rely on perceptual and central cognitive information to one of a more peripheral automated online control (Glover SR 2001). Accordingly, higher level factors would seem to be required at this early planning stage and more liable to disruptive effects of a secondary task. Indeed this is what Sergent, Hellige & Cherry (Sergent 1993) found when they examined the effect of anagram solving on free finger tapping they showed after decomposing the variance according to the WK model that only the time-keeper variance was affected.

The VWS model concentrated primarily on one type of error correction, that of phase correction typically induced in isochronous meters. However a different type of correction, that of period correction, could be distinguished to account for changes required when adjusting to a change in tempo. Repp (2001b) following Mates (1994) explored error correction in both changes of phase and period and pursued the conscious/automatic distinction in these two types of error correction. This distinction has tended to preserve the dissociation between an automatic online control process (phase correction) whereas a more conscious perception based process that involved planning was proposed in period correction. Repp and Keller (2004) proposed a model referred to as RK model (Fig 23) relating these two types of error correction (period and phase) to the WK tiered model to include motor variance.

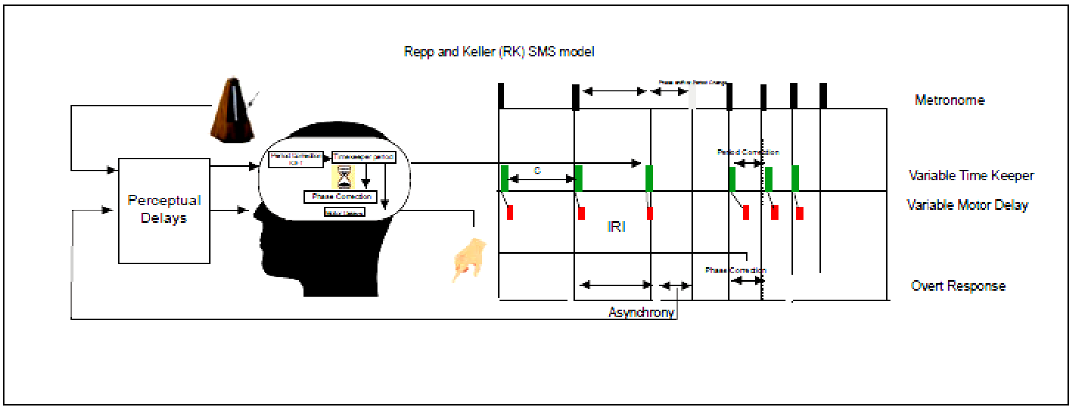


Fig 23. Schematic illustration of Repp and Keller (RK) SMS Model

Empirical support for this dissociation of peripheral/automatic/phase change and central/explicit/period change is drawn on the one hand from the findings that error corrections can occur to subliminal perturbations of sequence timing (Hary & Moore 1985, Repp 2001a; Thaut, Miller & Schauer 1998), which suggest that a direct coupling of sensory information and synchronised action can occur without mediation by awareness or perceptual judgement; and on the other hand from findings that this corrective process is difficult to suppress intentionally even when directly requested (Repp 2002a 2002c; Repp and Keller 2004.) Furthermore phase correction seems as effective above or below the perception detection thresholds (Repp & Penel 2002). By contrast when a change in tempo is required to adapt synchrony with a change in target interval duration, attention has been found necessary to effect a period change (Repp and Keller 2004; Repp 2001b).

The empirical findings are therefore highly suggestive of a dissociation between automatic bottom up, stimulus driven phase correction and a top down period correction process influenced by intentions and awareness. Further support for such a dissociation can be found from neurophysiological research based on the relationship between brain areas activated during the performance of different timing tasks. Although not intended to map onto Repp's phase and period mechanisms, Lewis & Miall's (2003) literature review led them to suggest two mechanisms or networks that seemed differentially responsible for short and long intervals. One mechanism associated with areas of the brain associated with movement such as the cerebellum and premotor cortex which are activated mainly during shorter time interval (< 1 sec). In contrast a cognitive controlled mechanism was associated with the areas linked to higher brain function such as the prefrontal cortex observed in perception of longer time intervals (> 1 sec).

However the distinction between controlled and automatic processes involved in SMS may not be so distinct and indeed, their functions may overlap as Repp & Keller (2004) also found some automatic error correction of period change in the absence of awareness. Furthermore, Repp's (2006) research into an auditory perceptual illusion on both period and phase corrections following event onset shifts showed differential effects to positive and negative phaseshifts, strong individual differences and a more complicated pattern of effects to a perceptual illusion than would be expected for automatic error correction. Although no firm evidence has been found specifically for the role of attention in SMS models of phase correction, it has been proposed as relevant in explanations of upper and lower limits to SMS and subjective thresholds (Repp 2005) and moreover, SMS models imply that changes must be attended to (whether these changes are asynchronies or stimulus or movement intervals) even if the perceptual attending is below conscious thresholds.

According to the considerations outlined above, there are three main ways attention could be important for successful rhythmic synchronisation and error correction. Firstly, attention can be involved in the perception, detection, or monitoring of patterns of durations. These patterns could be the onsets of stimulus, onsets of movements or onsets of perceived asynchronies (Aschersleben 2002; Repp 2005). Secondly, attention can be involved in accessing and comparing recent memory of intervals of taps or stimulus (Repp 2005) Aschersleben (2002), Thirdly, attention can be required to initiate and stop, (Repp 2001a, 2002b; Glover and Dixon 2001, 2002) continue and adjust, (Vorberg & Wing 1996) movements while ignoring internal or external distractions of irrelevant timings and movements (Repp 2001b, Miyake, Onishi & Pöppel 2004).

Present Research

There seems agreement amongst researchers (Vorberg & Wing 1996; Sergent et al 1993; Repp 2002c; Repp & Keller 2008) that to initiate synchrony of tapping to a metronome requires directing attention to the pattern of the stimulus subject to experimental instructions (Repp 2001b, 2005). However once initiated both controlled and automatic processes may be involved to different degrees in maintaining synchrony.

The goal of this study was to explore the cognitive context of synchronisation abilities by changing the demands put on attention during a tapping task to observe the effects on timing variability and error correction. A dual task paradigm was used to increase the demands on attention. Mental arithmetic was chosen for the secondary task as this was considered an attention demanding exercise that could be easily varied for complexity and any errors could be easily verified and coded. Furthermore it has been used as a secondary task in SMS research (Repp & Keller 2004) and is commonly used to modify attention in cognitive research (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle 2005).

Two aspects of asynchrony were of particular interest in this study, the variability of tapping in synchrony with the metronome in differentially attention-demanding conditions, and secondly, the effect of these conditions on the pattern of recovery from a metronome perturbation. According to the VWS and RK models, without a change of tempo, any adjustments required to maintain synchrony with the isochronous metronome is hypothesised to be accomplished with phase correction alone, and would therefore show little effect of secondary task demands to the extent that phase correction could be accomplished in an automatic fashion

In keeping with the findings of the previous Chapters, and in contrast to the assumption of automaticity of error correction, we hypothesise that any component attention plays in perceiving and comparing relevant stimulus and movement onsets to maintain or assist synchrony would become increasingly compromised as attentional demand is increased by the secondary task conditions. As a consequence it would be expected that as attention is increasingly demanded, that variability of tapping would increase, as would errors in the secondary task. Secondly, to the extent that recovery from phase shifts in the stimulus requires attentional resources to notice asynchronies, we would expect a slower recovery during conditions of high attentional demand. Finally, to the extent that executive attention is the critical component in working memory (Conway et al, 2005), and primarily responsible for ignoring irrelevant transient associations, we expect that as secondary task difficulty increases, that asynchrony increases with task condition and recovery from perturbation is slower.

4.3 **METHOD**

Participants: The original sample consisted of 16 participants (7 male, 9 female) paid for their participation.

Apparatus and stimuli: Participants rested the index finger of their dominant hand on a wooden surface (4×3cm) mounted on top of a force transducer (see fig 3). The auditory metronome was delivered by an amplified loudspeaker played through a computer speaker. Stimulus presentation and movement recordings used a National Instruments data acquisition card (DAQ) controlled by MATLAB. An auditory waveform sent to the loudspeaker was fed back into the DAQ, enabling measurement of the timing difference between the metronome pulse and the corresponding participant tap response with sub-millisecond accuracy and precision. Dual task information was displayed on the screen of a Pentium 4 portable computer running windows XP placed on the lab bench in front of participants (fig 24)

Fig 24a. *Experimental arrangement with subject tapping a force transducer whilst watching the screen*

Procedure

Participants were instructed to tap in the closest synchrony they could manage with an auditory metronome that might occasionally vary. Participants were given 4 trials to get used to the task set up and to allow a check that their tap strength was sufficient to provide a clear signal through the force transducer. Trials alternated the inclusion of either a positive or negative phase shift at 15% of the otherwise isochronous metronome beat at 500ms (s.d. 10). These pre-test trials also allowed a vetting of any subjects who might perform too erratically at a simple auditory synchronisation task. Participants would then receive 5 trials in each of 5 conditions, an Ignore condition (1), where participants were able to see presentation stimulus at the same rate of presentation as dual task conditions but were instructed to ignore the stimulus, and then 4 increasingly demanding dual task tapping conditions (2-5) where participants were asked to perform simple arithmetic operations on the presented stimulus.

Secondary Task

To scale the effect of increasing demand, two manipulations were used in the secondary task, the first was to offer two levels of difficulty of the arithmetic calculations The other was to offer two levels of complexity a simple condition that required participants to hold one resultant calculation in memory between stimulus presentations, and a more difficult condition of holding two resultant calculations in memory between stimulus presentations. Thus there were five levels of executive attentional demand from the low level ignore condition to the highest demand of complexity and difficulty and this are detailed below:

Ignore Condition (1): Participants would face the screen displaying “Ready?” and press the space bar to initiate a flash movie which would cycle through 1 complete trial of presentation stimuli at a fixed paced before pausing at a “Ready?” screen for the next trial Participants were asked to watch the screen but to ignore the presented stimuli which made sequential requests for simple calculations, whilst maintaining synchrony with the metronome even if it seemed to vary (fig 24b).

DT (2): In this condition, in addition to the auditory synchronization, participants were requested to perform the requested calculations of the stimulus, which involved retaining a running total as a result of sequential additions and subtractions until the end of the trial (8 small integers needed to be added or subtracted per trial ranging from -1<0<1). Each calculation request was displayed sequentially every 3.75s. At the end of the trial participants were requested to report back the cumulative total of all 8 calculations. After reporting the total, participants would press the space bar to initiate the next trial.

DT (3): identical to DT2 whilst undertaking a more demanding mathematical task of addition and subtraction of numbers that ranged from -7<0<7(fig 24b).

DT (4): identical to DT2 but Subjects were here requested to compute operations of pairs of stimuli (stimuli pairs were consistently coloured, and spatially separated) at low range (-1<0<1), reporting back two cumulative totals at the end of each trial.

DT (5): identical to DT (4) but the two parallel display of sequential numbers were of the greater potential range of -7<0>7 (fig 24b).

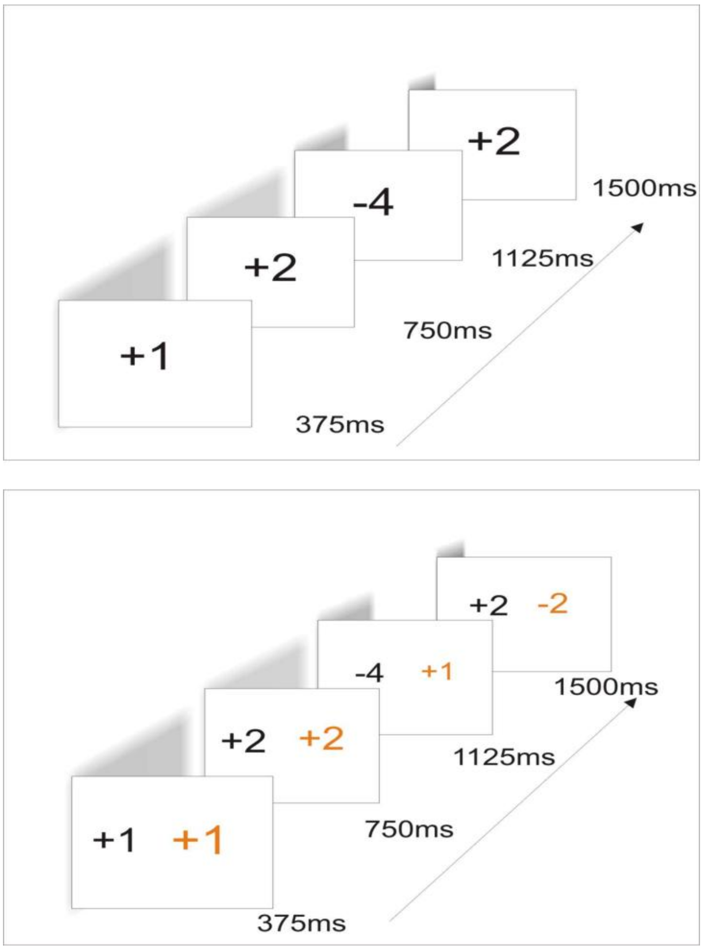


Fig 24b Examples of sequential stimuli presented on screen instructing participants to perform arithmetic operations with one (top) or two (bottom) totals to keep in memory

Data Processing

One participant was excluded from analysis due to excessively erratic and asynchronous tapping at a base rate level according to criterion reported below. This left 15 participants (7 male and 8 female mean age=27) for analysis.

Synchronisation performance was quantified in terms of the asynchrony between the metronome pulse onset and the participant's tap onset as registered by the force-transducer. Mattap programme (Elliott, Welchman & Wing 2009) was used to run the experiment via Matlab and recorded both the onsets of metronome pulses and responses calculating asynchrony using an algorithm for matching pulses and responses.

Relative Asynchrony was calculated by taking a mean of 4 taps (IRI) prior to the phase shift and subtracting this from each subsequent tap at the occurrence of the phase shift onwards. The 15% phase shift of 500ms interval resulted in a forced positive or negative asynchrony of approximately 75ms at the phase shift (once normalized to zero) allowing a slope of recovery from this perturbation to be illustrated when plotted. See Fig 28. This also allowed an estimation of alpha as the percentage of correction on the first tap after a phase shift (PCR Repp 2008).

The standard deviation of asynchrony of 4 taps before the phase shift was taken for each subject and collapsed between trials for compatible direction of phase shift, and a second average measure of standard deviation was taken 15 taps after the phase shift of another 4 taps and similarly collapsed across trials for each subject. These before and after measures were used to assess the effect of the dual task conditions on the variability of tapping before and after a phase shift

The results of the dual task calculations were also recorded to assess accuracy trade off and a division between a low error group (less than 4 total errors/30) and a high error group between 4-10 errors/30). An error constituted any incorrect cumulative total from any of the 5 trials per condition.

4.4 **RESULTS**

In accordance with the hypothesis stated earlier, the results are grouped into three sections, namely, the effect of dual task condition on timing variability, on secondary task errors; and the effect of dual task condition on phase-shift recovery.

Dual task condition and Timing Variability

When compared directly a within subject ANOVA was run with condition (5) x phase (2) x position (2) as factors, a significant difference was found between the greater deviation after the phase shift compared to before F(1,14)=12.731; p=0.03 (partial eta squared 0.476) (fig 25) and a significant interaction was found between condition*phase*postition measures F(1,4)=3.465; p=0.01 partial eta 1.98

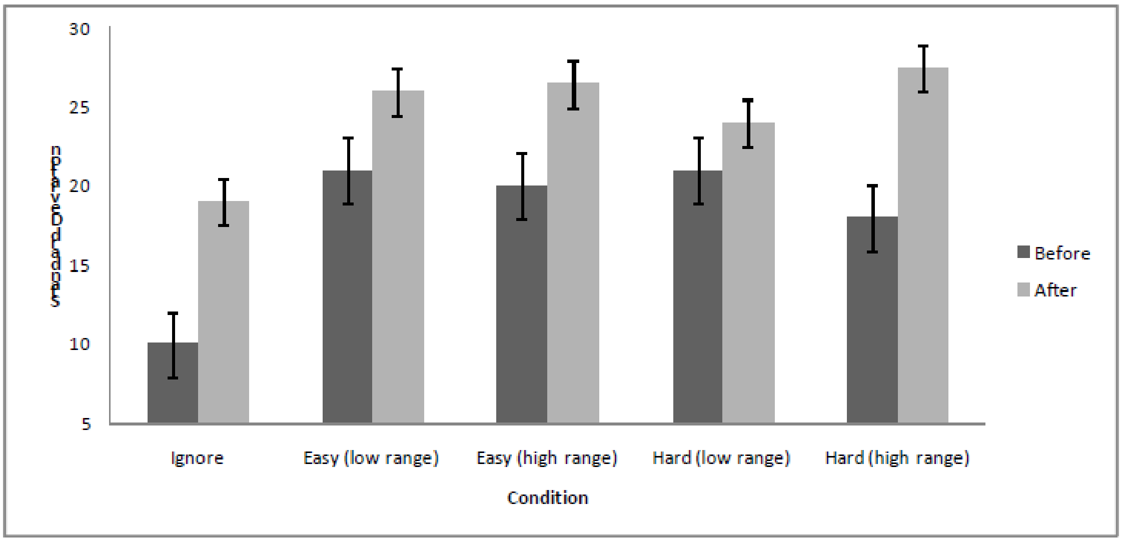


Fig 25 Relative Variability (standard deviation) before and after the phase shift collapsed across all conditions

Errors and Condition

Although 3.75 seconds was more than enough time for an adult to calculate small additions and subtractions, the cost of task switching seems to have resulted in increasing errors (fig 26) as the conditions became more demanding. More errors were produced during negative phase-shift trials than positive phase-shift trials in all conditions with a slightly higher proportion of errors in the hardest condition.

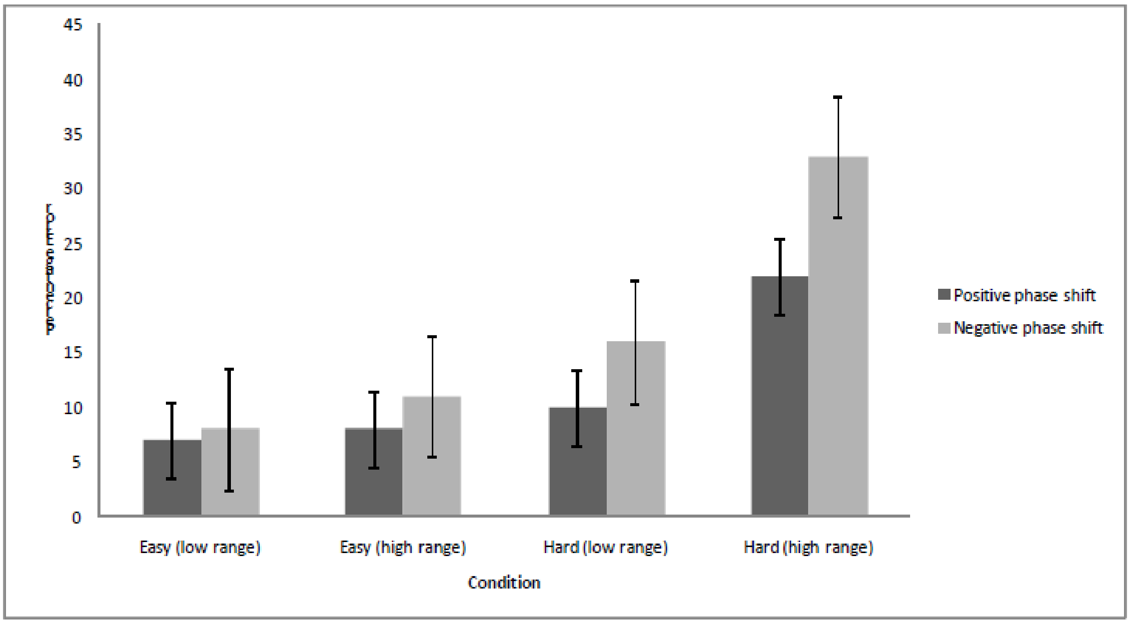


Fig 26. Effect of Condition on Perceptage Error in Secondary Task

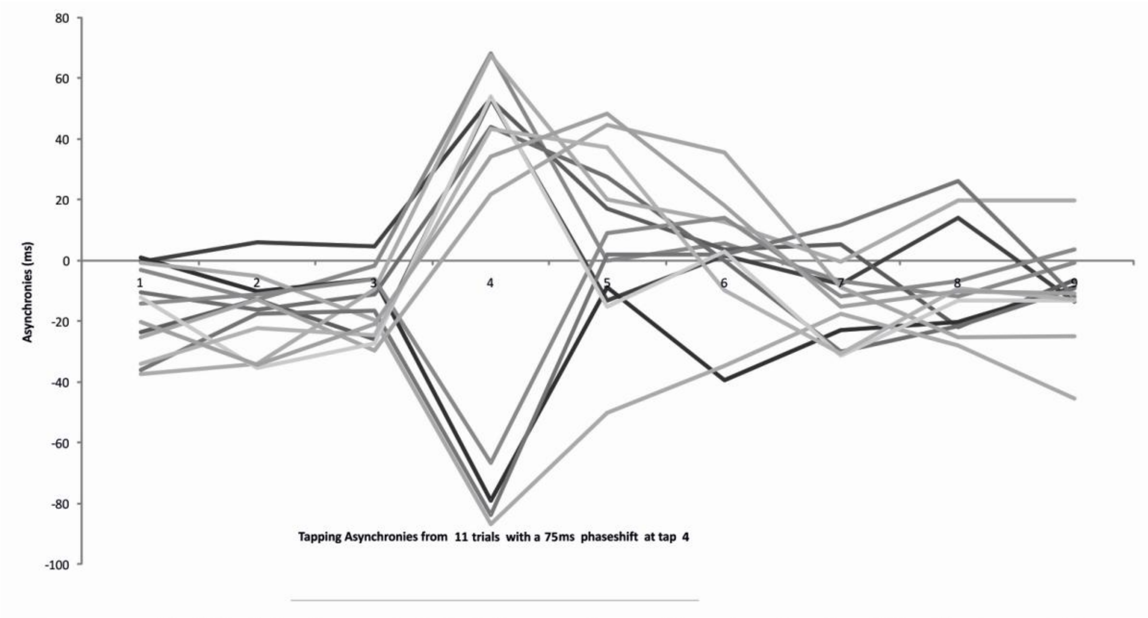


Fig 27. Illustration from one individual of recovery from positive and negative phaseshifts with subsequent 5 taps

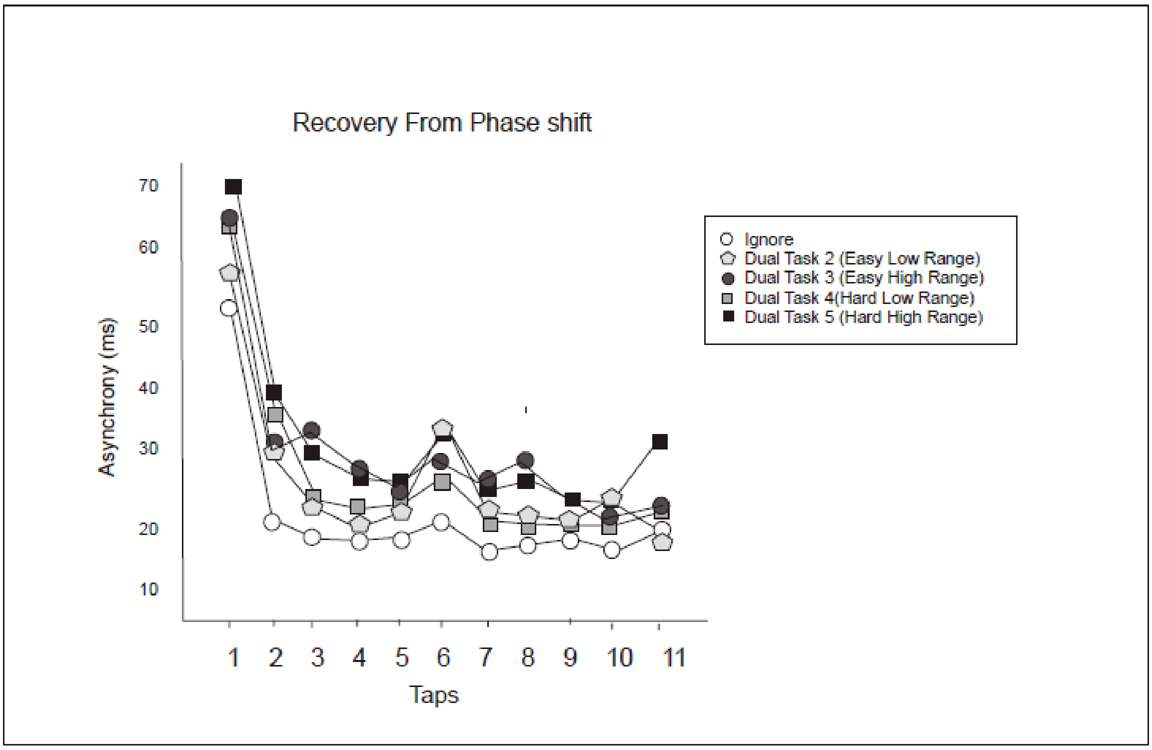


Fig 28. Illustration of relative asynchrony in recovery from positive and negative phase shifts (with signs adjusted) at tap 1, followed by recovery over the next 10 taps for all subjects (Lines represent different conditions of increasing demand)

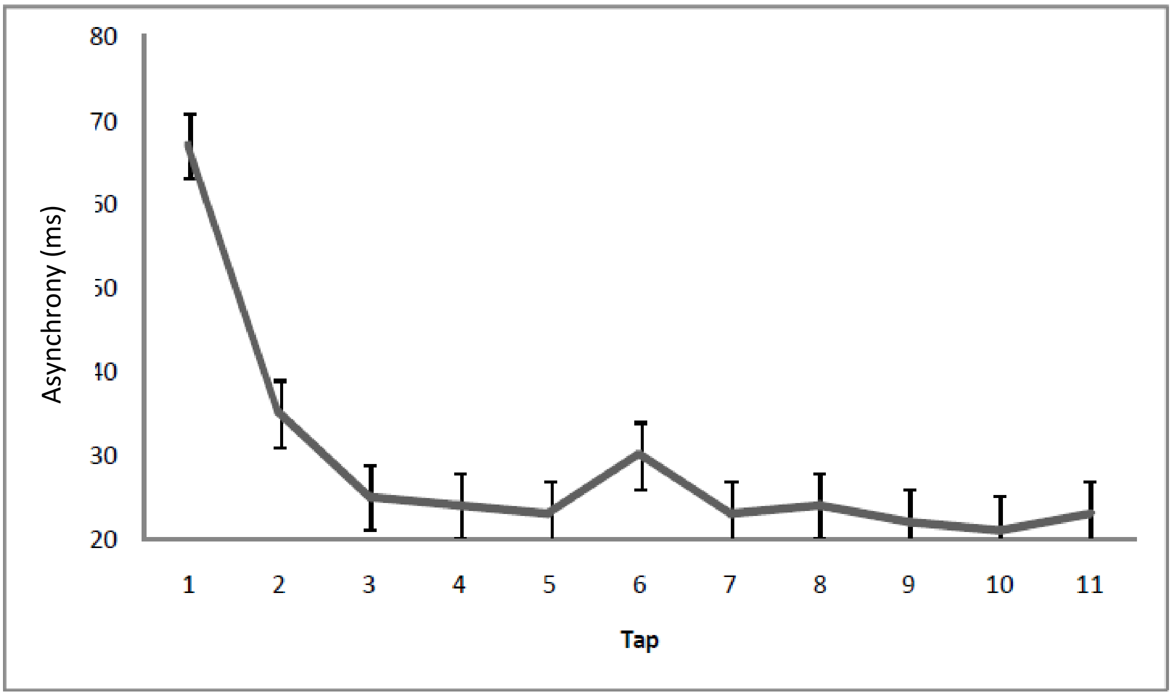


Fig 29. Illustration of phase shift at tap 1, followed by recovery over next 10 taps collapsed for direction of phase shift for all subjects

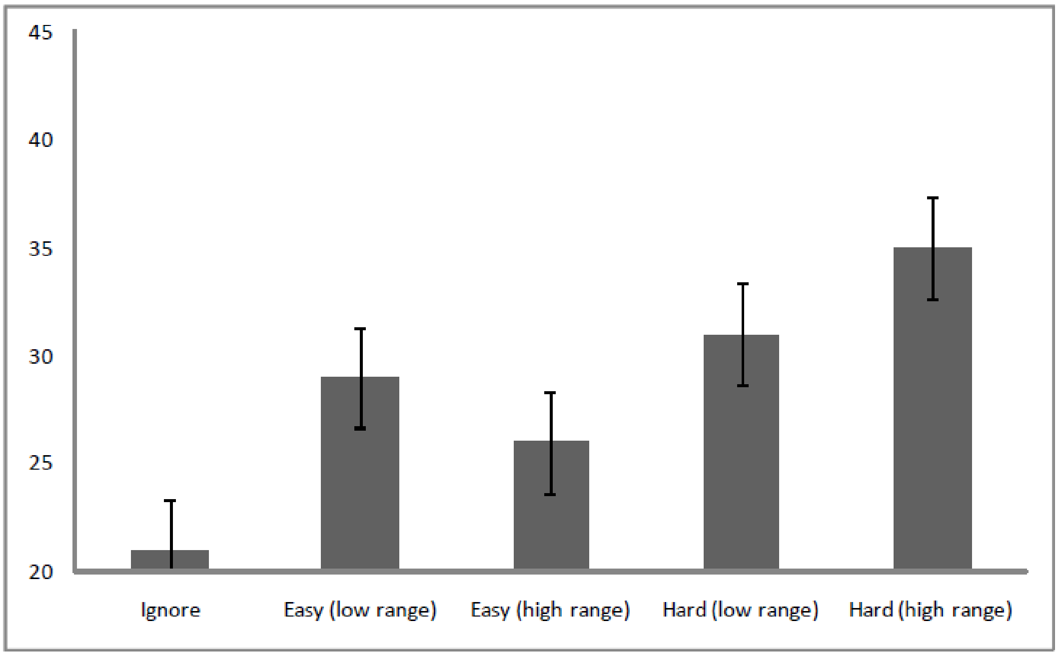


Fig 30. Relative asynchrony collapsed across all subjects and illustrated across the 5 conditions

Effect of Condition on Phase shift recovery

For illustrative purposes the (fig 27) includes the phase shift at point 4 and the recovery from both positive and negative phase-shifts over subsequent 5 taps for one individual in one condition (following Semjen et al, 1998). Fig 28 illustrates this same general pattern of recovery for all subjects including the subsequent 10 taps after a phase shift (once the signs have been adjusted). Different conditions are represented by different lines in fig 28, whilst all conditions are collapsed across all 15 subjects in fig 29. As the asynchrony is forced to increase by the phase-shifted onset of the metronome, only the taps after the phase shift where participants have a chance to correct this forced asynchrony were included for analysis in 5(conditions) x2(direction of phase shift) x10(measure of relative asynchrony by tap) within subject repeated measures ANOVA.

The relative asynchrony was calculated for the first 10 taps after either a positive or negative phase shift and these results were collapsed over trials within each condition for each subject for each tap. A within subject repeated measures ANOVA with the following factors, condition (5) x direction of phase shift (2) x tap (10) was run on these valuse. Condition was found to be significant F (4, 56) =3.328; p=0.040 (Partial eta squared 1.92) after greenhouse geiser adjustment (fig 31).

Relative asynchrony for (alpha) the first tap after the phase shift in each condition was found to be highly significant F(4,56)=3.53; p=0.12 (Partial eta squared =0.202) Phase seemed to have no significant effect or interaction at alpha with both positive and negative phase shifts resulting in increasing asynchrony with increasingly demanding conditions (fig 31).

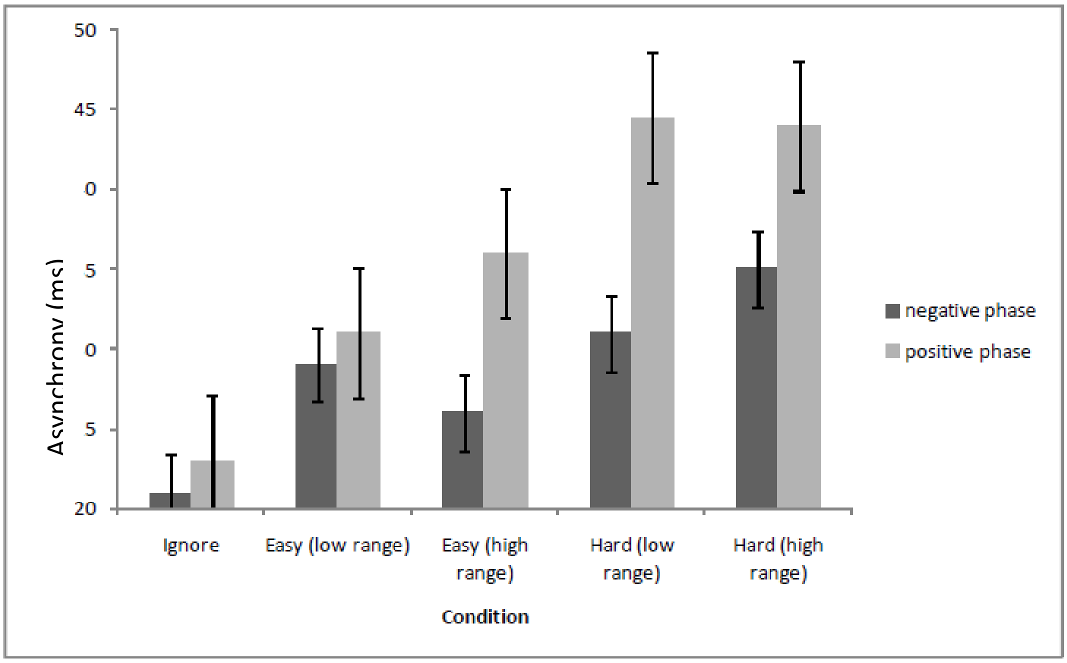


Fig 12. Relative Asynchrony separated by direction of phase shift (withs signs adjusted) across all conditions

Fig 31 Relative Asychrony separated by direction of phase shit (with signs adjusted) across all conditions

4.5 **DISCUSSION**

The main goal of the present study was to investigate the effect of increasing attentional demand on the ability to maintain synchrony with an auditory metronome when regular and perturbed. A comparison of the level of asynchrony found during the ignore task with all other dual task conditions gives the clearest indication that an increase in attentional demand results in an increase in asynchrony for all measures utilised. This is instructive, as for any automatic responses, the disruptive effects on attention of both the novelty of the stimulus presentation and its period (which was a complicated ratio of the metronome rate) could have been difficult to ignore or control. However any automatic effects elicited during the ignore task were clearly dwarfed by the consequence of more demanding conditions on measures of asynchrony. Together with the increase in errors found for the secondary task, this result seems to support the hypothesis that attention is required to maintain synchrony and recover from perturbations. However the levels of asynchrony do not increase in direct proportion to the attention demands of all secondary task conditions.

The relative increase in variability 15 taps after the phase correction in the ignore condition (see Fig 25) was unexpected as recovery from phase perturbations typically occur within 3 or 4 taps (Repp 2005). Excluding error correction from the reason for this increase in variability later in the trial might suggest that the cumulative effect of stimulus presentation increased the attentional demands required to ignore them. This increasing attention cost for ignoring may then have resulted in less attention free for timing control and consequently led more variability. Alternatively, the consequence of a phase shift and its associated recovery may have continued to interfere with the attentional demand of all secondary task conditions much longer than is generally expected.

The second hypothesis predicted a slower rate of recovery to a phase shift as a consequence of increasing demands on attention during the secondary tasks. Our results show support for this hypothesis most clearly in the ignore condition where recovery was maximal and the hardest dual task condition where recovery was minimal (see Fig 28). However, the levels of recovery in the intermediate conditions do not describe a clear trade-off between attentional demand and cost in recovery from perturbation. The last hypothesis predicted that difficulty in noticing the asynchrony might be hardest during the hardest dual task condition, however excluding the ignore conditions, the levels of asynchrony and variability before a phase shift were very similar for all other dual task conditions (see Fig 25) which suggests the role of attention specifically in detecting the stimulus onsets was not the role most compromised by increasingly demanding conditions.

The main findings of this study were an increase in asynchrony, an increase in variability and a slowing recovery PCR following conditions of increasing demands on attention. These findings provide strong evidence to question the assumption of automaticity in phase shift compensation and highlight a more active role for attention than previous research had suggested, however some limitations in the study design with regard to control for individual differences force a more cautious interpretation of the findings.

Individual Differences

Although none of the participants were professional musicians, no attempt was made to control for their variable musical training. The difference between novice and expert musicians can account for as much as 5% variability (Franek, Mates, Radil, Beck, & Pöppel 1991; Keele, Pokorny, R, Corcos & Ivry 1985; Repp 1999, 2005). Similarly, the mean asynchrony can vary by up to 100ms between individuals with musically untrained participants showing larger negative asynchronies than even amateur musicians (Franek et al, 1991; Keele et al 1985; Repp 1999). Controlling for musical experience would help to minimise any more subtle differences underlying the averages used to assess the effect of secondary task conditions. In a similar vein, differences between participants in their affinity and ability with mental arithmetic would give competent individuals potentially more resources to devote to timing. Steps are taken to address these concerns of individual differences that might impact variability in both the primary and secondary tasks in the following Chapter.

CHAPTER 5:

PERTURBATION RECOVERY II - Skill

5.1 INTRODUCTION

In the previous Chapter the main findings were that an increase in asynchrony, variability and a slowing recovery PCR followed from conditions of increasing demands on attention. These findings highlighted a more active role for attention than previous research had suggested in synchronization, and perturbation recovery. While results of the interference were strong, they were not parametrically increased in line with the assumed difficulty of the secondary task. This could have been due to uncontrolled individual differences in the levels of skill at managing either the timing of the secondary task or the ability to perform fast mental arithmetic calculations. To assess how important these factors may have been a similar but simplified paradigm was used to explore the effects of dual task complexity on timing accuracy using a group of professional musicians as participants. Additional improvements to the paradigm were to include a continuation phase to allow comparisons with timing variability of non musicians and amateur musicians in ChapterChapter 2 and 3, and a free tap before and after the experimental blocks. This would enable an assessment of any tendency toward a shorter preferred tempo leading to shorten length of IRI (speeding up) in continuation phases as found in ChapterChapter 2 and 3.

5.2 METHOD

Participants: The participants were professional session musicians working at Shepards Bush Music Studio in London (7 male, 2 female, mean age 28) and all were paid for their participation. All participants practiced playing music on a daily basis and all had proficient experience with at least 3 types of musical instrument yet greatest expertise in one. The favoured instrument of the participants was 3 drummers, 4 guitarists (1 base guitar, 3 lead/rhythm) and 2 keyboard players/pianists.

Apparatus and stimuli:

Participants were comfortably seated at a desk facing a Pentium 4 portable computer. Participants rested the index finger of their dominant hand on a wooden surface (4×3cm) mounted on top of a force transducer (see fig 24 last Chapter). The auditory metronome was delivered by an amplified loudspeaker played through a computer speaker. Stimulus presentation and movement recordings used a 6229 National Instruments data acquisition card (DAQ) controlled by MATLAB. An auditory waveform sent to the loudspeaker was fed back into the DAQ, enabling measurement of the timing difference between the metronome pulse and the corresponding participant tap response with sub-millisecond accuracy and precision. Dual task information was displayed on the screen of a Pentium 4 portable computer.

Procedure

Participants were instructed how to perform the synchronise and continuation paradigm by tapping in the closest synchrony they could manage with an auditory metronome that might occasionally vary then to continue tapping after the metronome stopped at the same rate until they heard an end of trial beep. Participants were given 2 trials to get used to the task set up and to allow a check that their tap strength was sufficient to provide a clear signal through the force transducer. After the practice trials, participants were asked to perform a free tap, which was to tap without any pacing stimulus at their preferred tempo (or a tempo they felt comfortable maintaining) until they heard an end of trial beep after 30 seconds. Participants then started the blocks of experimental trial conditions. 6 blocks of 3 trials for each secondary task condition resulted in a total of 54 experimental trials. Trials included both positive and negative phase shift at 15% of the otherwise isochronous metronome beat at 500ms. The phase of the phaseshift was alternated like the experimental blocks with a latin square design. Finally participants performed a final freetap trial which ended the experiment.

Secondary Task

The secondary task was simplified from the previous experiment to offer only two levels of mathematical difficulty to scale the effect of increasing cognitive demand and two different instructions sets, either to ignore the stimulus or keep a running total of the additions and subtractions. Participants were instructed prior to starting each block whether to ignore or silently count according to the block design. This resulted in 3 types of trial condition listed below that were evenly distributed in the block design.

Ignore Condition (1): Participants would face the screen displaying “Ready?” and press the space bar to initiate a flash movie which would cycle through 1 complete trial of presentation stimuli at a fixed paced before pausing at a “Ready?” screen for the next trial Participants were asked to watch the screen but to ignore the presented numerical stimuli which made sequential requests for simple calculations, whilst maintaining synchrony with the metronome even if it seemed to vary (fig 24b).

Counting Easy (2): In this condition, in addition to the auditory synchronization, participants were requested to perform the requested calculations of the stimulus, which involved retaining a running total as a result of sequential additions and subtractions until the end of the trial (8 small integers needed to be added or subtracted per trial ranging from -3<0<3). Each calculation request was displayed sequentially every 3.75s. At the end of the trial participants were requested to report back the cumulative total of all 8 calculations. After reporting the total, participants would press the space bar to initiate the next trial.

Counting Hard (3): identical to DT2 whilst undertaking a more demanding mathematical task of addition and subtraction of numbers that ranged from -7<0<7

Data Processing:

Synchronisation performance was quantified in terms of the asynchrony between the metronome pulse onset and the participant's tap onset as registered by the force-transducer. Mattap programme (Elliott, Welchman & Wing 2009) was used to run the experiment via Matlab and recorded both the onsets of metronome pulses and responses calculating asynchrony using an algorithm for matching pulses and responses.

Relative Asynchrony was calculated by taking a mean of 4 taps (IRI) prior to the phase shift and subtracting this from each subsequent tap following the occurrence of the phaseshift to its recovery. The 15% phase shift of 500ms interval resulted in a forced positive or negative asynchrony of approximately 75ms at the phase shift followed by its return to baseline in subsequent taps. The first tap following the phaseshift represented alpha as the percentage of correction on the first tap (PCR Repp 2008).

Standard descriptives (Means and Standard Deviations) were taken from 30 IRI in continuation phase after the first 3 taps of transition were eliminated, to characterise timing variability in the continuation phase.

Any incorrect scores of the dual task calculations were also totalled for each trial and averaged by condition and by individual to assess bidirectional accuracy trade off . An error constituted any incorrect cumulative total from any of the 56 trials.

5. 3 **RESULTS**

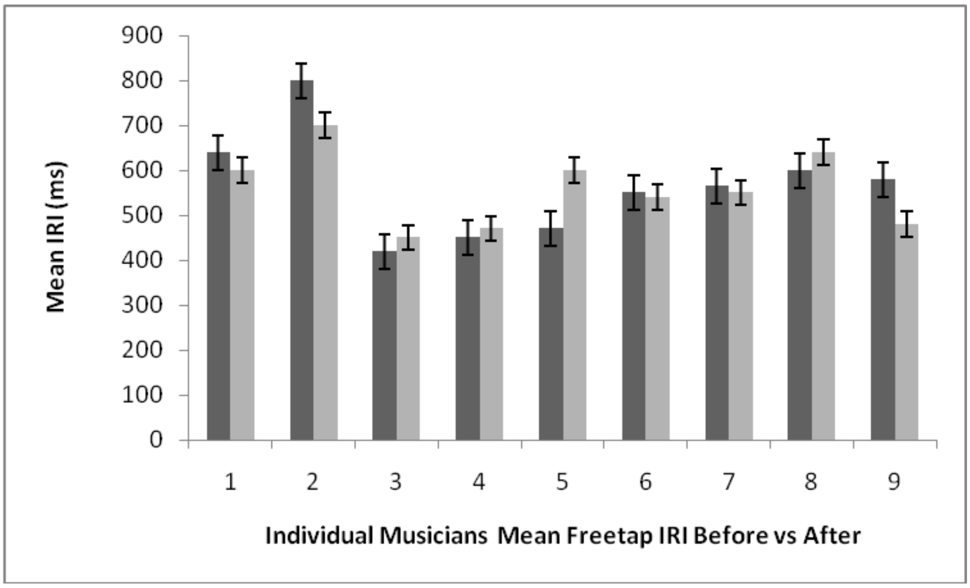


Fig 32. Illustrates the mean IRI for each individual in their free tap trials before the experiment (dark columns) and after the experiment (light columns).

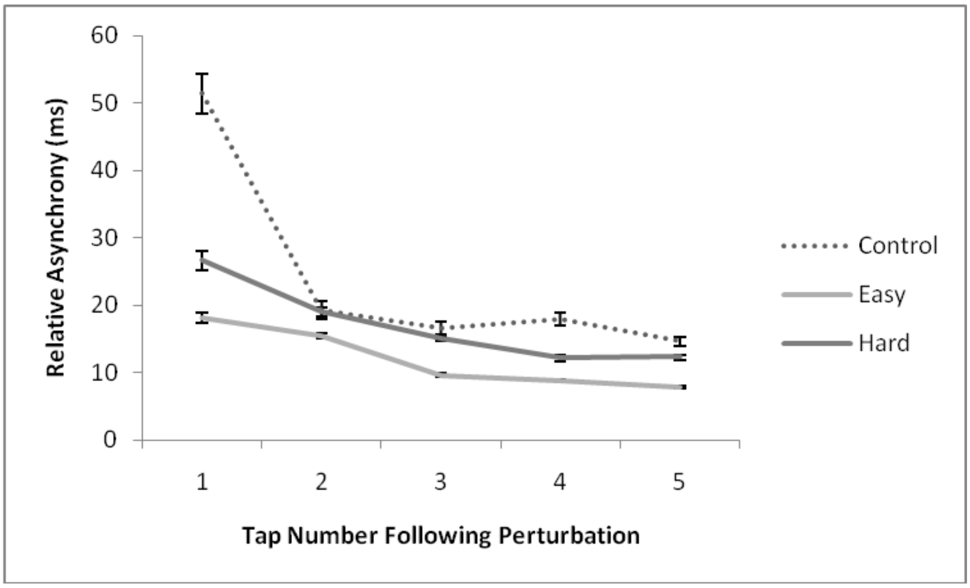


Fig 33. Illustrates the average recovery from perturbation for all participants separated by Condition. Error bars represent the standard deviation

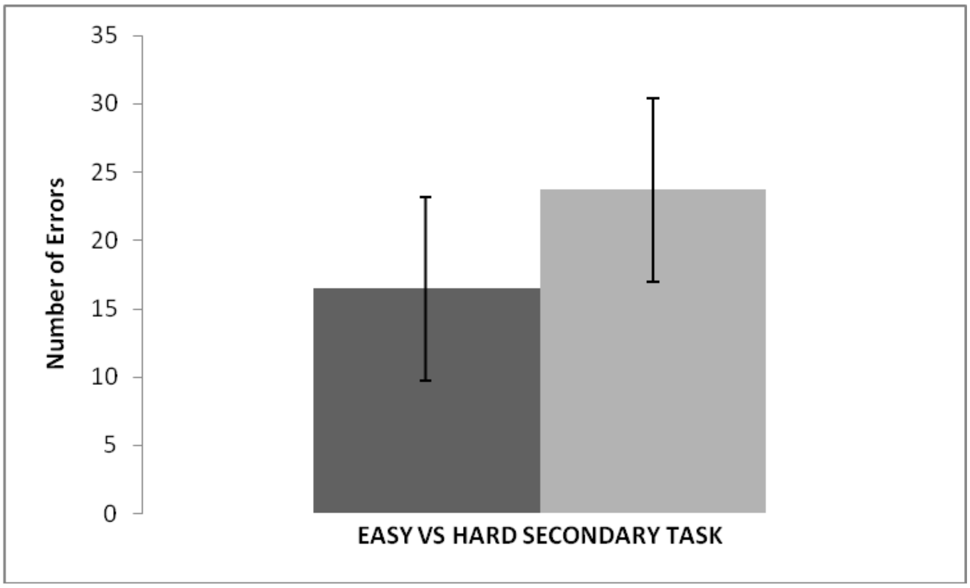


Fig 34. Illustrates the Total number of Errors in the secondary task (easy or hard) counting trials accumulated by all participants

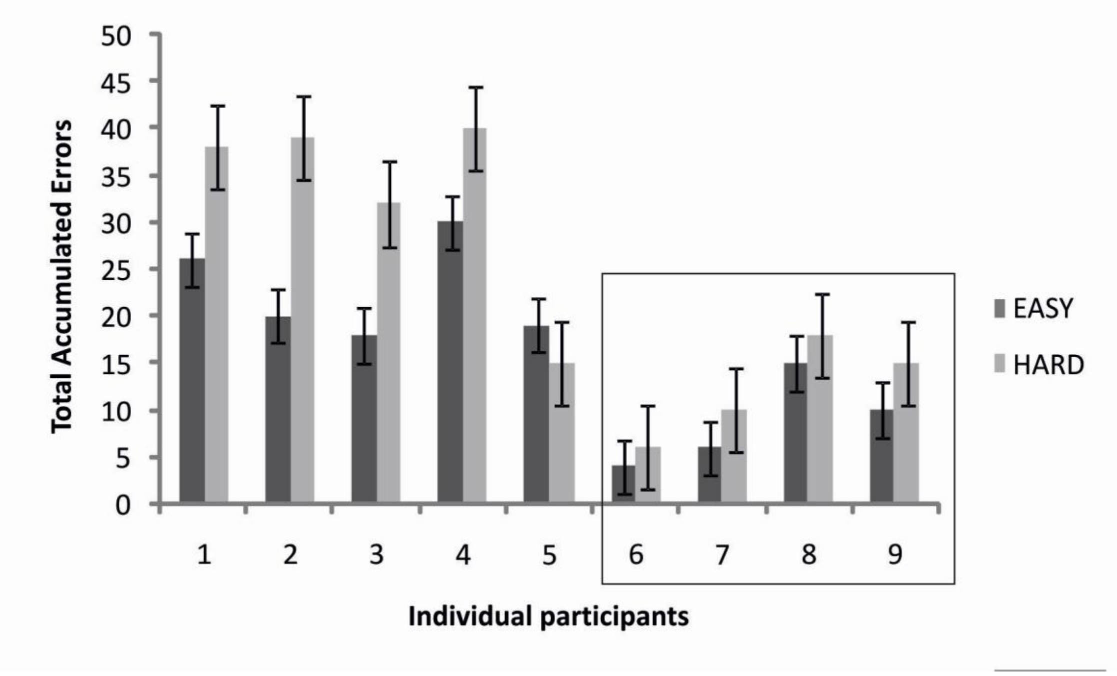


Fig 35 Illustrates the total secondary task errors separated by individual participants. The square highlights participants who scored less than the mean error for easy counting trials.

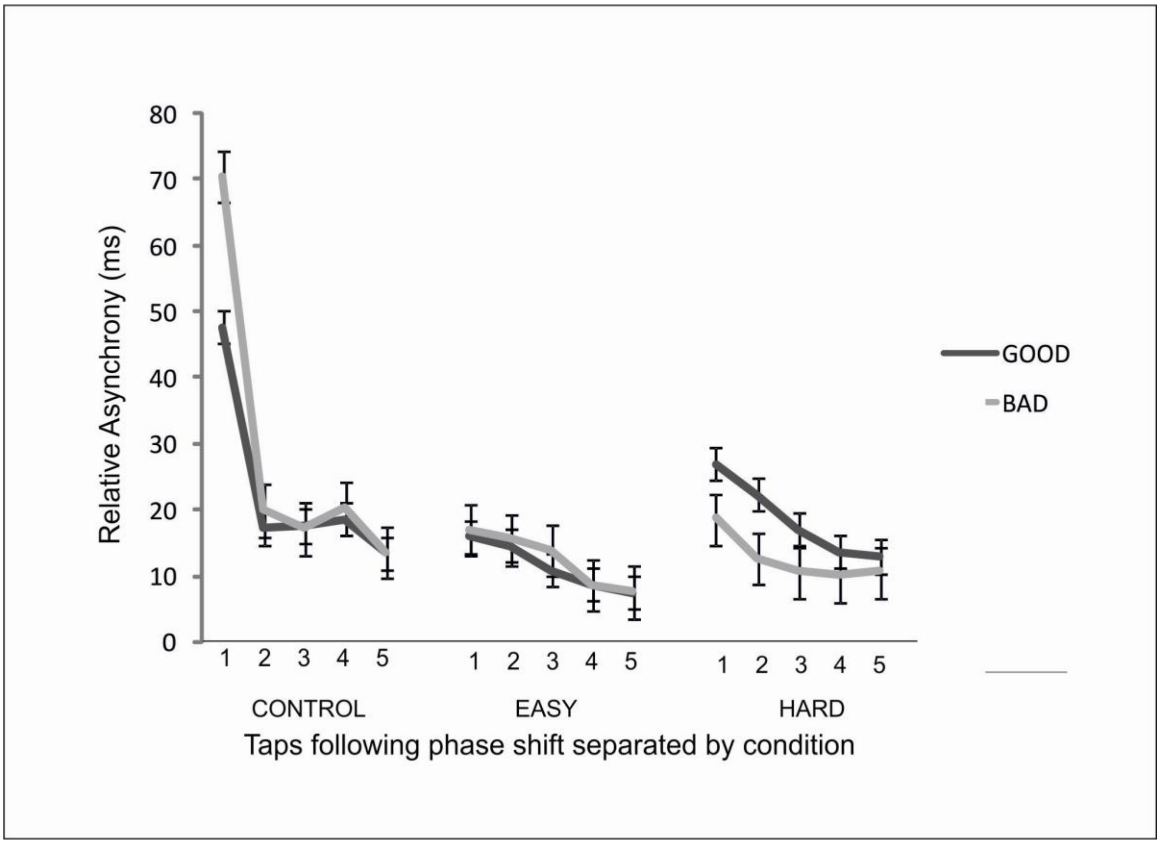


Fig 36 Illustrates a comparison of the phaseshift recovery over 5 taps for those participants who were identified as ‘good’ at mental arithmetic (with less than mean error) from those who scored more errors .

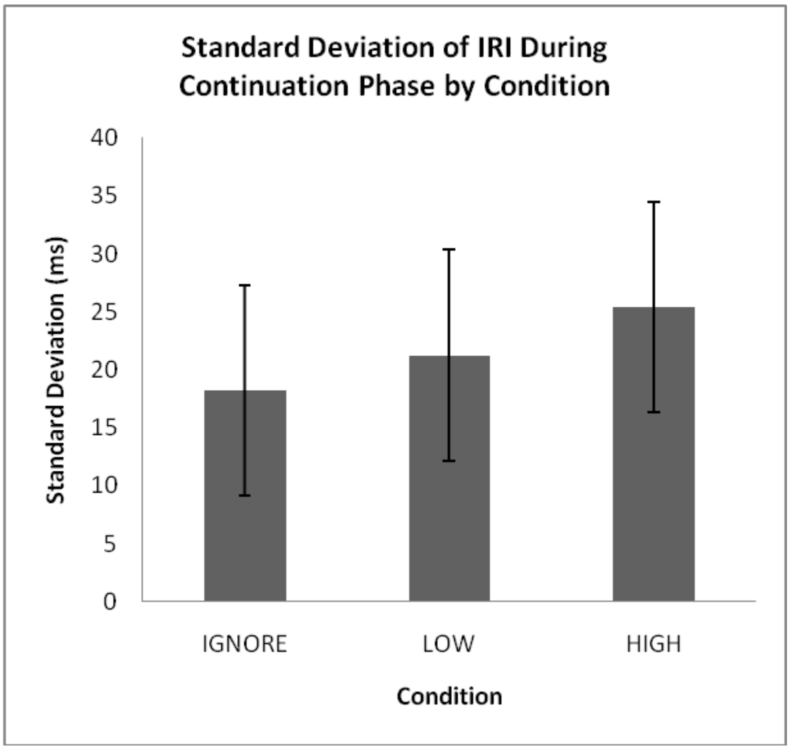


Fig 37 Illustrates a slight trend toward more variability of tapping in the continuation phase following trials with counting tasks. Error bars represent Standard deviation.

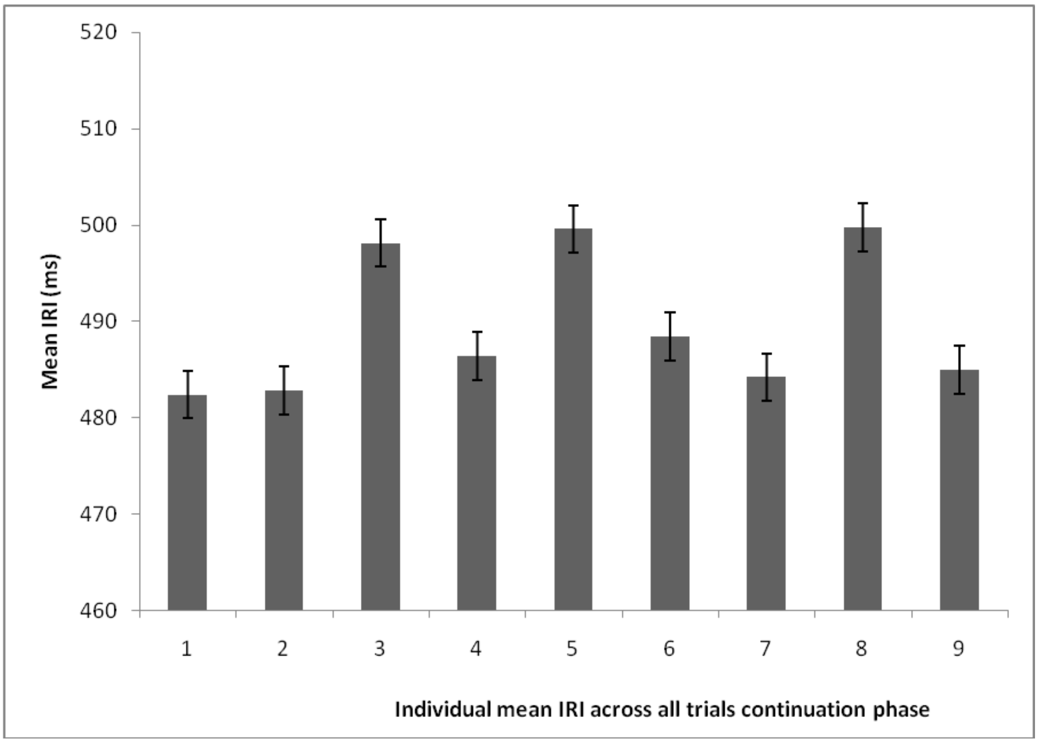


Fig 38. Illustrates the Mean IRI for each participants continuation phase. Error bars represent standard error.

EFFECT OF SECONDARY TASK CONDITION

Repeated measures ANOVA was run on the first 5 taps following the phase shift resulting in Condition (easy vs hard vs ignore) * Tap (5) with pairwise comparisons. The effect of condition revealed the secondary task had a dramatic effect on the pattern of recovery . With significant differences between the recovery pattern of the first 5 taps following the phaseshifts. the [$F(2, 7) = 330.4$, $p<.0.01$]. Pairwise comparison reveals a significant difference between all conditions p<0.01 between either the easy or hard task and the control, and p<0.05 between easy and hard conditions. (fig 33)

EFFECT OF SECONDARY TASK CONDITION AT ALPHA

The effect of condition at alpha confirmed that the effect of condition significantly influenced the recovery of the first tap following a perturbation (PCR) [$F(2, 7)$ =

17.40, *p*<.0.01] and pairwise comparisons confirmed this way not due only to the slow ignore condition recovery but also between easy and hard conditions (p=0.03).

FREE TAP COMPARISON

There was a not a significant difference in the Mean IRI of participants freetap before (M=563.8, SD=114.9) and after (M=558.8, SD=83.8) experimental conditions; t(8)=0.2, p = 0.8 see fig 32. This indicates that participants had not become entrained by the experimental conditions

CONTINUATION DATA

The mean IRI of the continuation data for all musicians was 489.6 which was only slightly more than 10ms away from the target pacing stimuli. Standard deviation (fig 37) grouped by condition and Mean IRI grouped by participant (fig 38) show how well the musicians maintained the target ISI, with all individual mean totals being <20ms from the target ISI.

5.4 **DISCUSSION**:

The effect of condition revealed the secondary task had a dramatic effect on the pattern of recovery which adds further support to the previous finding that attention when manipulated by different demands plays a greater role in even the most automatic aspects of movement timing. As predicted the easy-calculation condition resulted in less interference to the recovery, than the hard-calculation conditions, which significantly slowed the recovery. However the ignore condition, which was found to be the least demanding task for non-musicians, seemed to result in the biggest interference for these musicians. As musicians often illustrate much smaller NMA than non musicians, we might have expected much better performance than nonmusicians for such a low demanding task. There is nothing in the literature to lead this us to expect this result, in fact musicians tend to show lower variability, smaller asynchronies and greater perceptual sensitivities (Repp 2010). While Repp was surprised to find in his 2010 paper, even more sensitive and immediate responses to phase-shifts and perturbations from musicians who had not conducted his research before I can only posit that the simplicity of the task leant to more sensitivity and reactivity to their own ideation given nothing of any external difficulty.

On the basis of the individual cumulative errors (Fig 35) a group of 4 participants were identified as being good at mental arithmetic as demonstrated by accumulating less trial errors than the mean number of errors (16.44) for the total group at the easy maths task. This division was used to compare average phase recovery of the two groups to look for any additional bidirectionality beyond the number of errors by condition (Fig 34)

Having established a role for attention in synchronisation and error correction an important development would be to dissociate any contribution that period corrections may be making to add or minimise phase correction responses (Repp 2002b; Repp & Keller 2004, 2008). The addition of a tempo change would enable a separation of period and phase correction processes and any differential effects of secondary task conditions on these processes accordingly.

Size of Perturbation

According to Repp (2002b), when perturbations larger than10% of the sequence interonset interval (IOI) are introduced the function relating the average PCR to perturbation magnitude begins to exhibit nonlinearities. As 15% was used, some increase in variance could be because of the inherent non-linearities. This might explain some of the intermediate dual task condition variability in PCR response, but it is unlikely to explain the clear difference between the maximal PCR (ignore condition) and minimal PCR (hardest dual task condition).

Period of Secondary Task

The presentation rate of the secondary task was both fixed and unsynchronised with the metronome onsets. It is possible this stimulus onset could have provided a competing tempo to entrain to which increased both asynchrony and variability. This was not expected as the period of secondary task stimulus onsets was 3.75s which is much larger than distracter periods shown to have effects (e.g. Woodrow 1932) estimated what he called the “vanishing point of the capacity for synchronization” at about 3.4s). Furthermore, as it was a visual stimulus this tends to be less distracting than tones to the extent that even when instructed to tap to flashes rather than tones, the tones tend to drive the synchronisation (Repp & Penel 2002). Repp & Penel (2002) also found auditory attractor effects began to wear off after128ms. Lastly, as the free tap following the experimental conditions was not significantly different from the free tap before, this casts doubt on the notion of entrainment, but does not rule out distraction.

Despite the massively improved acuracy of continuation tapping from this group of musicians, all mean IRI were shorter than the pacing signal. One factor that could lead to shortening and to increasing variability in continuation tapping is any systematic drift after the metronome is switched off. The increasing time elapsing without the reinforcement or feedback of the metronome pacing signal could be one factor that increases the chance of drift or increases the reliance on memory (retrospective) memory of the reproduction standard. These questions are explicitly investigated in the next Chapter**.**

CHAPTER 6:

GAP TAP -The Art of Motor-Synchronisation Maintenance

6.1 ABSTRACT

Resuming rhythmic activity after a pause results in a drift toward shorter inter-response intervals, which has been identified with memory decay. To investigate underlying memory process in motor timing we investigated the effect of both short and long pauses. When gaps of either 14 or 56 s were introduced to synchronisation and continuation tapping, two classes of behaviour were identified. Firstly, the introduction of the gap reduced the speeding up that was associated with initiating continuation tapping. Secondly, the introduction of the gap increased the amount of drift away from the target interval. Taken together these findings are difficult to explain with traditional models of timing performance that rely on the dependence between mean interval and variance. The findings are discussed with reference to memory models and time perception models in addition to models of sensory motor synchronisation.

6.2 **INTRODUCTION**

Adept movement often amounts to achieving coincidence between self-initiated actions and perceived regularities in the environment. For a child catching a ball, a dancer keeping in step with music, or an athlete jumping hurdles, the synchronization of perception and action can be explained with reference to precise timing control drawing on a common mechanism (a central timekeeper) to mediate between perception and action initiation. Alternatively, timing control might be understood as an emergent property deriving from the inherent dynamics of the task and different internal processes each with their own durational specificities or modal constraints (Jones 1989; Kelso 1995). A potential difficulty in assuming that timing emerges from dynamics is how to account for timing when actions are temporarily inhibited. However, if movements following such a “silent” phase are considered to be internally represented by a motor image (Todd, O'Boyle et al. 1999), it might be assumed that timings ‘emerge’ from a motor image that mimics the biological and physical constraints of the musculoskeletal system when moving.

Strong evidence in favour of the use of a internal timekeeper by the central nervous system has been provided by simple timing tasks, such as finger tapping in synchrony with the regular beat from a metronome. Such research has reliably shown that a stable phase-relation between stimulus (metronome) and response (tap) can be established relatively quickly within 3-5 taps (Fraisse 1966). The timing of the produced tap is characteristically found to be slightly ahead (negative asynchrony) of the stimulus metronome beat (Dunlap 1910; Woodrow 1932).

Negative asynchrony and the ability to continue tapping at a similar rate when the metronome is switched off are suggestive of internal time-keeping mechanisms and provide strong contrast to the positive asynchrony (lag) one might expect from simple reaction-time responses to regular external stimuli.

Further support for the assumption of an internal clock follows from the success of the Wing-Kristofferson model (WK model) (Wing 1973). This model can account for the negative lag-1 correlation in continuation tapping by partitioning the variance into two parts; a central and more peripheral source of variability. Under this model, short term fluctuations around the mean of the produced intervals are attributed to peripheral noise associated with motor implementation. Whereas a second source of variability is related to the length of the interval to be timed and is independently attributed to central (clock) timing processes. The independence of these two sources of variance implies that producing longer intervals increases the variability of the central timing processes but not the variability of the peripheral motor implementation. Indeed when investigating tapping behaviour at a range of different tempo's between 290ms and 540ms, the decomposed variance of the central timing processes were found to increase linearly with the mean target interval whereas the peripheral motor delay variance were found to be relatively constant in accord with the Wing-Kristofferson (WK) model predictions (Wing 1980).

Notwithstanding the success of the WK model, the assumption that a unitary 'internal clock' underpins movement timing control is perhaps overly simple. For example, different forms of internal clocks or pacemakers have been proposed

(Gibbon 1984; Treisman 1990; Wearden 1995) and the outputs of these different internal clocks might interact in various ways with other processes such as sensory feedback, memory and decision mechanisms. A possible role for memory mechanisms in timing behaviour is suggested by the presence of drift in the continuation phase away from the desired tempo (Gibbon 1984; Staddon 1999; Delignieres, Lemoine et al. 2004) and erratic adjustments for the first few taps in the immediate transition from synchronisation to continuation (Drewing 2003). Although both of these phenomena are widely recognised, they have often been considered more as a practical problem for analysis rather than being of theoretical interest in their own right. Thus, to obtain stationary time series data (no change in moments - mean, variance etc - with time, which is a requirement of the WK model), it is common practice to remove the first few taps of continuation tapping behaviour (Daffertshofer 1988; Flach 2005; Vardy, Daffertshofer et al. 2008) and to use short continuation time-series data to minimise the chance of drift away from the desired tempo in the continuation phase. Another approach to the problem of drift during continuation tapping has been to detrend the data, leaving a stationary sequence which can once again be analysed in terms of the WK model (Vorberg and Wing 1996). Collier (Collier 2004) extended the WK model by including a drift component in the decomposition of variance independent of and in addition to the drift-free timekeeper variance.

In an analysis of drift during intentional slowing down during tapping, (Vardy, Daffertshofer et al. 2008) showed the WK model accounts for the structure of variability in the interresponse intervals after the drift component was extracted.

These methodological approaches to treating drift in time-series data have tended to bypass the interesting question of whether drift reflects the operation of memory mechanisms in timing. For example, if memory degradation was a contributing factor we might expect that drift would show up in extended continuation tapping as a consequence of the increased absolute duration from the original metronome pacing signal. This would be expected if memory for movement intervals were treated akin to other serial order memory data investigated by (Brown 2001). Brown et al found costs in a wide range of serial order memory data, including the effects of item lag and separation in judgments of relative and absolute recency, probed serial recall data, and grouping effects at various temporal resolutions. If the memory of a tapped interval suffers the same interference over temporal gaps as other serial order phenomena we might place limits on the time that temporal representations can be maintained without exhibiting drift.

An interesting approach to study memory mechanisms in timing is to introduce a temporal gap with a pause in tapping between synchronise and continue phases. (Jantzen 2007) used such periods of movement cessation while comparing brain activation during synchronisation and syncopation tapping. On finding that activation during continuation reflected the context during the initial synchronise vs syncopate phase, they sought to demonstrate a reduction in this contrast with longer gaps. However, no effect of gap length in the 3 - 9 s range was found, indicating a degree of permanency in the context effect – and hence robustness of the associated memory set up in the initial phase. The authors also noted with interest that the cessation and reestablishment of motor activity did not disrupt the context dependent activation.

The goal of the present study was to explore the effect of different length delays (cessation of tapping) in rhythmic movement on behavioural measures of timing performance after the gap in order to probe further the role of memory in sensorimotor synchronization. By extending the durations and methods used in the previous study (Jantzen 2007), we expected to find more variability in tapping after a longer pause. We also wanted to explore any interaction between the length of the IRI and the length of the pause to contrast the effect of event based or duration based factors which might mitigate or exaggerate the role of memory in the timing of movements once reinitiated.

6.3. **METHOD**

Participants and Apparatus

9 right handed participants, mean age 26 yrs, gave written informed consent to take part. The behavioral paradigm was implemented via Matlab. Mattap software (Elliott, Welchman et al. 2009) was used to initiate metronome sequences and record tapping responses via Matlab and a National Instruments 6229 DAQ Force transducers were used to receive tapping responses with temporal resolution <1 ms.

Experimental Setup and Behavioural paradigm

Participants were seated comfortably in a chair in front of the computer screen. Their dominant forearm was supported by a cushion on the table top allowing a comfortable tapping motion onto a force-transducer which was used as response manipulandum. The auditory metronome was delivered by an amplified loudspeaker. Both the auditory stimulus presentation and the tap onsets were recorded using a National Instruments data acquisition card (DAQ) controlled by MATLAB. The square waveform sent to the loudspeaker was fed back to the DAQ, enabling precise measurement of timing differences between the metronome pulse and the corresponding participant response. After reading instructions, participants were given a chance to familiarize themselves with the setup and tapping motion before commencing a self-paced tapping trial for 30 (s). After this trial, participants were tested in a synchronise and continuation paradigm with a block design. Participants synchronised to the auditory metronome for 30 s followed by 30 s continuation tapping subsequent to either: Pause of 14 s, 56 s or no pause in their tapping for 86 s. The pace of the metronome inter-stimulus interval was 400, 700, or 1000ms respectively with a fixed tone duration of 100ms.

Analysis:

Descriptives were calculated on individual trials then averaged within condition and across participants. Examining the autocovariance values, a number of approaches were followed from the literature in how to treat positive values, including using positive lag1 autocovariance values, or changing the positive lag1 values to zero, as results were similar for all treatments only one is reported below. Data from the continuation stage were assessed in terms of interresponse interval mean, variance, slope of the variance vs mean and the contribution of clock and motor variance (lag1 autocovariance) according to the WK model. Results were assessed in gap length (none, short or long) by tempo (400, 700 or 1000 ms) ANOVAs for each descriptive variable.

6.4 **RESULTS**

Our results show that participants are capable of maintaining the appropriate tempo even after a long 56 s gap between synchronization and continuation. This is shown by the mean IRI data (Figure 39a) in which there is only a main effect of tempo [$F(2, 7) = 330.4$, $p<.01$]. This tells us that Gap length did not differentially affect the IRI regardless of the tempo we asked them to produce.

Similarly, Gap length showed little effect upon the other standard dependent variables of the W-K model, including the clock variance estimate [$F(2,7) = 10.3$, $p<.01$], variance [$F(2,7) = 9.5$, $p<.01$], and the Lag1 Autocovariance [$F(2,7) = 7.8$, $p<.01$], (Figure 39b-d). Using these relatively standard analyses, these data suggest that, overall, participants were quite capable of performing the continuation tapping even after a long Gap of 56 s.

However, visual inspection of the series of taps in the continuation phase for each condition reveals a tendency to drift towards faster responses. To quantify this effect we calculated the slope of the best linear fit of the sequential taps in each continuation phase (Figure 40). The ANOVA for this slope data revealed that there is a significant main effect of Gap condition [$F(2, 7) = 14.1$, $p<.01$], and a significant interaction between Gap and tempo [$F(2, 7) = 4.8$, $p<.05$]. The main effect of Gap is driven by a steady increase in the negative drift as the gap is lengthened (Figure 41a). That is, the least negative slope is in the no Gap condition, followed by the 14 s

Gap, and finally the steepest slope in the 56 s Gap condition. Post-hoc comparisons of the interaction reveal that this effect is mostly driven by the 1000 ms tempo. At this tempo, the 56 s gap produced a slope that was more negative than the 14 s Gap, M_{diff}= -1.3,$t(14)$ = -2.96, p = .05, and no Gap, M_{diff}= -1.7,$t(14)$ = -3.63, p<.05.

These findings raise the question of whether drift is related simply to the absolute passage of time, or to the fact that they are not tapping in the 56 s Gap. In order to explore this question further, we conducted an analysis on the slope of the linear fit of the sequential taps on the time-matched series of taps from the no Gap condition instead of the entire series of taps. For the 14 s Gap (Figure 41b) no difference between the slope in this ANOVA. That is, there was no main effect of tempo (p > 0.1), or Gap (p> 0.5), and no interaction (p> 0.9). However, for the 56 s Gap (Figure 41c) the main effect of Gap in the slope measure is still marginally significant [$F(2,7)$ = 4.8, p = .06], and in the same direction (i.e., the slope of the taps in the no gap condition is less negative than the long gap condition). This suggests that even when taps from the same time-point of the no gap condition are expected, participants drift at a faster rate with a long Gap, than they do when they are tapping the whole time. A final interesting finding from visual inspection of the series of taps was that the initial speeding of the first few taps in the continuation phase that commonly characterizes the initial transition from synchronization to continuation tapping seems to be absent when a 14 s, or 56 s Gap was introduced (Figure 42). To quantify this observation we calculated the best linear fit of the first 5 taps from each continuation phase. The ANOVA of this “initial slope” analysis reveals a significant main effect of Gap condition [$F(2, 7) = 13.1$, $p<.0.01$]. This main effect (Figure 42) confirms that the initial speeding up was largest when there was no gap between synchronization and continuation tapping, and was reduced as the gap was lengthened (i.e., less speeding up with a 14 s gap, and no speeding up with a 56 s gap)

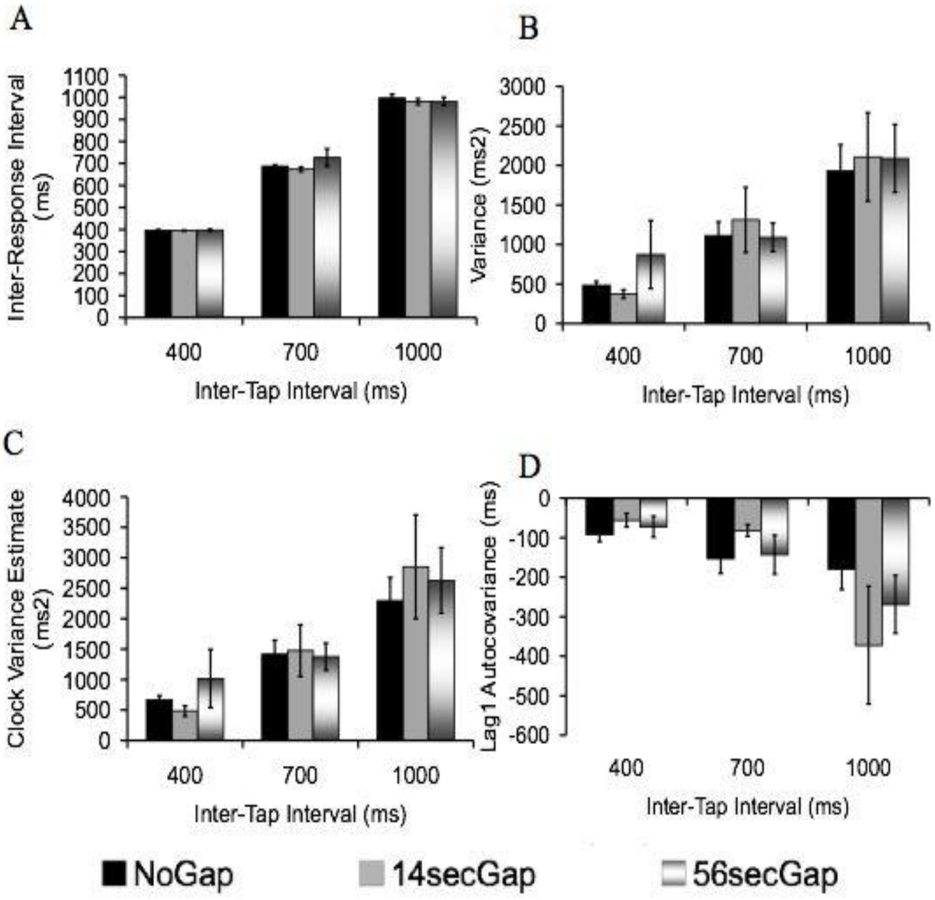
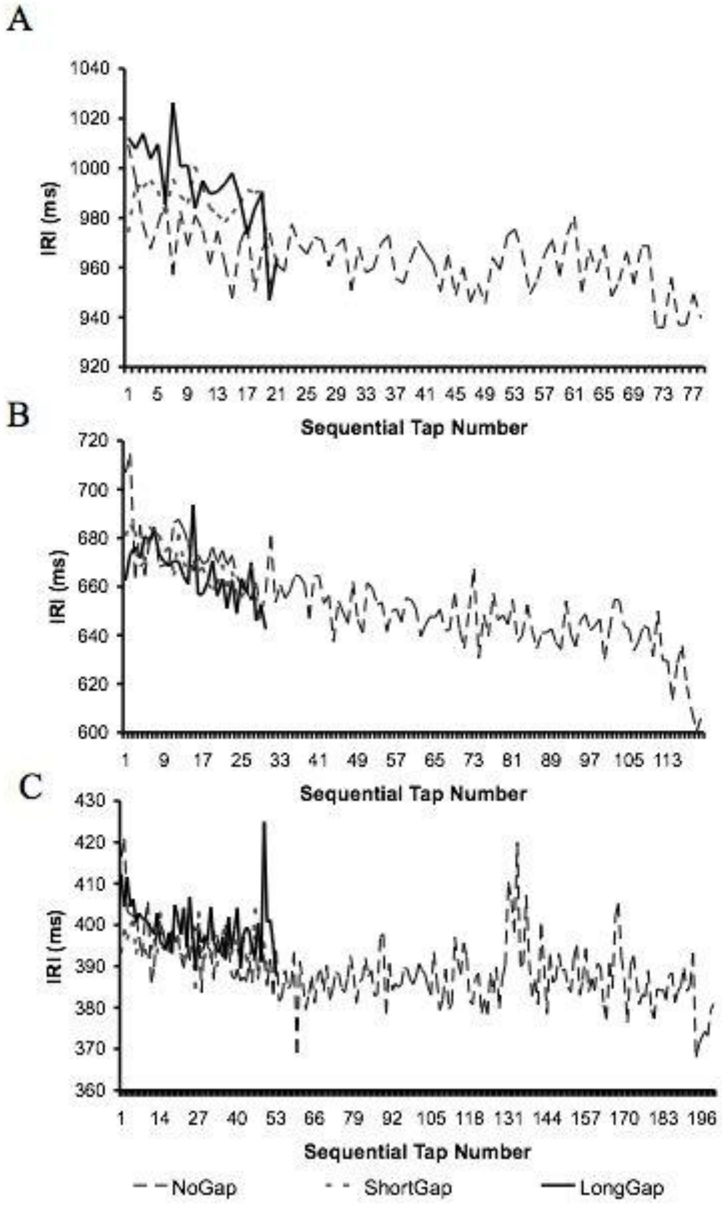
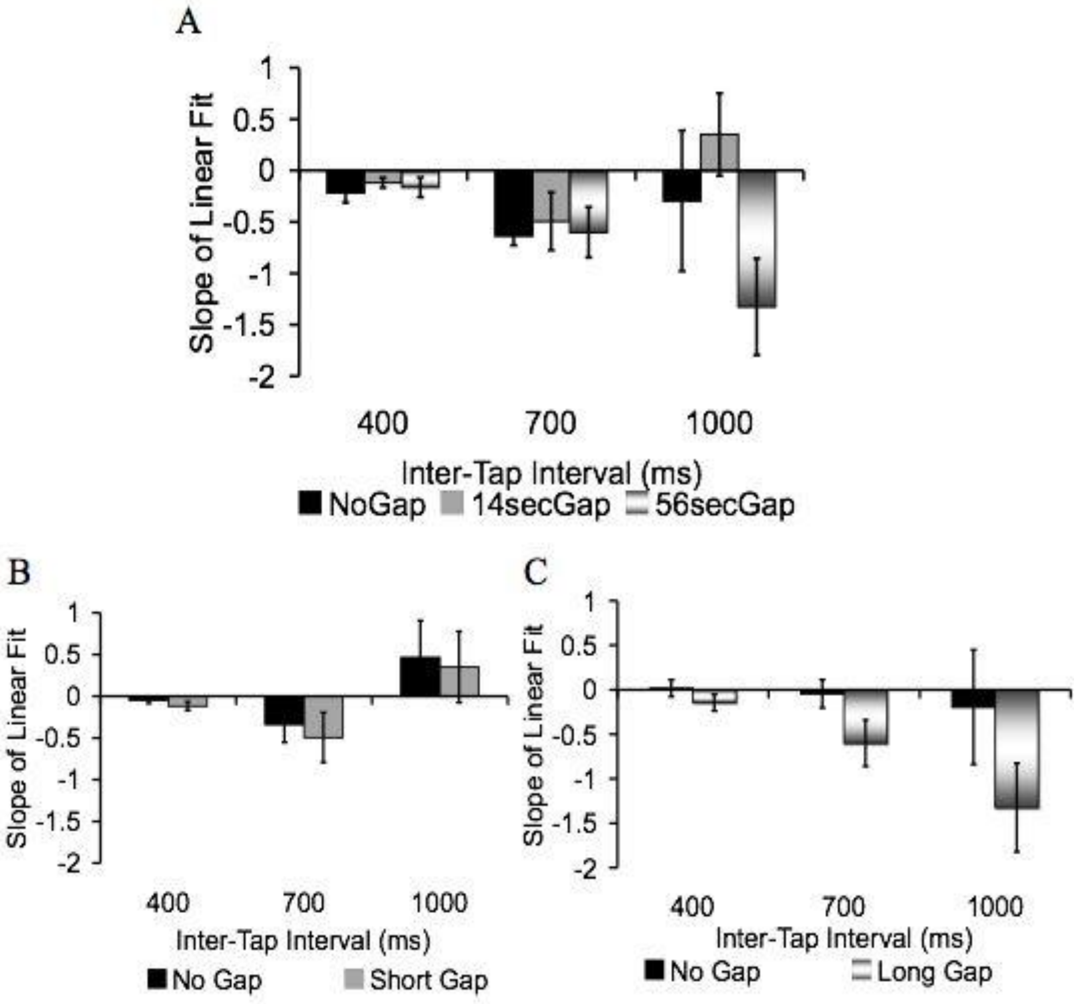


Figure 39. Illustrating the standard WK dependent variables: mean IRI (a), Clock Variance (b) Variance of the IRI (c), and Lag1 Auto-covariance (d) for each Gap condition, at each tempo. Note that for each measure there are significant effects of tempo, but no significant differences between the Gap conditions. Error bars represent standard error of the mean.


A
1040
1020
1000
980
960
940
920
IRI (ms)
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77
Sequential Tap Number
B
720
700
680
660
640
620
600
IRI (ms)
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113
Sequential Tap Number
C
430
420
410
400
390
380
370
360
IRI (ms)
1 14 27 40 53 66 79 92 105 118 131 144 157 170 183 196
Sequential Tap Number
NoGap
ShortGap
LongGap


A
Slope of Linear Fit
1
0.5
0
-0.5
-1
-1.5
-2
400
700
1000
Inter-Tap Interval (ms)
NoGap
14secGap
56secGap
B
Slope of Linear Fit
1
0.5
0
-0.5
-1
-1.5
-2
400
700
1000
Inter-Tap Interval (ms)
No Gap
Short Gap
C
Slope of Linear Fit
1
0.5
0
-0.5
-1
-1.5
-2
400
700
1000
Inter-Tap Interval (ms)
No Gap
Long Gap

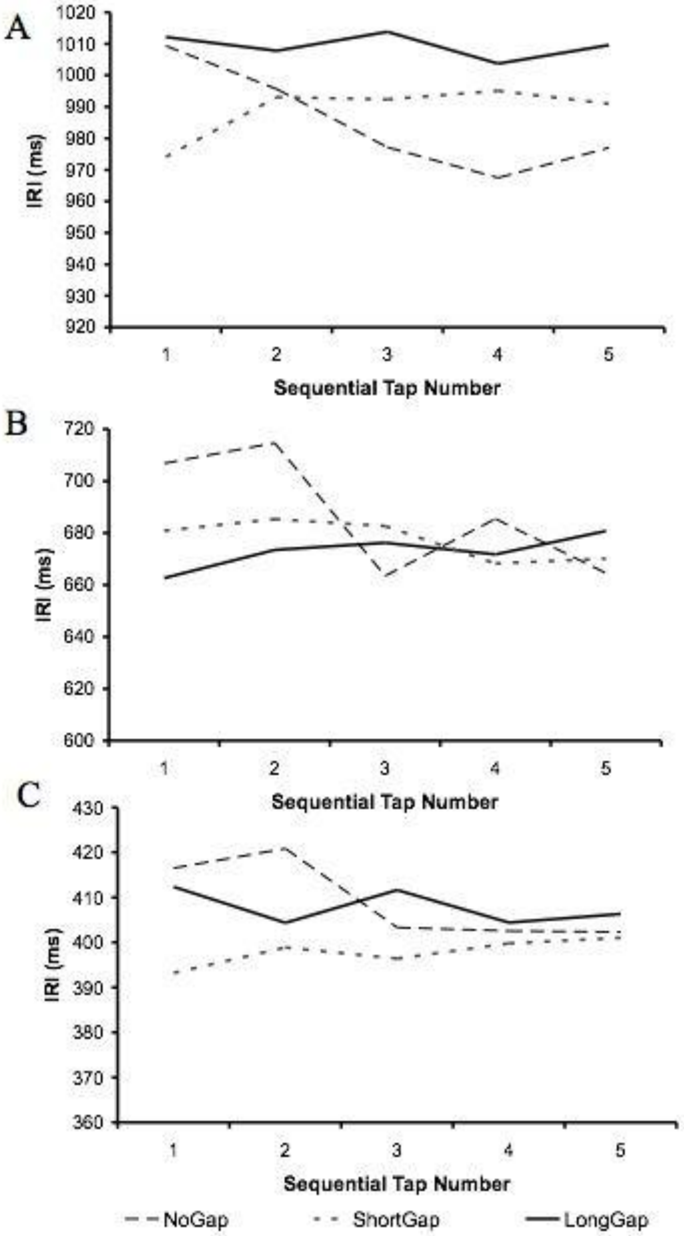


Figure 42. Graph of the first five taps from each series in sequential order from each Gap condition for the 1000 ms inter-tap interval (panel A), the 700 ms inter-tap interval (panel B), and 400 ms inter-tap interval (panel C). This graph demonstrates the drift away from the intended inter-tap interval during the continuation phase. The values are averaged across participants for each sequential tap.

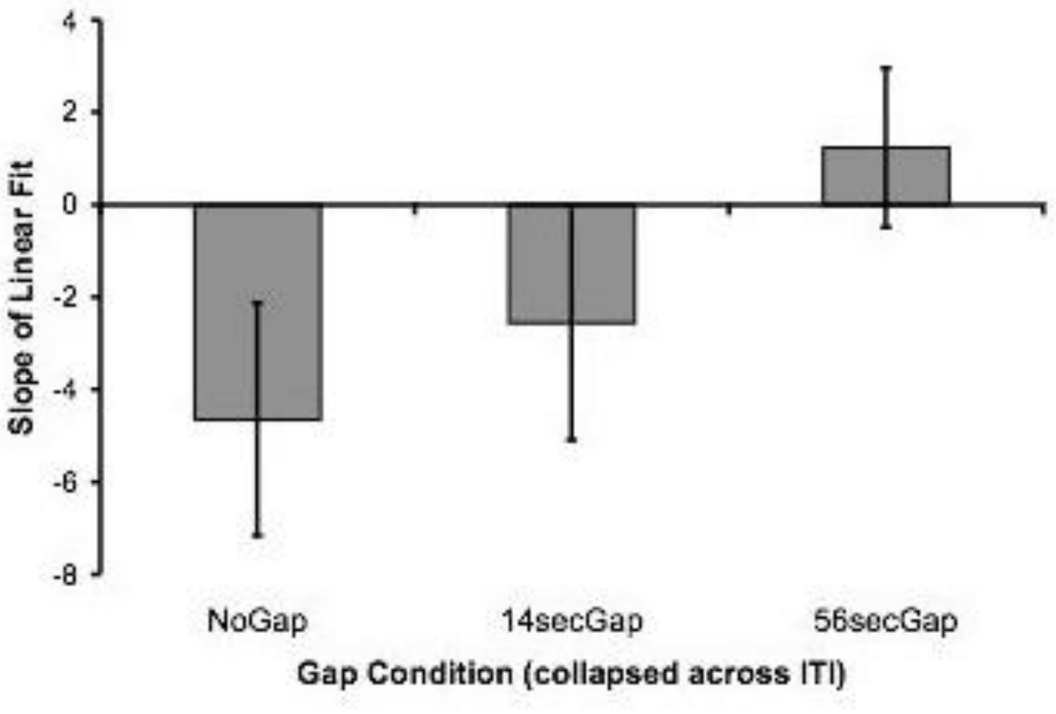


Figure 43. Illustrating the slope of the best linear fit of the first five taps from each Gap condition, collapsed across inter-tap interval (ITI). The values represent the slope averaged across each trial for each participant, and then averaged across participants. The error bars are standard error of the mean.

6.5 **DISCUSSION**

The focus of this Chapter has been the effect of suspending rhythmic movement on timing of continuation tapping to probe the role of memory for sensorimotor synchronization. By extending the pause durations used in previous work (Jantzen 2007), we expected to find more variability in tapping after a longer pause in the rhythmic tapping. We also wanted to determine whether there was an interaction between the length of the target interval and the length of the pause to contrast the effect of event based or duration based factors which influence memory for timing of movements after the pause.

In keeping with (Jantzen 2007), when the detrended data were analysed using traditional measures of timing variability, the results show that participants were able to perform the continuation task successfully whether tapping with or without gaps between synchronization and continuation phases. The increase in variability found at slower tempos is in line with early research findings (Wing 1980). On face value these results indicate that the representation of tempo can be maintained, stored or recalled beyond the 9 s found by Jantzen (Jantzen 2007) up to 56 s without feedback. As 56s without activity would cause any emergent timing property to be lost, this finding is suggestive of the need for an additional form of memory or explicit temporal representation to achieve this level of performance.

Nevertheless the mean continuation IRI was found to be shorter than the target interval set in the synchronization phase for all conditions. Although no significant differences were found between conditions based on gap length on mean IRI, closer inspection of the data revealed two different contributing factors to this shorter mean IRI. The first factor was a tendency to shorten the IRI during the initiation of continuation phase in no-gap conditions. The second factor was the presence of increasing drift in gap conditions toward shorter IRI.

The finding that participants tap slightly faster during the continuation phase has been reported by researchers incidentally when investigating other issues in timing (Repp 2006; Grondin 2009) and more directly in regard to a tendency toward returning to a preferred or spontaneous tempo (Fraisse 1980; McAuley 2006). An alternative explanation for shorter IRIs in the continuation phase was offered by Vorberg & Wing (Vorberg 1996). They proposed that shorter IRI's could minimise both the variability of the timekeeper intervals and the variabilities of asynchronies if compensated with error correction mechanisms during the synchronization phase. However, during the continuation phase, the shorter interval would be revealed in the shorter interresponse intervals, now without the possibility asynchrony-based error correction.

If we accept the explanation that a reduction in the represented interval is a means to reduce the variability of asynchrony during synchronization phase, we can explain an overall shorter mean IRI in the continuation phase. However this is insufficient to explain the two separate effects observed in the present study, namely the absence of acceleration at initiation of continuation following a long gap and increasing drift with long gap conditions. We now propose an account of the maintenance of timing during synchronization and then to those changes enforced by the gap to consider how this might relate to the two findings.

During synchronisation a single parameter error correction mechanism that (automatically) adjusts the phase relation between stimuli and response without affecting the period of the internally represented interval has been proposed by (Vorberg 1996). Another possibility is that errors could be minimized by (explicitly) changing the period of the internally represented interval. Dual process models of error correction (Harry 1985; Mates 1994a; Repp 2001) suggest both phase and period error correction are possible during synchronization with an external stimulus. In addition to these forms of correction, the interresponse intervals could be influenced by the asynchrony between the feedback of metronome to tap; or tap to metronome or a mixture of the two (Harry 1985). Repp (Repp 2008) suggested that these phase resetting sources (explicit, event-based; and implicit, emergent tap-based) are in dynamic competition.

Repp (2008) suggests that emergent timing corresponds to a tendency to maintain repetitive motor activity like the ‘maintenance tendency’ of (Holst 1937,1939/1973). Repp suggests that maintenance tendency is strongly reduced after a pause or gap, which lowers the interference this has with more explicit discrete timing. Accordingly, the absence of immediate acceleration after a gap could be explained by the reduction of maintentance tendency that the gap affords. In contrast, acceleration may result in an additive fashion during a small temporal window when explicit internally-paced timing takes over from more automatic externally paced timing.

The fact that the acceleration at the initiation of continuation disappeared not with a change in IOI, but only after a long gap, indicates that it is not the number of tapping events that is critical to this reorganisation, but the temporal constraints of this reorganization from more automatic externally paced timing to explicit internally paced timing required in the continuation phase.

The tendency to drift faster (and increasingly so after gaps of movement cessation) is not explained by the models of sensorimotor synchronization maintenance described above. It is a challenge for internal clock models to explain why increasing length gaps might influence the rate of drift once tapping recommences at close to the correct ITI. Classical accounts of factors affecting clock rate such as arousal (Boltz 1994; Penton-Voak 1996; Burle 2001) suggest that clock rate when manipulated by stress-induced stimulation by light or noise frequencies can speed up the timing of movements. Thus an arousal account of the observed rate of drift would suggest that an effect of gap directly increases arousal leading to shorter productions due to an increased tick-rate of central timekeeper. Alternatively, a *relative-arousal* explanation would suggest that arousal was higher during early novel and engaging synchronization phase and then drops increasingly during the gap so that when tapping is reinitiated after the gap, the memory of the interval was quicker than whatever is currently performed at lower arousal levels leading to a speeding up to match the comparison. A more direct test of the effect of different length gaps on arousal levels would help to distinguish between these two contrasting possibilities. However as participants start close to the mean ITI and drift faster only after reinitiating tapping, arousal levels alone are insufficient to explain this data.

Information processing models that include clock-like components in conjunction with memory and comparator processes (Gibbon 1977; Gibbon 1984; Church 2003; Meck 2003) offer a chance to consider combinations of factors at a price of increased complexity. If we assume the memory for the interval is perfect (illustrated by very little effect of gap length on the mean IRI when initiating tapping after 56s), the increase in drift could then be due to errors in the comparison/decision component. When synchronizing to a metronome, this could equate to what (Block 1992) called *experienced duration*, a forward looking prospective production of regular movements (where attention play a greater role). However when continuing to tap after a gap, the assessment of current tapping in comparison with a remembered standard becomes a *remembered duration* (where memory and contextual factors play a greater role,(Block 1978; Block 1982; Block 1986; Block 1990; Block 1997; Block and Zakay 1997), in conjunction with an ongoing prospective task. Block following (James 1890) suggested different variables thus influence the retrospective and prospective aspects of the tasks. In retrospective judgments both positive and negative time-order effects have been noted. (Wearden 1993)obtain such evidence when asking people to judge the relative duration of two brief identical stimuli. The second (more recent) sound was judged to be longer than the first. They called this effect *subjective shortening* effect. It is unclear how a gap of 14 s compared to 56 s could influence the relative judgements of neighbouring intervals via *subjective shortening* to the extent that intervals approximately 400ms apart are seen to be more subjectively shorter than each other after 56 s than after 14 s. This would require an additional combination of memory trace decay or comparison with a standard that was increasingly distant from recency.

A temporal distance model of memory SIMPLE (Scale invariant memory perception and learning) is a model developed by (Brown 2001).The SIMPLE model assumes items are represented in terms of their position along a logarithmically transformed dimension of time elapsed since memory formation. Thus items arrayed along a logarithmically transformed temporal dimension become closer to one another as they recede into the past (compression). This would explain a subjective shortening in terms of distance from the original standard leading to a drift towards speeding to match the logarithmically compressed standard. However when the measures of drift after a 56s gap are compared with time matched portions of no-gap continuation conditions (fig 41c) the gap condition shows greater drift; therefore an explanation for this increased drift using a temporal distance model alone is not so simple!

Consistent with the results obtained it appears that Repp's distinction (Repp 2001) provides a useful starting point; whereby event-based resetting as a form of explicit or discrete timing is aided during the gap by removing the competing maintenance tendency of continuous motor activity and emergent timing. While this affords a smoother initiation of movement in the continuation phase of gap conditions compared to no-gap conditions, the experience of the gap leads to further consequences. One possible consequence of the experience of longer gaps of movement cessation is that greater attention can be drawn to the prospective production of movements once reinitiated which could inflate the comparison of recent intervals with those of a remembered or condensed (possibly logarithmically condensed) retrospective standard.

6.6. **CONCLUSION**

The introduction of gaps of movement cessation between the synchronise and continuation stages of tapping produces two novel types of behaviour. Firstly it removes a common acceleration found during the transition which we attribute to reduced *maintenance tendency*. Secondly it increases the rate of drift in IRI away from target ITI which we attribute to the effect of differently experienced duration during the gaps of movement cessation, and the consequent change in relations to contextual and cognitive processes that support timing abilities.

More specific targeting of the component cognitive processes assumed to be required at different stages of this paradigm will help to further elucidate the consequence of different durations of movement cessation; however it is clear from these early results that in terms of the art of motor synchronisation maintenance – we do mind the gap.

CHAPTER 7: CONCLUSION

THE COGNITIVE CONTEXT OF SENSORIMOTOR SYNCHRONISATION

7.1 CHAPTER SUMMARY

In Chapter 1 we saw that many temporal conceptions involve a framework of arguments and assumptions that shape the kinds of psychological knowledge that are produced by and through them, and further that the study of any particular temporal conception appears almost systematically beset with the problem of taking into account the role time has already played in constituting the very terms and standards within which such a study takes place.

Having explored some of the models used to predict movement variability and those designed to explain conditioning, perception, and time estimation, a clear role for attention memory and executive factors was contrasted with more automatic low level quantitative models of movement timing. This set the context for an important role being identified for attention and memory in many contexts that might also prove useful in motor context.

This thesis presented a series of studies investigating more precisely the role of executive control functions on the variability of repetitive production of movements. In the first study Chapter 2 we explored the cost of divided attention (single task vs counting backwards in threes) on the variability of repetitive finger tapping movements in 42 healthy participants. We used a 3-factor counterbalanced within-subjects design to explore the cost of divided attention in the interactions with 2 different movement types (index finger vs little finger) and 2 different intervals (400 vs 650ms). According to the Wing-Kristofferson (WK) timing model, motor variance is independent from the variance of central clock processes. Therefore we expected greater variability when participants tapped with the little finger compared to the index finger due to additional motor control variance. Whereas, we expected greater variability of tapping responses at the longer interval duration due to variability in central clock processes. Importantly, according to the (WK) model, we would expect no interactions of movement type with either interval duration or divided attention. In contrast we expect a strong interaction between divided attention and interval duration both due to variability of central clock processes.

Due to the independence of central timing processes and peripheral motor implementation processes assumed in the WK model, support was gleaned from both a significant interaction between factors acting on central timing processes (interval length and attention demanding task) and a lack of significant interaction on the factor targeted to influence peripheral motor processes (use of index finger or little finger). Therefore the results found offer strong support for the the logic of additive factors as introduced by Sternberg, and the independent sources of variability assumed in the WK two-level timing model. In line with the WK model we found a significant interaction with interval duration and divided attention and no interactions with movement. Further analysis revealed that the degree of prior musical experience heavily moderated the cost of divided attention on timing variability, particularly at longer intervals and with the more unusual movements.

A follow up study in Chapter 3 further explored the paradigm by varying the mode of the stimulus and responses to the secondary task. This enabled some further examination on the relative importance of structural vs capacity limits to attention as distinct from variability due to the mode of the secondary task and mode of response.

For example, we expected that the distraction of a regular auditory sound in the secondary task might result in greater interference with the continuation timing of responses than when the mode of the secondary task was visual (Kato and Konishi 2006; Repp 2006). We also expected that the secondary task stimulus might interfere more with any sub-vocal language mediating participants self-direction when presented in auditory mode rather than visual (Baddeley 2003). The finding that no main effects were found for the mode of the stimulus indicated that both the visual and auditory stimulus were treated in much the same way. However the significant interaction found between the response mode and the interval showed that slow speeds, speaking outloud significantly increased the variability suggests that speaking outloud shares some resource (structural or capacity) with timing processes.

Findings from these interactions were best explained by combining predictions of information processing models of variability that include both language, working memory, temporal accumulator and gate/switches which are influenced by the executive control of attention. whereby attention when drawn to the memory processes and information management of complex secondary tasks, attention is withdrawn from the switch to accumulators resulting in shorter time estimations/productions.

Chapter 4 introduced a perturbation paradigm which had previously been identified as a way to measure more automated rhythmic movement production and online control that was considered more insulated from executive functions. A dual task probed the assumption that higher level executive processes would not interfere in perturbation recovery. The main findings of this study were that an increase in asynchrony, an increase in variability and a slowing recovery from perturbations were found following conditions of increasing demands on attention. Having established a level of interference even in the most automatic process as identified in the literature, the importance of understanding the role of attention in motor timing was again emphasised.

A follow-up study in Chapter 5 using the perturbation paradigm was used with professional musicians to better understand the role of skill and musical training on both cognitive and motor sources of variability. Support was found for the lower variability of musicians in continuation tapping reported in the literature. Support was also found for the secondary task interference of attentional demand on recovery from perturbation even amongst this skilled group. Yet a finding of increased variability in the condition with the lowest external demand (the ignore condition) was a definite surprise. Despite their better accuracy, musicians also showed some speeding up in the continuation tapping similarly found non musicians suggestive of an underlying memory decay.

Chapter 6 introduced a novel paradigm for assessing the variability of memory processes and specifically any trend for memory to decay in rhythmic movement resulting in shorter IRI in continuation tapping. This was investigated by looking at the statistics of rythmic tapping following different length gaps between synchronisation and continuation tapping movements. Two classes of behaviour were identified which help to explain a general trend of shortened IRI in continuation tapping found in the literature and in all the experiments from Chapters 2-5. Firstly, the introduction of the gap reduced the speeding up that was associated with initiating continuation tapping which was attributed to a reduction in motor maintenance tendency. Secondly, the introduction of the gap increased the amount of drift away from the target interval which was attributed to memory processes.

7.2 DISCUSSION

We can I think return with better understanding to the themes introduced by Feynman in Chapter 1 . He described his surprise that physical activity did not seem to disrupt the timing of his subvocal counting. Like Sergent (Sergent 1993), our first experiment showed that simple quick movements did not interact with the secondary task of counting backwards but simply added a stable amount of motor variance whether the movement was fast or slow. This lack of interaction we now understand to be due to the independence of more central and peripheral sources of variability as predicted by the WK model. Feyman also found that nothing interfered with his count more than speaking aloud. In Chapter 3 our follow-up experiment would suggest this was due to memory processes drawing executive attention away from accumulation of timing information. Our attempt to introduce a combination of Church and Baddeley information processing model and working memory allowed us to consider the role of language and working memory components not traditionally modelled in SMS as necessarily interacting and limiting the shared capacity of attention to timing.

In returning these findings to the broader themes still unresolved in SMS research, namely the role executive functions like attention, and memory may contribute to the variability of central timekeeping and sensorimotor synchronisation; we find support for both Sergent (1993) and Miyake (2004, 2007) who seemed to previously have conflicting or contrary findings. Like Sergent we found that at ISI less than 1500ms a secondary task could interfere with central timekeeping variability more than motor variability (Chapter 2&3). We found like Miyake that capacity limitations of attention rather than simply structural limitations were needed to understand and predict this interference.

In contrast to Repp (2001, 2003, 2005) who found a marked distinction between more automatic fast phase correction and more deliberate slow period correction, we found that attention and memory processes when pushed more through a demanding secondary task revealed a cost in variability of even the most automatic recovery patterns. This cost was visible even using a sensitive index of phaseshift recovery previously considered immune and distinct from interference of such factors.

Lastly, the novel paradigm introduced in Chapter 6 offers an important methodological contribution to SMS research in uncovering two contributory factors that could explain a common finding that IRI tend to shorten in continuation phase tapping. In the Sergent 1993 study, as with the majority of SMS research, it is common practice to remove from analysis the speeding taps in the transition from synchronisation to continuation tapping. Similarly any drift in the Time series is often corrected (detrended) before analysis. The fact that the pattern of drift could itself be a sensitive index to different length of timing intervals beyond those looked at by Jantzen (2007) highlights the importance of both the time-scale used, the methods of assessment and the assumptions inherent in any temporal research.

7.3 DIRECTIONS FOR FUTURE RESEARCH

The findings of the 5 experiments presented here offer a strong case for broadening the context of sensorimotor synchronisation to include more executive processes such as memory and attention. Each of the paradigms used provided a different avenue for exploring interacting factors. Nevertheless the paradigms were not without limitations. Despite the improvements in control of the secondary task rate introduced in Chapter 3, it shared with Chapter 2 a use of a visual pacing signal (rather than auditory or haptic pacing signal for example). An interesting development would be to systematically compare the sorts of interference patterns of the secondary task and the response mode with the mode of the pacing signal. This would allow a direct assessment of the assumption of Jancke et al (2000) who suggest the brain structures used when tapping in the context of an auditory pacing signal include networks shared with motor control, whereas when tapping in the context of a visual pacing signal include networks shared with imagination. If they are correct we may expect differentially more capacity limitations and interference to be found from responses and secondary tasks that utilise the same networks as the modes of the pacing signal.

Another development follows from the interesting implication of using information processing models such as those integrated with timing models in Chapter 3. These information processing models such as Baddeley (2000) show it may be possible to verbalise calculations required in a secondary task when presented visually, or similarly to visualise secondary task calculations when presented auditory. Separating individuals by preference or ability in verbal or visual calculations or controlling for modal strategy may also help understand some of the variability in secondary task interference during movement timing tasks.

Chapters 4 and 5 indicated that secondary task calculations could interfere with phaseshift recovery from perturbation. Chapter 5 also indicated that an ignore condition could also interfere with recovery patterns for professional musicians to a surprising degree. It is possible that frustration and lack of stimulation may be more difficult to ignore for professional musicians when conducting simple rhythmic movements than for non musicians. The implication is that the executive control of attention, whether attention is drawn from either sources of internal frustration or external sources of task difficulty, can both disturb movement timing by drawing resources away from timing. Individual differences in the ability to manage this executive control of attention, and any anxiety or arousal that might be induced when executive control is required or pressured would be an interesting avenue to explore. For example, if an individual were to find either meditation or exercise more beneficial for managing executive control, we might expect less interference in a secondary task following a relaxation break than an unrelaxing break. Such a line of enquiry might help to distinguish the more high level explanations of disruption to movement timing from more classical accounts of arousal and anxiety affecting clock rate (Boltz 1994; Penton-Voak 1996; Burle 2001) which suggest that it is more directly the rate of an internal clock that changes when manipulated by stress-induced stimulation.

A natural development of the final paradigm would be to explore the cost of a secondary task conducted during the different length gaps between synchronisation and continuation tapping. For example if during the gap, which we suggest requires the use of working memory to hold the timing information before continuation, participants were required to listen to distracting timing information presented in mixed or complementary modes we might expect that participants could be induced to shorten or lengthen their continuation tapping toward the direction of the distracting stimuli. We might expect this distraction would bias more if the mode was auditory according to Repp & Penel (2002). It may induce more bias if it were the same mode as the pacing signal according to Jantzen (2007). It may also represent more or less difficulty due to differences in the individual strategy of executive control management which could be enhanced or reduced by practice and breaks. In this way the component processes and associated variability of memory, attention and the timing of motor actions could be further teased out.

Finally, while variability and reliability are the complimentary concepts required to understand our subjective experience of timings and our timing behaviour, they are also the complimentary concepts required to assess them. As our understanding grows, it is in the interactions of these different sources of variability that I think our more reliable findings about the broader cognitive context of movement timing start to emerge.

At the start of the thesis there was clear sympathy for the views expressed by Nicols (Nichols 1891) in attempting to review the timing research of the day:

> "Casting an eye backward we can be struck by the wide variety of explanations offered for the time-mystery. Time has been called an act of mind, or reason, of perception, of intuition, of sense, or memory, of will, of all possible compounds and compositions to be made up of them. It has been deemed a General Sense accompanying all mental content in a manner similar to that conceived of pain and pleasure. It has been assigned a separate, special, disparate sense, to nigh a dozen kinds of 'feeling', some familiar, some strange invented for the difficulty. It has been explained by 'relations', by 'earmarks', by 'signs', by 'remnants', by 'struggles', and by 'strifes', by 'luminous trains', by 'blocks of specious-present', by 'apperception'. It has been declared a priori, innate, intuitive, empirical, mechanical. It has been deduced from within and without, from heaven and from earth, and from several things difficult to imagine as either."

However at the end of the thesis I feel more support for the quote of (Fisher 1926)

> "No aphorism is more frequently repeated…than that we must ask Nature…ideally, one question at a time. The writer is convinced that this view is wholly mistaken. Nature, he suggests, will best respond to a logical and carefully thought out questionnaire; indeed, if we ask her a single question, she will often refuse to answer until some other topic has been discussed".

APPENDIX

Assessing Temporal parameters of stimulus presentation

LV-App, Mattlab & Flash Presentation Data

The LV-App, written in labview was an application for both stimulus presentation and recording of IRI (key taps or mouse clicks). The temporal accuracy of the intervals were contingent on the polling rate of the usb mouse and the amount of available RAM on the machine it was run on, plus any additional operating system delays. As these sources of variability are considered <5ms and the range of timings of interest were in the hundreds of milliseconds, this was not considered a problem. However when running the application on a different system (with Windows Vista operating system and associated antivirus applications competing for RAM) some unusual results during pilot studies raised the need for calibration. All calibration and subsequent testing was conducted on a computers running windows XP with minimal background tasks.

To calibrate, a Force Sensitive Resistor pad (Model FSR406) http://www.steadlands.com/data/interlink/fsr406.pdf was placed over the key and connected to National instruments 6229 in a similar set up to the Force transducer used in Chapters 4a and 4b. Using Mattap software with the same ISI as the lV-APP program, a tapping could be simultaneously recorded in mattap and the LV-app and their recorded IRI could be compared. Over comparable lengths of time to experimental conditions (60-80 taps for a synchronise and continue trial, difference between the two programs was <1ms for runs at 200ms, 400ms 800ms IOI. variability.

Secondary Task Visual Stimulus presentation from both matlab and LV-APP utilised executable flash files, written using Macromedia Flash. The timing of stimulus onsets in flash files is restricted by their use of frames. The smallest frame is 33 ms. Scripting onsets by the frame rates available in Flash is utterly reliant on RAM buffer for the accuracy of their display.

To test the variability of the flash file script and stimulus onsets, a black square was inserted in alternate frames of the flash movie (playing at 60 fps) and a photoreceptor attached to the analogue input of the 6229 allowed the intervals of the alternating signal to be processed by MATTAP to produced a sequence of IRI to compare. Variability of the frame rate for all experimental length stimulus (less than 2 mins) was <1ms from expected. However when trying an extended run for comparison of up to 10 minutes, huge variability crept in that seemed to be related to buffer underun. This resulted in frozen frames and variability >100ms compared to data collected on the 6229 which is protected from such operator system delays. Ending a trial and loading another flash file cleared the buffer and accuracy was returned.

One additional factor apparent when launching the flash files from Mattap (in experiments Chapter 4 and 5), was that the first flash file window took about 300ms to load into memory. Once open, new trials would start without this initial delay. Accordingly, the flash file window was preemtively loaded before any experimental trial scripts were initiated.

Example data from 2 trials of Mattap recorded Asychronies between expected IOI and analogue recording of data from the photoreceptor

	-0.344	-0.264
	-0.395	-0.857
	-0.325	-0.743
	-0.597	-0.447
	-0.456	-0.498
	-0.514	-0.428
	0.049	-0.7
	-0.253	-0.559
	-0.511	-0.617
	-0.596	-0.054
	-0.538	-0.356
	-0.475	-0.614
	-0.438	-0.699
	-0.623	-0.641
	-0.679	-0.577
	-0.633	-0.54
	-1.346	-0.725
	-0.757	-0.781
	-0.655	-0.735
	-0.742	-1.448
	-0.677	-0.859
	-0.753	-0.757
	-0.698	-0.844
	-0.82	-0.779
	-0.862	-0.856
	-0.361	-0.801
	0.198	-0.923
	-0.19	-0.965
	-0.099	-0.464
	-0.404	0.095
	-0.459	-0.293
	0.001	-0.202
	-0.307	-0.507
	-0.242	-0.562
	0.039	-0.102
	-0.096	-0.41
	-0.83	-0.345
	-0.608	-0.064
	-0.257	-0.199
	-0.494	-0.933
	0.018	-0.711
	-0.356	-0.361
	-0.281	-0.598
	-0.258	-0.086
	-0.354	-0.46
	-0.372	-0.385
	-0.02	-0.362
	-0.137	-0.458
	-0.175	-0.476
	-0.332	-0.125
	-0.257	-0.242
	-0.322	-0.28
	-0.195	-0.437
	-0.241	-0.362
	-0.363	-0.427
	-0.504	-0.3
	-0.356	-0.347
MEAN	**-0.40793**	**-0.51702**
STD	**0.275532**	**0.282071**

REFERENCES:

Alan, B. (2000). "The episodic buffer: a new component of working memory?" Trends in Cognitive Sciences 4(11): 417-423.

Ames, L. (1946). "The development of the sense of time in the young child." Journal of Genetic Psychology 68: 97-126.

Aschersleben, G. (1995). "Synchronizing actions with events - the role of sensory information."

Aschersleben, G. (2002). "Temporal Control of Movements in Sensorimotor Synchronization." Brain and Cognition 48(1): 66-79.

Baddeley, A. (2003). "Working memory and language: an overview." Journal of Communication Disorders 36(3): 189-208.

Baddeley, A. D. (1986). Working memory. Oxford, Oxford University Press.

Baddeley, A. D. (2003). "Working memory and language: an overview." Journal of Communication Disorders 36: 189–208.

Barnes, R., & Jones, M. R. (2000). "Expectancy, attention, and time." Cognitive Psychology 41: 254-311.

Barnes, R. and M. R. Jones (2000). "Expectancy, Attention, and Time." Cognitive Psychology 41(3): 254-311.

BIPM. (2012). Retrieved Feb 2012, from http://www.bipm.org/en/si/si_brochure/chapter2/2-1/metre.html.

Block, R. A. (1978). "Remembered duration: Effects of event and sequence complexity." Memory & Cognition 6: 320-326.

Block, R. A. (1982). "Temporal judgments and contextual change." Journal of Experimental Psychology: Learning, Memory, and Cognition 8: 530-544.

Block, R. A. (1986). "Remembered duration: Imagery processes and contextual encoding." Acta Psychologica 62: 103-122.

Block, R. A. (1990). Cognitive models of psychological time. Hillsdale,

NJ, Erlbaum.

Block, R. A., Ed. (1992). Prospective and retrospective duration judgment: The role of information processing and memory. Time, action and cognition: Towards bridging the gap. Dordrecht , Netherlands, Kluwer Academic.

Block, R. A., & Reed, M. A. (1978). "Remembered duration: Evidence for a contextual-change hypothesis." Journal of Experimental Psychology: Human Learning and Memory 4: 656-665.

Block, R. A., & Zakay, D (1997). "Prospective and retrospective duration judgments: A meta-analytic review." Psychonomic Bulletin & Review(4): 184-197.

Block, R. A., George, E. J., & Reed, M. A. (1980). "A watched pot sometimes boils: A study of duration experience." Acta Psychologica, 46: 81-94.

Block, R. A., Hancock, P. A., & Zakay, D. (2010). "How cognitive load affects duration judgments: A meta-analytic review." Acta Psychologica 134: 330-343.

Block, R. A. and D. Zakay (1997). "Prospective and retrospective duration judgments: A meta-analytic review." Psychonomic bulletin & review 4(2): 184-197.

Boltz, M. (1994). "Changes in internal tempo and effects on the learning and remembering of event durations." Journal of Experimental Psychology: Learning Memory Cognition 20: 1154-1171.

Boltz, M. G. (1995). "Effects of event structure on retrospective duration

judgments." Perception & Psychophysics 57: 1080-1096.

Bradley, N. (1948). "Growth of the knowledge of time in children of school age." British Journal of Psychology 38: 67.

Brown, G. D. A., & Chater, N. , Ed. (2001). The chronological organization of memory: Common psychological foundations for remembering and timing. Time and memory: Issues in philosophy and psychology. Oxford, England, Oxford University Press.

Brown, S. W. (1997). "Attentional resources in timing: Interference effectsin concurrent temporal and nontemporal working memory tasks." Perception & Psychophysics 59: 1118-1140.

Brown, S. W. (2006). "Timing and executive function: Bidirectional interference between concurrent temporal production and randomization tasks." Memory & Cognition 34: 1464-1471.

Brown, S. W., & Boltz, M. (2002). "Attentional processes in time perception: Effects of mental workload and event structure." Journal of Experimental Psychology: Human Perception & Performance 28: 600-615

Brown, S. W., & West, A. N. (1990). "Multiple timing and the allocation of attention." Acta Psychologia 75: 103-121.

Bruno H, R. (2001). "Processes underlying adaptation to tempo changes in sensorimotor synchronization." Human Movement Science 20(3): 277-312.

Bruno H, R. (2011). "Comfortable synchronization of cyclic drawing movements with a metronome." Human Movement Science 30(1): 18-39.

Buhusi, C. V., & Meck, W. H. (2009). "Relative time sharing: New findings and an extension of the resource allocation model of temporal processing." Philosophical Transactions of the Royal Society B 364: 1875-1885.

Burle, B., & Casini, L. (2001). "Dissociation between activation and attention effects in time estimation: Implications for clock models." Journal of Experimental Psychology: Human Perception and Performance(27): 195-205.

Carrel, A. (1931). "Psychological time." Science 74: 618-621.

Church, R. M. I. E., (pp.). : (2003). A concise introduction to the scalar timing theory. *Functional and neural mechanisms of interval timing*. W. H. Meck. Boca Raton, FL, CRC: 3-22.

Collier, G. L., & Ogden, R. T. (2004). "Adding drift to the decomposition of simple isochronous tapping:An extension of the Wing–Kristofferson model." Journal of Experimental Psychology: Human Perception and Performance 30: 853–872.

Coull, J. T. (2004). "Functional Anatomy of the Attentional Modulation of Time Estimation." Science 303(5663): 1506-1508.

Curtis, J. (1916). "Duration and the temporal judgement." American Journal of Psychology 27: 1-46.

Daffertshofer, A. (1988). "Effects of noise on the phase dynamics of nonlinear oscillators." Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Topic 58: 327–338.

Davidson, C. (1941). "A syndrome of time agnosia." Journal of Nervous and Mental Disease 94: 336-337.

Delignieres, D., L. Lemoine, et al. (2004). "Time intervals production in tapping and oscillatory motion." Human Movement Science 23(2): 87-103.

Delignières, D. and K. Torre (2011). "Event-Based and Emergent Timing: Dichotomy or Continuum? A Reply to Repp and Steinman (2010)." Journal of Motor Behavior 43(4): 311-318.

Drewing, K. A., G. (2003). "Reduced timing variability during bimanual coupling: A role for sensory information." Quarterly Journal of Experimental Psychology 56A: 329–350.

Dunlap, K. (1910). "Reactions to rhythmnic stimuli with attempts to synchronize." Psychological Review 17: 399-416.

Dunlap, K. (1915). "The shotest perceptible time-interval between two flashes of light." Psychological Review 22: 226-250.

Eisler, H. (1975). "Subjective duration and psychophysics." Psychological

Review 82: 429-450.

Eisler, H. (1976). "Experiments on subjective duration 1878–1975:

A collection of power function exponents." Psychological Bulletin 83: 1154-1171.

Eisler, H., Eisler, A. D., & Hellström, Å. , Ed. (2008). Psychophysical issues in the study of time perception. Psychology of time. Bingley, U.K, Emerald Group.

Elliott, M. I., A. E. Welchman, et al. (2009). "MatTAP: A MATLAB toolbox for the control and analysis of movement synchronisation experiments." Journal of Neuroscience Methods 177(1): 250-257.

Engle, R. W., & Kane, M. J., Ed. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. he psychology of learning and motivation. New York, Academic Press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). "Working memory, short-term memory, and general fluid intelligence: A latent variable approach." Journal of Experimental Psychology: General 128: 309-331.

Farber, M. (1944). "Suffering and time perspective of the prisoner." University of Iowa Studies in Child Welfare 20: 153-227.

Feynman, R. P. (1988). What Do You Care What Other People Think? United States, W. W. Norton.

Fisher, R. (1926). "The Arrangement of Field Experiments." Journal of the Ministry of Agriculture of Great Britain 33: 503-513.

Flach, R. (2005). "The transition from synchronization to continuation tapping." Human Movement Science 24(4): 465-483.

Ford, A. (1937). "Perceptive errors in time judgement." Journal of Experimental Psychology 20: 528-552.

Fortin, C. M., Nathalie (2000). "Expecting a break in time estimation: Attentional time-sharing without concurrent processing." Journal of Experimental Psychology: Human Perception and Performance 26(6)): 1788-1796.

Fraisse, P. (1957). Psychologie du temps [Psychology of time]. Paris, Presses Universitaires de France.

Fraisse, P. (1966). "Anticipation of Rhythmic Stimuli, Rate of Establishment and Precision of Synchronization." Annee Psychologique 66(1): 15-15.

Fraisse, P. (1980). "Latencies and Interstimulus Intervals in a Sequence of Motor-Responses." Bulletin of the Psychonomic Society 16(1): 47-50.

Fraisse, P. (1984). "Perception and estimation of time." Annual Review of Psychology 35: 1-36.

Franek, M. (1991). "Finger tapping in musicians and nonmusicians.pdf>." Internattonul Journal of Psychophysiology, 11: 277-279.

Gibbon, J. (1977). "Scalar expectancy theory and Weber’s law in animal timing." Psychological Review 84: 279-325.

Gibbon, J. (1991). "Origins of scalar timing." Learning & Motivation(22): 3-38.

Gibbon, J. (1992). "Ubiquity of scalar timing with a Poisson clock." Journal of Mathematical Psychology 36: 283-293.

Gibbon, J., Church, R. M., & Meck, W., Ed. (1984). Scalar timing in memory. Annals of the New York Academy of Sciences 423. New York, New York Academy of Sciences.

Gibbon, J., Church, R. M., & Meck, W. H., Ed. (1984). Scalar timing in memory. Timing and time perception. New York, New York Academy of Sciences.

Glover SR, D. P. (2001). "Dynamic illusion effects in a reaching task: evidence for separate visual representations in the planning and control of reaching.

." J Exp Psychol Hum Percept Perform 27(3): 560-572.

Goodfellow, L. (1934). "An empirical comparison of audition, vision, and touch in the discriminationof short intervals of time." American Journal of Psychology 46: 243-258.

Gridley, P. (1932). "The discrimination of short intervals of time by finger tap and by ear." American Journal of Psychology 44: 18-43.

Grondin, S., & Killeen, S. (2009). "Effects of singing and counting during successive interval productions. ." NeuroQuantology(7): 77-84.

Grondin, S., Roussel, M.-E., Gamache, P.-L., Roy, M., & Ouellet, B. (2005). "The structure of sensory events and the accuracy of time judgments." Perception(34): 45-58.

Guilford, J. P. (1926). "Spatial symbols in the apprehension of time." American Journal of Psychology 37: 420-423.

Hammer, E. (1949). "Temporal factors in figural aftereffects." American Journal of Psychology 62: 337-354.

Harry, D., & Moore, G.P. (1985). "Temporal tracking and synchronisation strategies." Human Neurobiology 4: 73-77.

Harry, D., & Moore, G.P. (1987a). "On the performance and stability of human metronome synchronisation strategies." British Journal of Mathematical and Statistical Psychology 40: 109-124.

Harry, D., & Moore, G.P. (1987a). "Synchronizing human movement with an external clock source." Biological Cybernetics 56: 305-311.

Harton, J. (1939c). "The relation of time estimates to actual time." Journal of General Psychology 21: 219-224.

Hellige, J. B. and L. E. Longstreth (1981). "Effects of concurrent hemisphere-specific activity on unimanual tapping rate." Neuropsychologia 19(3): 395-405.

Hiscock, M., M. Kinsbourne, et al. (1985). "Effects of speaking upon the rate and variability of concurrent finger tapping in children." Journal of Experimental Child Psychology 40(3): 486-500.

Hiscock, M., M. Kinsbourne, et al. (1987). "Dual task performance in children: Generalized and lateralized effects of memory encoding upon the rate and variability of concurrent finger tapping." Brain and Cognition 6(1): 24-40.

Hoagland, H. (1933). "The physiological control of judgements of duration: Evidence for a chemical clock." Journal of General Psychology 9: 267-287.

Hoagland, H. (1934). "Physiological control of judgements of duration." American Journal of Psychology 109: 54.

Holst, E. v. (1937,1939/1973). The behavioral physiology of animaland man. Coral Gables, FL, University of Miami Press.

James, W. (1890). The principles of psychology. New York, NY, Henry Holt and Co.

Jäncke, L., R. Loose, et al. (2000). "Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli." Cognitive Brain Research 10(1–2): 51-66.

Jantzen, K. J., Oullier, O., Marschall, M., Steinberg, F.L. & Kelso, J.A.S. (2007). "A Parametric fMRI Investigation of Context Effects in Sensorimotor Timing and Coordination." Neuropsychologia 45(4): 673-684.

Jones, L. A., & Wearden, J. H. (2004). "Double standards: Memory

loading in temporal reference memory." Quarterly Journal of Experimental

Psychology and Aging 57B: 55-77.

Jones, M. R., & Boltz, M. (1989). "Dynamic attending and responses to time." Psychological Review(96): 459-491.

Kato, M. and Y. Konishi (2006). "Auditory dominance in the error correction process: A synchronized tapping study." Brain Research 1084(1): 115-122.

Keefe, K. (1985). "Motor and cognitive interference effects on unimanual tapping rates." Brain and Cognition 4(2): 165-170.

Keller, P. E. and B. H. Repp (2004). "Staying offbeat: Sensorimotor syncopation with structured and unstructured auditory sequences." Psychological Research Psychologische Forschung 69(4): 292-309.

Kelso, J. A. S. (1995). Dynamic patterns: The self-organization of brain and behavior. Cambridge, MA, MIT Press.

Krampe, R. T., U. Mayr, et al. (2005). "Timing, Sequencing, and Executive Control in Repetitive Movement Production." Journal of Experimental Psychology: Human Perception and Performance 31(3): 379-397.

Landes, D. S. (1983). Revolution in Time: Clocks and the Making of the Modern World, Belknap Press of the Harvard University Press

Landes, D. S. (1983). Revolution in Time: Clocks and the Making of the Modern World, Harvard University Press

Lejeune, H., & Wearden, J. H. (2009). "Vierordt's The experimental study of the time sense (1868) and its legacy." European Journal of Cognitive Psychology(21): 941-960.

Lewis, A. (1931-1932). "The experience of time in mental disorder." Proceedings of the Royal Society of Medicine 25: 611-620.

Lewis, P. A. and R. C. Miall (2006). "Remembering the time: a continuous clock." Trends in Cognitive Sciences 10(9): 401-406.

Lifshitz, S. (1933). "Two integral laws of sound perception relating loudness and apparent duration of sound impulses." Journal of the Acoustical Society of America 5: 31-33.

Macar, F., Grondin, S., & Casini, L. (1994). "Controlled attention sharing influences time estimation." Memory & Cognition(22): 673-686.

Macleod, R., & Roff, M. (1935). "An experiment in temporal disorientation." Acta Psychologia 1: 381-423.

Mates, J. (1994a). "A model of synchronization of motor acts to a stimulus sequence. I. Timing and error corrections." Biological Cybernetics 70: 463-473.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (). T. (2006). "The time of our lives: Life span development of timing and event tracking." Journal of Experimental Psychology: General(135): 348-367.

Meck, W. (2002). "Dissecting the Brain's Internal Clock: How Frontal–Striatal Circuitry Keeps Time and Shifts Attention." Brain and Cognition 48(1): 195-211.

Meck, W. H., Ed. (2003). Functional and neural mechanisms of internal timing. Boca Raton, FL, CRC.

Miyake, I. (1902). "Researches on rhythmic activity " Stud Yale Psychol Lab 10: 1-48.

Nakajima, Y., ten Hoopen, G., Sasaki, T., Yamamoto, K., Kadota, M., Simons, M., & Suetomi, D. (2004). "Time-shrinking: The process of unilateral temporal assimilation." Perception(33): 1061-1079.

Needham, J. (1935). "The effect of the time interval upon the time error at different intensity levels." Journal of Experimental Psychology 18: 530-543.

News, A. S. (2012). "Science News." from http://news.sciencemag.org/ scienceinsider/2012/02/ breaking-news-error-undoes- faster.html?ref=hp.

Nichols, H. (1891). "The psychology of time." The American Journal of Psychology 3 (4): 453-529.

NIST, I. S. o. U. (2012). 2012, from http://physics.nist.gov/cuu/Units/index.html.

Nitardy, F. (1943). "Apparent time acceleration with age of the individual." Science 98: 110.

Oakden, E., & Stuart, M. (1922). "The development of the knowledge of time in children." British Journal of Psychology 12: 309-336.

Oberauer, K., E. Lange, et al. (2004). "Working memory capacity and resistance to interference." Journal of Memory and Language 51(1): 80-96.

Ogden, R. S., E. Salominaite, et al. (2011). "The role of executive functions in human prospective interval timing." Acta Psychologica 137(3): 352-358.

Penney, T. B., Gibbon, J., & Meck, W. H. (2000). "Differential effects of auditory and visual signals on clock speed and temporal memory." Journal of Experimental Psychology: Human Perception & Performance(26): 1770-1787.

Penney, T. B., Gibbon, J., & Meck, W. H. (2008). "Categorical scaling of duration bisection in pigeons (Columba livia), mice (Mus musculus), and humans (Homo sapiens)." Psychological Science(19): 1103-1109.

Penton-Voak, I. S., Edwards, R., Percival, K., & Wearden, J. H. (1996). "Speeding up an internal clock in human? Effects of click trains on subjective duration." Journal of Experimental Psychology: Animal Behavior Process 22: 307-320.

Postman, L. (1944). "Estimates of time during a series of tasks." American Journal of Psychology 57: 421-424.

Quercetani, R. L. (1964). A world history of track and field athletics 1864-1964. London, Oxford University Press.

Repp, B. (2002). "Perception of timing is more context sensitive than sensorimotor synchronization." Perception & Psychophysics 64: 703-716.

Repp, B. (2006). "Does an auditory distractor sequence affect self-paced tapping?" Acta Psychologica 121(1): 81-107.

Repp, B. H. (2001). "Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization." Journal of Experimental Psychology: Human Perception and Performance 27: 600–621.

Repp, B. H. (2001). "Processes underlying adaptation to tempo changes in sensorimotor synchronization." Human Movement Science 20: 277-312.

Repp, B. H. (2002a). "Automaticity and voluntary control of phase correction following event onset shifts in sensorimotor synchronization." Journal of Experimental Psychology: Human Perception and Performance 28: 410–430.

Repp, B. H. (2003b). "Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision." Journal of Motor Behavior 35: 355-370.

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

Repp, B. H. (2008). "Perfect phase correction in synchronization with slow auditory sequences." Journal of Motor Behavior 40(5): 363-367.

Repp, B. H. (2010). "Sensorimotor synchronization and perception of timing: Effects of music training and task experience." Human Movement Science 29(2): 200-213.

Repp, B. H. and R. Doggett (2007). "Tapping to a Very Slow Beat: A Comparison of Musicians and Nonmusicians." Music Perception 24(4): 367-376.

Repp, B. H. and P. E. Keller (2008). "Sensorimotor synchronization with adaptively timed sequences." Human Movement Science 27(3): 423-456.

Repp, B. H., P. E. Keller, et al. (2012). "Quantifying phase correction in sensorimotor synchronization: Empirical comparison of three paradigms." Acta Psychologica 139(2): 281-290.

Repp, B. H. and G. P. Moseley (2012). "Anticipatory phase correction in sensorimotor synchronization." Human Movement Science.

Repp, B. H. and A. Penel (2004). "Rhythmic movement is attracted more strongly to auditory than to visual rhythms." Psychological Research 68(4): 252-270.

Rodger, M. and C. Craig (2011). "Timing movements to interval durations specified by discrete or continuous sounds." Experimental Brain Research 214(3): 393-402.

Roeckelein, J. E. (2000). The concept of time in psychology: A resource book and annotated bibliography. Westport, CT, Greenwood.

Roeckelein, J. E. (2000). The concept of time in psychology: A resource book and annotated bibliography. Westport, CT, Greenwood Press.

Roeckelein, J. E., Ed. (2008). History of conceptions and accounts of time and early time perception research. Psychology of time. Bingley, U.K, Emerald Group.

Saito, S. (1977). "When articulatory suppression does not supporess the activity of the phonological loop." British Journal of Psychology 88(4): 565-578.

Saito, S. (1994). "What effect can rhythmic finger tapping have on the phonological similarity effect?" Memory & Cognition 22: 181-187.

Saito, S. (2001). "The phonological loop and memory for rhythms: An individual differences approach." Memory 9(4): 313-322.

Schneider, D. (1948). "Time-space and the growth of the sense of reality." Psychoanalytic Review 35: 229-252.

Sergent, H., Cherry . (1993). "Effects of Responding Hand and concurrent verbal processing on timekeeping and motor implementation processes." Brain Cognition 23(2): 243-262.

Spencer, L. (1921). "An experiment in time estimation using different interpolations." American Journal of Psychology 32: 557-562.

Staddon, J. E. R., & Higa, J. J. (1996). "Multiple time scales in simple habituation." Psychological Review 103: 720-733.

Staddon, J. E. R., & Higa, J. J. (1999). "Time and memory: Towards a pacemaker-free theory of interval timing." Journal of the Experimental Analysis of Behavior 71: 215-251.

Stevens, L. T. (1886). "On the time sense." Mind 11: 393-404.

Stott, L. (1935). "Time order errors in the discrimination of short tonal durations." journal of experimental research 18: 741-766.

Swift, E. M., J. (1925). "An experimental study of the perception of filled and empty time." Journal of Experimental Psychology 8: 240-249.

Takano, K. and Y. Miyake (2007). "Two types of phase correction mechanism involved in synchronized tapping." Neuroscience Letters 417(2): 196-200.

Thaut, M. H. and G. P. Kenyon (2004). "Response to Bruno Repp's “Comments on `Rapid motor adaptations to subliminal frequency shifts during syncopated rhythmic sensorimotor synchronization' by Michael H. Thaut and Gary P. Kenyon (Human Movement Science 22 [2003] 321–338)”." Human Movement Science 23(1): 79-86.

Thornton, C. D. and M. Peters (1982). "Interference between concurrent speaking and sequential finger tapping: Both hands show a performance decrement under both visual and non-visual guidance." Neuropsychologia 20(2): 163-169.

Todd, N. P. M., D. J. O'Boyle, et al. (1999). "A sensory-motor theory of rhythm, time perception and beat induction." Journal of New Music Research 28(1): 5-28.

Torre, K. and R. Balasubramaniam (2009). "Two different processes for sensorimotor synchronization in continuous and discontinuous rhythmic movements." Experimental Brain Research 199(2): 157-166.

Treisman, M. (1963). "Temporal discrimination and the indifference interval. Implications for a model of the "internal clock".

." Psychol Monogr 77(13): 1-31.

Treisman, M., Faulkner, A., Naish, P. L. N., & Brogan, D. (1990). "The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency." Perception 19: 705-748.

Triplett, D. (1931). "The relation between the physical pattern and the reproduction of short temporal intervals: A study in the perception of filled and unfilled time." Psychological Monographs 41: No. 187.

Van Beers, R. a. H., P and Wolpert, DM (2004). "The Role of Execution Noise in Movement Variability." Journal of Neurophysiology 91: 1050-1063.

Vardy, A. N., A. Daffertshofer, et al. (2008). "Tapping with intentional drift." Experimental Brain Research 192(4): 615-625.

Vorberg, D., & Wing, A. M. , Ed. (1996). Modelling variability and dependence in timing. Handbook of perception and action. Motor skills. London, Academic Press.

Wearden, J. H., & Ferrara, A (1993). "Subjective shortening in humans' memory for stimulus duration." Quarterly Journal of Experimental Psychology 46B: 163-186.

Wearden, J. H. D., M.F. (1995). "Exploring and developing a connectionist model of animal timing: Peak procedure and fixed-interval simulations." Journal of Experimental Psychology: Animal Behavior Processes(21): 99-115.

Weber, A. (1927). "The properties of space and time in kinesthetic fields of force." American Journal of Psychology 38: 597-606.

Wing, A., Kristofferson, AB (1973). "The timing of inter-response intervals." Perception Psychophysics 13: 455–460.

Wing, A. M. (1980). The long and short of timing in response sequences. In Tutorials in motor behavior, ed G.E. Stelmach and J. Requin. Amsterdam: North Holland: 469-486.

Woodrow, H. (1928a). "Behaviour with respect to short temporal stimulus forms." Journal of Experimental Psychology 11: 167-193.

Woodrow, H. (1932). "The effect of rate of sequence upon the accuracy of synchronization." Journal of Experimental Psychology XV(4): 357-379.

Woodrow, H. (1933). "Individual differences in the reproduction of temporal intervals." American Journal of Psychology 45: 271-281.

Woodrow, H. (1934). "The temporal indifference interval determined by the method of mean error." Journal of Experimental Psychology 17: 167-188.

Woodrow, H., & Stott, L. (1936). "The effect of practice on time order errors in the comparison of temporal intervals." Journal of Experimental Psychology 19: 694-705.

Zelaznik, H. N., Biberstine J, Kennedy L, Whetter E. (2005). "Timing precision in circle drawing does not depend on spatial precision." J Mot Behav 37(6): 447-453.