‘*Sensorimotor Synchronisation and Entrainment in Musical Timekeeping: Metronome Configurations and Preliminary Implications for Music Education*’.

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy by Steffan Rhys Owens.

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The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit.

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Abstract

Timekeeping whilst playing music is a skill all musicians, especially drummers, require. Following a review of the literature on this subject, this thesis explores methods of measuring timekeeping accuracy of individuals and groups, and offers recommendations for approaches for future training.

Using equipment and techniques accessible to musicians and non-musicians alike, the researcher has investigated how individual timekeeping, specifically the measure of Inter-tap Interval (ITI), is influenced by the presence, absence, and reintroduction of metronomes of various designs. The thesis also investigates how the influence of these differing metronome states interact with tempo and with the type of metronome (audio and visual).

Similarly, the dynamics of group timekeeping and the interaction (or entrainment) between individuals in the group is also investigated.

Participants were asked to report their perception of their individual performances under the different conditions of the experiments.

The results show that tempo influenced the accuracy of timekeeping and the presence, absence and reintroduction of the metronome also had effects on accuracy.

Individuals thought their timekeeping to be more accurate when the metronome was present and that they performed better as individuals as opposed to being part of a group.

Detailed analysis of the results showed that the reintroduction of the metronome proved to have a significant effect on average ITI produced by participants, as did tempo. Metronome type had no significant influence on ITI in an individual or group setting.

In the conclusion of the thesis, the author provides recommendations for future assessment and training of musicians in the skill of timekeeping, with respect to the measure of ITI.

Glossary of terms

This list provides definitions of key terms used throughout the research thesis:

Inter-onset Interval (IOI): Duration between the onset of two sequential events in stimuli.

Inter-tap Interval (ITI): Duration between the onset of two sequential events performed by participants. In this thesis, the term is used interchangeably to represent the tap of a sensor pad or the strike of a cowbell with a drumstick.

Isochronous: A regular pattern of auditory or visual events with even durations.

Cross-rhythm: Patterns that subdivide the isochronous events. These patterns are related in meter and tempo.

Entrainment: "*The interaction of autonomous rhythmic (oscillatory) processes, often resulting in their synchronization*" (Clayton et al, 2020).

Sensorimotor Synchronisation: "[*T]he rhythmic coordination of perception and action*'' (Repp, 2005). In a musical context, the process by which musicians use sensory input to synchronize with co-performers (Clayton *et al*., 2020).

Tempo/Tempi: The speed of the target isochronous pattern or, more generally, the speed of a piece of music. Tempo is expressed as beats per minute (bpm). Inter-onset Interval, expressed in milliseconds (ms), can also give an indication of tempo.

Meter: "*A hierarchical structure, comprising two or more levels, into which beats and beat subdivisions are organised*" (Clayton *et al*., 2020).

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1. Introduction and Background.

> *"I was told at a young age that I was Father Time. I didn't know what that meant, but I understood much later that time and rhythm go together. They are two different entities, but they go together, they become one".* (Purdie, 2004)

Musical timekeeping lies at the centre of rhythm, coordination, and performance, influencing the way musicians synchronise with both external stimuli and each other. Whether performing as an individual or in an ensemble, timekeeping is an essential skill that requires both cognitive and motor coordination. In this musical context, a metronome acts as an external timekeeper that helps performers develop internal rhythmic stability. As its overall Research Aim, this thesis seeks to explore the technical configurations of metronomes and their effects on musical timekeeping to provide preliminary recommendations for music education and assessment.

The research is directed by four interrelated questions that are aimed at exploring the effects of metronome type, condition and tempo in both individual and group settings.

Traditional metronomes are predominantly isochronous, producing evenly spaced beats with a steady tempo. While effective, this standard configuration may not be compatible with the more nuanced demands of certain musical genres or performance contexts.

Research Question 1: *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping*? will examine the influence of intermittent metronome conditions and varying tempi on musical timekeeping. This research question will explore the notion that intermittent metronomes may promote greater autonomy in internalising rhythm, enabling musicians to develop more consistent and precise timekeeping skills compared to continuous cues.

Musical performance is often a social activity, requiring individuals to synchronise not only with external timekeepers but also with fellow performers. Group dynamics introduce additional considerations, such as leader-follower relationships and mutual entrainment. **Research Question 2**: *What effect does playing in a group, versus individually, have on musical*

timekeeping? will explore group timekeeping. By contrasting individual and ensemble performances, the study aims to uncover how interpersonal interactions influence musical timekeeping.

Group performance may enhance timekeeping through distributed cognition, where each performer contributes to a collective sense of rhythm. However, it may also introduce challenges, such as maintaining coherence amid fluctuating tempi or varying levels of skill within the group. Understanding these dynamics and each participants' perception of their timekeeping will inform strategies for both individual practice and ensemble training.

Modern metronomes are no longer limited to auditory signals. Advances in technology have expanded the range of sensory inputs available to performers to include visual and haptic cues. **Research Question 3**: *What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping*? will investigate how different metronome types (including auditory, visual, and cross-rhythmic configurations) can affect musical timekeeping. The multimodal nature of this strand of inquiry will explore whether the type of metronome potentially enhances or hinders accurate musical timekeeping.

Research Question 4: *What implications do the findings of the previous research questions have for musical timekeeping education and assessment*? will synthesise the findings from the earlier research questions to develop evidence-based recommendations for teaching strategies and assessment frameworks. This final research question shifts focus from empirical findings to their practical implications.

This research is concerned with the key themes of *entrainment* and *sensorimotor musical timekeeping*. There is a significant amount of research in each of these areas and this thesis will specifically investigate the relationship between these two themes and try to establish any significant effects the relationship has on musical timekeeping for individual musicians and for groups of musicians.

Timekeeping in musicians is assessed formally in grade exams, typically through the subjective lens of an examiner or assessor in a one-to-one test environment. Assessment of timekeeping in an exam environment has changed in recent years (ABRSM, 2019; LCM Examinations, 2018; LCM Examinations, 2009). The subjective judgment of timekeeping was traditionally measured through instrumentalists performing pieces along with an accompanist, and the examiner or assessor reporting on their interpretation of the musicians' timekeeping accuracy. Although grade exam syllabuses have evolved in recent times to include group and individual timekeeping studies and pieces accompanied by backing tracks and click tracks, the timekeeping accuracy of musicians in these tasks is based on the subjective assessment of whether they have precisely matched regular tempo markers. We can think of this as "hitting the fenceposts", i.e. striking or sounding an instrument at the same time as a target tempo pattern (see Fig 1.1). Whilst this remains a useful means to express the accuracy of musical timekeeping, it might be more representative of real-world musical experiences to broaden that assessment to include other measurements of timekeeping consistency.

This thesis will investigate what effect the removal and reintroduction of a metronome may have on the timekeeping abilities of test participants. Previous published studies are generally limited to the removal of a metronome only, in order to test the continuation skills of participants for a short period of time (Repp B. H., 2010; Repp B. , 2006; Repp B. H., 2001). It is important to understand the effect the reintroduction of a metronome may have after a more extended absence, and if there are differences in any observed effect between individual and group settings. In addition, no research has been found that studies the removal and reintroduction of a metronome in combination with differing conditions i.e. tempo and audio/visual metronomes. The variation in metronome type and metronome state could provide insight into the factors that influence continuation abilities, and specifically the ability to maintain a consistent note onset interval. The majority of existing research approaches sensorimotor synchronisation and entrainment from a psychological or ethnographical research standpoint (Clayton, et al., 2020; Clayton, 2012). This thesis intends to determine the extent to which the differing conditions of metronome type, state, and tempo, can affect timekeeping, and how this is important in a musical context.

1.1 Entrainment

Entrainment is defined as:

> "*...a phenomenon in which two or more independent rhythmic processes synchronize with each other"* (Clayton, Sager, & Will, 2005).

Entrainment is one of the cornerstones of musical timekeeping (Reybrouck, 2023; Stupacher, Wood, & Witte, 2017). It is a phenomenon that every musician, through the complete spectrum of abilities or expertise, will experience throughout their musical career. A musician who is well-entrained in a musical task, whether it be with a metronome or a group of fellow musicians, will experience the sensation of rhythmic cohesion in that task.

The study of entrainment provides insight into a variety of human behaviors and interactions. For example, it has been used in ethnographic studies (Clayton, Sager, & Will, 2005) to investigate its role in speech therapy (Corriveau & Goswami, 2009) (Cummins, 2009), and musical perception studies (Phillips-Silver, Aktipis, & Bryant, 2010), in addition to musical and sensorimotor research (Phillips-Silver & Keller, 2012). There are also examples of entrainment studies that assess visual cues and stimuli, rather than auditory stimuli (Schmidt, Richardson, Arsenault, & Galantucci, 2007; Schmidt & Turvey, 1994; Hatzitaki, Grouios, Sofiandis, Johansen, & Wing, 2012). Ultimately, musical entrainment is a phenomenon that can be influenced by differing types of stimuli (e.g., audio, visual, tactile etc.) and by differing layers of complexity in the stimulus.

This thesis is aimed at combining relevant elements of this existing research to ascertain the influence different metronomic information has on an individual's entrainment. It is also aimed at ascertaining if different modalities or states can influence an individual's ability to entrain. In this instance, the introduction and removal of metronomic information will be used to assess the effect these changes in state will have on an individual's ability to entrain. This will be done through a series of experiments that will measure individual participants' capacity to reproduce a simple, consistent, isochronous rhythmic pattern when faced with differing metronomic variables and states.

There is value in understanding the factors that influence the ability to entrain effectively, and the ability to produce a consistent note onset interval. These factors can be used to develop training and tuition techniques for instrumentalists, and provide a more nuanced means of assessment in musical timekeeping.

1.2 Sensorimotor Musical Timekeeping

"*Movement is time, expressed"* (Cunningham, 2019)

In this research, sensorimotor musical timekeeping should be considered as "*beat-based auditory timing*" (Teki, Grube, & Griffiths, 2012). Certainly, that could accurately describe the initial planned test phase, although that definition might be amended slightly as the metronomic information used in testing is expanded to include other forms of stimuli, beyond auditory alone. In essence, sensorimotor musical timing is the combination of human senses and motor functions to produce a consistent rhythmic output. This area of study has been investigated over a number of years, with research conducted in the timekeeping of persons including professional musicians (Stoklasa, Lieberman, & Fischinger, 2012), dancers (Miura, Kudo, Ohtsuki, & Kanehisa, 2011) and non-musicians (Repp & Doggett, 2007). However, whereas the broad base of exploration in the field has been focussed on the capacity to synchronise with tempo markers that are either in-phase (see Fig. 1.1) or anti-phase (see Fig. 1.2), the research in this thesis is intended to investigate the ability of an individual to reproduce a simple isochronous pattern at a consistent, internal tempo (Inter-Tap Interval or ITI), rather than the ability to hit the tempo markers of a metronome (Inter-Onset Interval or IOI). With an in-phase pattern, participants would attempt to match the IOI of the metronome. Matching this pattern exactly is known as *asynchrony*. Anti-phase patterns would see the participants produce a regular pattern that would appear in the intervals between the onset of the metronome. Measuring the average distance of the participant's pattern from the metronome onsets is known as *mean asynchrony*.

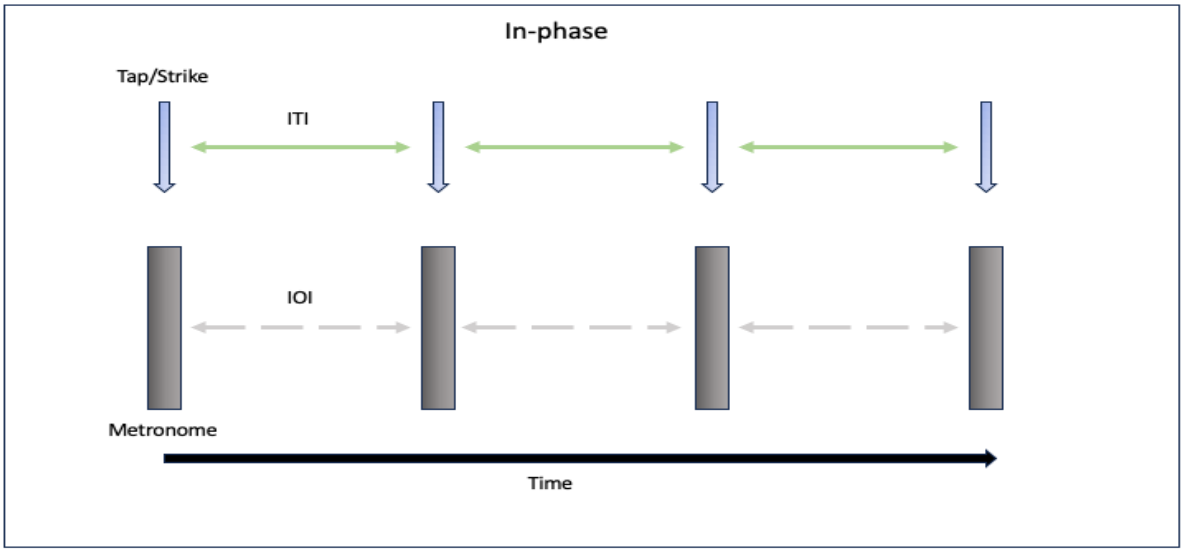

Fig. 1.1 An in-phase isochronous pattern.

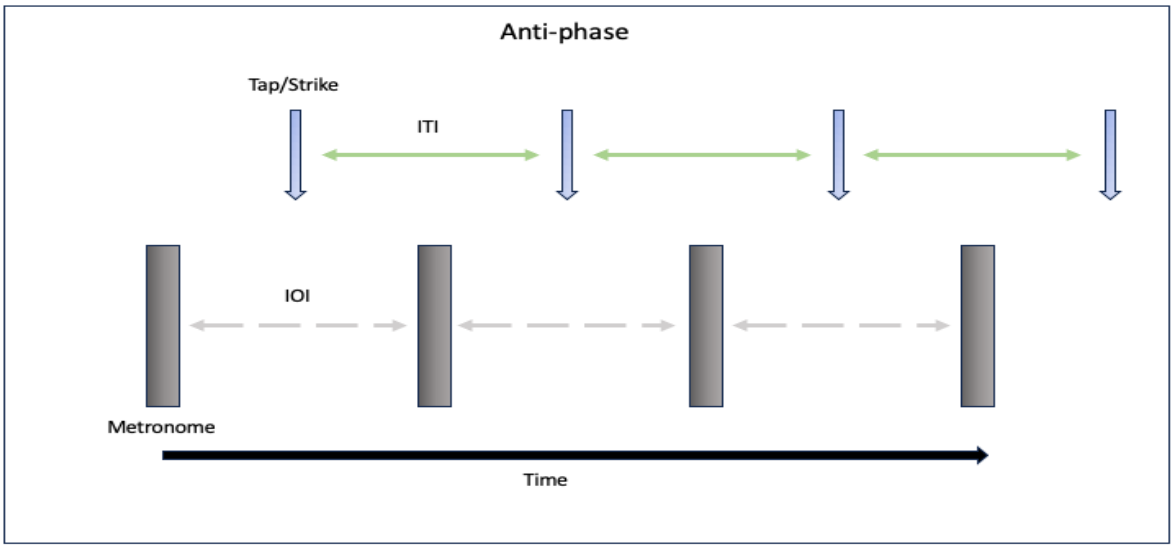

Fig. 1.2 An anti-phase isochronous pattern.

The experimental design for this thesis is concerned with a specific branch of sensorimotor musical timekeeping: continuous, isochronous tapping tasks. There is a wealth of research around sensorimotor synchronisation and the associated test methodologies, including methods for data collection and analysis (Georgi, Gingras, & Zentner, 2023; Anglada-Tort, Harrison, & Jacoby, 2022; Van Der Steen & Keller, 2013; Su & Repp, 2012; Repp B. H., 2006; Drewing, Aschersleben, & Li, 2006; Repp & Keller, 2004). The procedures identified in existing studies of conventional tapping tasks and interpersonal synchronisation will inform the experimental design in this thesis. The adoption of these core methodologies will allow this thesis to add to the existing state of knowledge through the combination of several strands

of current enquiry. Specifically, this thesis is focused on the factors that influence consistent note onset intervals, rather than the ability to precisely match a target metronome ("hitting the fenceposts"), and how this information can be applied to a teaching or assessment environment.

1.3 Aim of Research

The overall Research Aim of this thesis is to perform a technical exploration of different metronome configurations and develop preliminary recommendations for musical timekeeping education and assessment. The test phases have been designed to establish what effects the changes in metronome type, metronome state (present or removed) and tempo will have on an individual's ability to produce an isochronous pattern with a consistent ITI, both when performing individual tapping tasks or when part of a group.

The outcomes of the research will inform a series of recommendations that work towards developing ways to assess and teach instrumentalists to improve musical timekeeping.

1.3.1 Problem Statement

It is important to understand why this research is of significance. From a musical performance perspective, the ability to keep in time is an aspect of musical training that begins at the very early stages of development. It is widely believed that rhythmic engagement is developed by musical and metrically regular stimuli, although cultural differences can have an effect on this development (Ilari, 2015; Zentner & Eerola, 2010; Trehub & Trainor, 1993). As such, if we can establish a link between an improvement in an individual's ability to produce a consistent ITI and a particular set of metronomic variables, we may be able to positively influence instrumental practice regimes, classroom, and instrumental tuition, and, ultimately musical performance.

Individual and ensemble performance require the ability to keep accurate time. This is true of both live performance and performance in a studio setting. Traditionally, instrumental practice of timekeeping would be carried out with a physical, mechanical metronome that would produce an isochronous auditory and visual pattern for a musician to play along with.

In more modern times, timekeeping practice can take the form of playing along with backing tracks that offer more complex rhythmic stimuli. It is also important to recognise the ability to keep accurate time when there is an absence of rhythmic accompaniment, whether in the form of a metronome or other performers; this could take the form of a solo section of an ensemble piece or an entirely solo performance. It is appropriate to consider the impact any developments in the ability to keep time might have from a pedagogical perspective. Any changes could influence approaches to musical tuition, either in the classroom or in a more specific, one-to-one instrumental tuition setting.

1.4 Research Questions and Objectives

This research is ultimately designed to discover any potential benefits to musicians from altering or adapting the way they practice musical timekeeping or perform with the use of a metronome. This information can then be used to assist teachers in disseminating effective timekeeping techniques, and to inform and develop the way in which timekeeping is considered in examinations or assessments. Based on the findings of existing research and the researcher's personal professional experience, the goal is that this thesis can provide insight into what the most effective methods of improving a performer's ability to keep time are. The ambition of the research is to apply any insights gained and add them to the existing state of knowledge, and to contribute to the development of timekeeping practice and tuition techniques. Through the testing processes that will involve variation of metronome type, tempo and state, (alongside individual and group conditions) it is anticipated that this research will be able to contribute useful data to the field of sensorimotor synchronisation and entrainment research.

The following research questions have been developed and will inform the test structure:

Research Question (**RQ**)	Location of research and findings
1. What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?	Chapter 5, Chapter 6, Chapter 7, and Chapter 8.

2. What effect does playing in a group, versus individually, have on musical timekeeping?	Chapter 5, Chapter 6, and Chapter 8.
3. What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?	Chapter 4, Chapter 5, Chapter 6, Chapter 7, and Chapter 8.
4. What implications do the findings of the previous research questions have for musical timekeeping education and assessment?	Chapter 8.

These research questions and consideration of existing literature are intended to address the overarching Research Aim of this thesis: ***to perform a technical exploration of different metronome configurations and develop preliminary recommendations for musical timekeeping education and assessment*.**

1.5 Scope and Limitations

This research will assess the ability of a mixture of musicians and non-musicians to produce a consistent ITI across differing tempi, metronome types and metronome conditions. Whilst musicians that play any instrument will be included in the participant pool, the test methodology will be designed to specifically investigate percussive, sensorimotor tapping tasks. Therefore, the research will not address the differing motor functions that might be needed to play or voice instruments in alternative families e.g., brass or string instruments. However, these tapping tasks reflect core skills for most musicians and, as such, will provide results that can be applied to musicians of any instrument type.

The primary research activities that follow in this thesis will analyse the data gathered in a series of test phases to establish the factors that influence participants to produce a consistent ITI. Many studies have investigated the synchronisation of participants and their ability to accurately predict the IOI of an external metronome (Ning, Trosman, Sabin, & Wright, 2019; Hasuo, Nakajima, Wakasugi, & Fujioka, 2015; Ungan & Yagcioglu, 2014). This is

not the specific area of interest for this research, as the test methodology is designed to measure the internal spacing of participants' taps or strikes, and not to measure their distance from tempo markers (see Fig. 1.1 and Fig. 1.2).

Group entrainment will be measured by comparing individuals' ITI when performing timekeeping tasks in the presence of others, who are also undertaking the same activity. The comparison of several groups will allow for meaningful conclusions to be made concerning the metronomic variables (and their influence on ITI). The number of participants required to conduct a test of this size may prove challenging to recruit, so due consideration will be made to assess what size of participant pool will be sufficient to yield valuable data.

In the first instance, audio metronomes will be used as stimuli for participants in the testing phase. The expectation is that this test methodology can then be expanded to include visual stimuli, and potentially combinations of auditory and visual stimuli together. Time and financial constraints are likely to prevent the further expansion of these stimuli variations to include tactile metronomes. Whilst primary research may be unobtainable within the scope of this thesis, existing research in tactile metronomes and timekeeping tasks will be considered when drawing any conclusions or recommendations.

1.6 Experimental Design

This thesis will draw upon a variety of research methods to devise tests and analysis to synthesise meaningful conclusions to the research questions posed. Desktop research will inform the test methodology and experimental design that will be used to collect data throughout the test phases. It is the secondary research data of existing studies that will inform the primary research stages and their activities.

A review of current literature will be used to investigate the established testing processes for sensorimotor timekeeping tasks and the stimuli involved, such as auditory or visual cues. This is particularly relevant to the thesis as these techniques will be emulated in the testing process to allow for continuity with existing research and to ensure that conclusions of this thesis integrate with, and contribute to, the existing knowledge base.

Primary data collection will be carried out during the experimental test phases. Timing data points will be recorded for each individual participant and these data points will provide the basis for the quantitative data analysis. The physical equipment used to collect this data will be informed by existing research but may differ slightly as the test methodology develops and improves.

Each participant will be asked to provide demographic information, such as age and gender and will be asked if they would classify themselves as a musician or not (according to a definition provided by the researcher). A post-test survey of participants will be conducted, with the intention of gaining insight into the perception of the individual participants' own timekeeping performance. These responses can then be used to provide subjective quantitative data to accompany the experimental data and analysis.

Due to the nature of the research enquiry, it is not necessary to include children or vulnerable individuals in the testing phases. All data collected will be anonymised and therefore it is anticipated that ethical considerations will be limited to physical conditions of the test process e.g., ensuring sound levels are within recommended limits and to avoid participant fatigue.

1.7 Thesis Structure

The following chapters form the remainder of the thesis, along with brief outlines of the content within each:

2. **Literature Review**: The literature review is a comprehensive appraisal of existing relevant research and publications. The review explores current thinking in terms of timekeeping experimentation, test methodologies, entrainment, and group testing. This chapter explains the reasoning behind the linear nature of the test phases leading to the research findings of the thesis in chapter eight**.**

3. **Methodology**: Chapter three outlines the experimental design that underpins the thesis. Broad test methodologies are established and discussed in connection with the thesis questions. Whilst test variables (e.g., metronome type and conditions) are set, it is acknowledged that initial findings will influence future test conditions as experimental phases progress.

4. **Stimulus to Research – A Pilot Study**: A pilot study, carried out by the thesis author which led into this PhD research journey is discussed in this chapter. This experiment establishes the initial test methodology and provides tentative research findings upon which subsequent test phases are based.

5. **Experiment 1: Individual study with Cross-rhythmic and Isochronous Metronomes**: In this chapter, the findings of the first comprehensive test stage are discussed. This chapter introduces the key concepts that shape the successive test phases, looking exclusively at quantitative data collection.

6. **Experiment 2: Group Study with Cross-rhythmic and Isochronous Metronomes**: This chapter reflects upon the data collection and subjective responses from participants who took part in this experimental phase. This experiment introduced the combination of group testing and altered metronome states – withdrawing and reintroducing the metronome playback – to assess the impact of its variation on group entrainment.

7. **Experiment 3: Audio Visual Metronome Test**: This chapter describes the final phase of testing, culminating in the implementation of bespoke software that uses a combination of audio and visual stimuli. The results of the quantitative data collection are discussed and the potential implications of the subjective research data of this test phase are examined.

8. **Conclusions**: In this chapter, all the unique findings from the test phases are discussed and the new contributions to knowledge are established. The impact and effect of these contributions to the research area are outlined and critically analysed.

9. **Future Work**

10. **References**

11. **Appendix**

1.8 The Researcher: Musician, Teacher & Engineer.

This section is a discussion of my personal professional experience and observations from my time as a musician, teacher, and engineer, which are relevant to the research thesis as they provide context and further demonstrate my suitability as a researcher for this topic.

1.8.1 Musician.

I have been a professional musician for 25 years. During that time, I have worked as a performing musician, studio musician, music teacher, and audio engineer. In all these guises, musical timekeeping ability has been the catalyst for a number of discussions and debates, as the skill of keeping good time is so important for a musician.

It is widely accepted that the original role of drums was to act as a provider of tempo and reference for dancers, musicians and even soldiers (Brensilver, 2015). As a drummer, it often feels like this perception remains, and that the responsibility of keeping other musicians in an ensemble in time is yours alone. Having worked with many musicians consistently over the course of my career, it is my experience that accurate timekeeping in an ensemble is a reciprocal relationship.

Early on in my career, I would regularly record in a studio setting and be required to play along with a metronome. Typically, this metronome consisted of a standard tone, akin to a high-pitched percussion instrument. The metronome pattern would be isochronous and only represent the tempo of the music being played. I worked with a well-known producer who introduced me to the concept of a cross-rhythmic metronome and my timekeeping in the studio setting immediately improved, or certainly my perception of my own timekeeping. The use of different metronome types has also proved effective in some of the groups I played

with, where each individual musician is playing to the same tempo but has differing amounts of rhythmic information in their metronome feed, according to personal preference. Though these responses have been largely instinctive, this research hopes to test, evaluate, and provide evidenced tools and workflows for other musicians approaching the challenge of timekeeping. Over the course of the research, I have also observed many instances where the perception of performance in timekeeping has differed from the measured data. For instance, those performing poorly felt that they were highly effective and vice versa, those with excellent timekeeping believed that their abilities were sub-optimal or poor. This research hopes to foreground the often-overlooked skill of timekeeping and increase awareness and understanding of its function and importance.

The terms ’feel’ and ‘groove’ are naturally subjective descriptions of the perception of the way in which a piece of music is played. Drummers, in particular, are often described as playing slightly ahead or slightly behind the beat, as this changes the ‘feel’ of the piece of music that’s being performed. With this in mind, those performers could be judged to be less-effective timekeepers than musicians who match the onset of the beat more precisely on average.

Throughout my career, I have acquired a breadth and depth of experience in areas that are impacted by timekeeping. Having worked internationally as a musician and recording artist in Canada, North America, Europe, and the UK, I have participated in, and observed, a range of tools and practises that support and require effective timekeeping.

1.8.2 Teacher

Teaching, whether instrumental or classroom music lessons, provides challenges when supporting young musicians or beginners in learning the concepts of beat, meter, and rhythm. The process of practicing timekeeping in an effort to improve, is often lower on the list of priorities for many musicians, despite its importance. As Emile Jaques-Delcroze discovered, if we can teach learners to control the interactions of conscious thought and physical action, we can train them to alter and adjust their rhythmic responses, both as an individual and as part of a group:

> "*They would be in a state of attention and concentration; they would be alerted to the slightest change in sound or rhythm; they would become aware of their own rhythms and the rhythms of others;…they would become more aware of the differences between individual and ensemble performance; and they would be better able to solve the problems that arise when different people have different approaches to rhythmic movements that must be synchronized or harmonized by the group*". (Choksy, Abramson, Gillespie, & Woods, 1986)

Having worked as a peripatetic music tutor for 15 years, I am all too aware of the pressures, of both time and resources, allocated to music tuition in the education system. I have observed first-hand the understandable focus on learning to reproduce pieces of music for assessment, rather than a skills-focussed approach, where timekeeping is valued in and of itself as a facet of musicality.

Whilst efforts have been made to include timekeeping exercises in assessment, these typically require musicians to play music along with rigid, isochronous target patterns. These target patterns remain unbroken, although at higher levels of assessment, there are often variations in tempo and meter (see Fig 4.1). There has been development of ensemble-based syllabuses for instrumental tuition too, and during the course of my teaching career, there has been an expansion to include examinations as a group and for individual musicians to play with pre-recorded backing tracks (ABRSM, 2019; LCM Examinations, 2018).

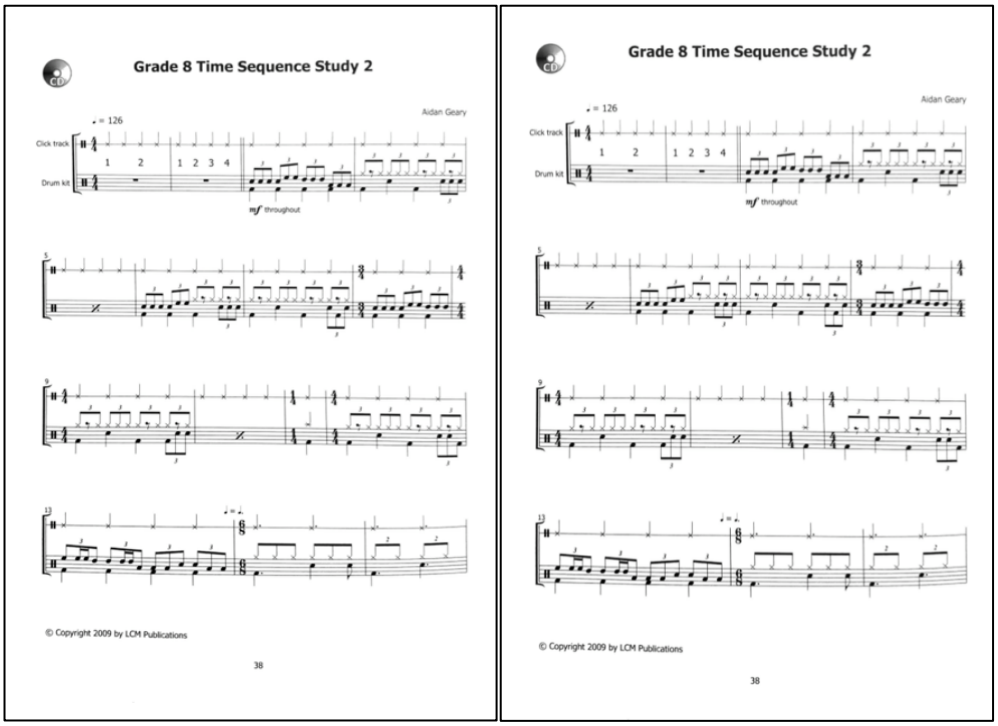

Fig 1.3 An example of a timekeeping study for a Drum Kit grade 8 exam (Geary, 2009, from LCM Publications).

I am keen to understand the factors that affect timekeeping, the ways in which we might measure timekeeping and retain a sense of musicality, and what tools or methods could be applied and be developed to assist musicians with this core skill. I have seen many examples where the time afforded to instrumental students simply isn't enough to go beyond the instruction of fundamental techniques. I have experienced the challenge of teaching students on a shared instrument, with a finite window available each week and with the added requirement to ensure that these students were able to demonstrate measurable progress e.g. grade exam success. When calculating the time available to each student in these circumstances, where they were directly able to play the instrument under instruction, the window of availability has been as small as four minutes per week, per student.

In one instance, after a student had failed an assessment, we undertook extra-curricular lessons to try and rectify any shortcomings in the student's playing ability. Once we were able to spend a longer period of time together each week on a one-to-one basis, the student successfully progressed through the assessment. The main shortfall in the student's skillset were a timekeeping exercise and a piece that involved playing to a backing track.

Whilst the aspiration to provide democratic access to music tuition is to be lauded, limited resources can force a student and their teacher to prioritise certain technical aspects of playing an instrument, over other, less obvious skill requirements. If we can understand the factors that influence musical timekeeping, we may give ourselves the tools to enhance the way in which we instruct, assess or guide musicians who are learning their instrument.

1.8.3 Engineer

As an audio engineer, the work you undertake is directly affected by the timekeeping abilities of the musicians you work with, when recording live performance or in a studio environment. With developments in software, the ability to edit and polish performances is more readily available than ever before. The tools available in software allow for the adaption of metronomic information available to musicians (Cook, 2013), but these metronomes are still framed in the context of "hitting the fenceposts". The process of editing those recordings introduces an overhead of time and associated cost, and from an artistic perspective, could be seen as less authentic or pure, removing much-celebrated elements of 'feel' or 'groove'.

I have experienced this, as a recording engineer, producing a series of musical performances for the BBC (BBC, 2021). Ten artists performed across multiple venues with limited recording time and resource due to the restrictions COVID 19, where only a few takes were possible. Performers that used click tracks or backing tracks were significantly more consistent in accurately matching the target rhythm or metronome (akin to the concept of "hitting the fence posts), than those that did not, and the latter group of performers required substantial postproduction in order to produce recordings that met the required standards for broadcast.

The catalyst for this research thesis has been my experiences as a musician during my professional career. As an undergraduate student, I designed a test to measure ITIs (Inter-tap Intervals) of participants under different tempo conditions and using two different metronome types: one a more traditional isochronous audio metronome, and the other a cross-rhythmic audio metronome. Whilst the design of that test constituted the formal submission for another higher education award, the statistical analysis of the ITI data was not part of the submission and was conducted subsequently, specifically for the purposes of this thesis. As such, the results have formed a stimulus to research for this thesis.

A brief explanation of the test process is described in the subsequent section, as the test methodology contributed to the experimental design of the experiments described in later chapters. It is the statistical analysis of the ITI data that has had particular influence on the nature of the experiment stimuli and test conditions selected for testing in this thesis.

I returned to education in my thirties, pursuing an undergraduate degree in Music Technology. I have continued to teach music alongside my roles as a lecturer, recording engineer and professional musician, and these differing strands of my professional experience have influenced and motivated my interest in this research area.

It is entirely appropriate that we measure the ability to synchronise with a metronome or other musicians and use that measurement to express the accuracy of a person's timekeeping. There is a significant amount of research in this field that concerns itself with variations of these types of sensorimotor experiments; investigations that examine asynchrony or distance from a target pattern marker to express timekeeping accuracy. There are examples of continuation tests that measure interval durations after participants have synchronised with a metronome, although this has not been considered as a trait of musicality necessarily - I feel this should be investigated further. Using a metronomic stimulus is undoubtedly a useful tool for refining musical timekeeping in the traditional sense of meeting target note onset. However, I believe that if we are able to measure the consistency of the musician's note onset, rather than the distance from a target metronome pattern, and establish any influence variations in the metronomic information we provide to musicians (whether as an individual or as a group) might have, we might reveal an alternative or complimentary way in which to consider and assess good timekeeping.

1.9 Summary

This research aims to investigate the factors that affect a person's capacity to produce and maintain a consistent ITI, and to provide recommendations for the tuition and assessment of this ability. The research questions provide the structure to devise and implement a series of test phases, in addition to existing research that will enable rigorous examination of the

concept that differing combinations of metronome type and state can positively influence the musical timekeeping of individuals.

The identification of the key themes considered in the thesis are *entrainment* and *sensorimotor musical timekeeping*, alongside their relationship with each other. These themes will act as a binding concept throughout the test phases and help shape the conclusions that come with the research findings.

The linear nature of the testing phases should provide a platform from which to build and adapt test methodologies, learning from previous test results and processes and constructing more complex test designs that yield more quantitative data which can inform the conclusions of the thesis.

2. Literature review

The literature review is a comprehensive appraisal of existing relevant research and publications. The review explores recent thinking in terms of timekeeping experimentation, sensorimotor test methodologies, entrainment, and group testing. This chapter explains the reasoning behind the linear nature of the test phases leading to the research findings of the thesis in chapter eleven.

2.1 Introduction

The purpose of this literature review is to establish central test methodologies and to examine current literature in key areas of entrainment and sensorimotor timekeeping. This literature review will assess the relationship and correlation between central research questions and the current thinking in timekeeping research, leading to the formation of a research framework.

The literature review is structured to reflect the key themes of the thesis: entrainment and sensorimotor musical timekeeping, and within those themes, sub-categories of group testing, metronome state (present or removed), metronome type and the testing of untrained and trained participants. These themes and categories are reflected in the research questions established in section 1.4 of the previous chapter: *Research Questions and Objectives*.

2.2 Search Strategy

This literature review is comprised of the key research in entrainment and sensorimotor musical timekeeping to date. It was collated over a six-year period, started at the commencement of the PhD studies, and was updated and amended up until the time of writing the final thesis. The strategy for compiling the literature review was primarily focused on utilising several research databases, including OpenAthens, Google Scholar, ACM Digital Library, AES E-Library, Taylor & Francis and IEEE Xplore.

The search for significant literature utilised key words and phrases to identify relevant research. These key words and phrases were *timekeeping, sensorimotor synchronisation, tapping experiment, isochronous pattern, inter-onset interval, inter-tap interval, ITI, IOI,*

entrainment, pattern reproduction, isochronous pattern reproduction, preferred tempo, groove, metronome, metronome present, metronome removed, and *metronome reintroduced.* The scope of these search criteria was then refined based on the results of the initial searches.

2.3 Discussion

2.3.1 Theoretical Literature - *Groove*

It is important to understand the context in which the experimental work for this thesis is set. Although empirical data collection will inform the outcomes and answers to the Research Questions, it is necessary to establish a conceptual framework in which this research sits. Empirical, quantitative data collection enables practical recommendations to be made, but it is relevant to consider other areas or research that may shape these recommendations.

In "*The evolutionary neuroscience of musical beat perception: the Action Simulation for Auditory Prediction (ASAP) Hypothesis*" (Patel & Iversen, 2014), the authors describe a theoretical model that they developed through the synthesis of a broad review of practical research. The hypothesis is not informed by practical testing conducted for the authors' article specifically but rather brings together several strands of inter-connected research. In their hypothesis (ASAP), they predict that motor planning and auditory regions of the brain communicate in a specific fashion when predicting rhythms or beat periods. As such, the ASAP hypothesis proposes that physical movement has a "*causal role in beat perception"* (Patel & Iversen, 2014, pp. 8) and that moving in synchronisation with a beat enhances timing perception. Furthermore, it is suggested that disruption to the motor planning region of the brain may have a negative impact on beat perception.

This is a comprehensive article that provides a thorough review of neuroscientific research in the area of beat perception, culminating in the proposition of a number of testable predictions. The article does not contain any test data for these predictions or provide specific instructions for how best to conduct any testing of enhanced timing perception through synchronised movement.

Patel & Iversen (2014) discuss the practical, empirical approach to measuring beat perception and event prediction, but it is also important to consider the more nuanced and subjective concepts surrounding sensorimotor synchronisation and musical timekeeping.

Malone (2022) in "*Two Concepts of Groove: Musical Nuances, Rhythm, and Genre*", discusses the concept of *groove* from a musicology and ethnomusicology standpoint. The author posits that there are:

> "*at least two distinct concepts of groove. On one account, the groove is "the feel of the music" and, on the other, the groove is the psychological feeling (induced by music) of wanting to move one's body"* (Malone, 2022, pp. 345).

In terms of feel, Malone argues that one popular theory of groove is centred around deviations in microtiming within music, stating that proponents of what Malone calls "*musical nuance theories*" agree on these microtiming variations as the "*sonic correlates of groove*" (Malone, 2022, pp. 347). As a direct example, Malone suggests that a piece of music may be notated identically but interpreted differently by two different drummers, suggesting that some performers may choose to "push" or "pull" bass drum or snare drum strikes, effectively sounding the notes slightly earlier or later in the beat window. It is, in fact, these microtiming choices that give the music its *feel* or *groove*. This concept suggests that whilst groove can be perceived subjectively in some respects, there are some quantitative parameters that can measured objectively.

Malone does pose an interesting question: who or what is responsible for generating the groove? As the article points out, there is some disagreement amongst musical nuance theorists as to whether the groove is generated by an individual musician, an ensemble, the piece of music itself or perhaps even the genre of the music (or some combination of all of these possibilities). Once again, if some measurable parameters of groove or feel can be established, it may be possible to move toward an answer to this question.

In "*Embodied Mind, Situated Cognition, and Expressive Microtiming in African-American Music*", Iyer (2002) discusses similar ideas of microtiming as the construct of groove. Whilst

this article is occasionally quite philosophical in its assessment of the concept of groove, there is a large amount of discussion that is focused on the practical parameters of timekeeping within a piece of music. As Iyver states: "*In groove contexts, musicians display a heightened, seemingly microscopic sensitivity to musical timing (on the order of a few milliseconds)*" (Iyver, 2002, pp.398). This statement may not, therefore, apply to non-musicians or non-performers. Iyver also goes on to suggest that:

> "*Individual players have their own feel, that is, their own ways of relating to an isochronous pulse…..This variety of expressive timing against an isochronous pulse contains important information about the inner structure of groove*" (Iyver, 2002, pp. 398).

It is possible to surmise from this that musicians are able to adapt their performance and adjust their timekeeping to create or establish a groove. In this case, Iyver uses the example of an isochronous pulse as an anchor point from which musicians may stray slightly, through the use of deliberate microtiming variations. However, this discussion is directed specifically at experienced musicians. It may inform the dialogue further to test whether non-musicians have the same ability. It is possible that a non-musician has a sense of groove, and therefore an innate sense of event arrival, but is not experienced or aware enough to purposefully adjust their timekeeping.

In general terms, *groove* isn't seemingly a term that has a universal, agreed definition. As Kiel (2010) discusses in his article "*Defining 'Groove'"*:

> "*A groove can happen whenever two or three different personal "time-feels" or "intrinsic motive pulses" interact. Typically this could be a bassist and drummer in a jazz, rock, blues, or any "rhythm section" but it could also be one person, a drummer at a trapset whose feet and hands are generating "participatory discrepancies." The Participatory Discrepancies or PDs are measurable differences or discrepancies in attack points and release points along a time continuum*" (Kiel, 2010, pp. 3).

Kiel discusses the almost intangible quality of what defines groove, even going as far as to suggest that the term "entrainment" is too in-organic to fully explore or describe the concept of *groove*. However, the author is able to provide examples of how real-world scenarios might go some way to defining groove; the inter-play between a rhythm section, the slight discrepancies in phase between musicians, or even the interaction between the limbs of a drummer. These microtiming variations are, in essence, the measurable parameter of *groove*. The extent, duration or variance of these timing discrepancies (intentional or not) and how they define groove may be debatable, but it would appear clear that the ability to entrain perfectly with external stimuli or other musicians isn't the only parameter that might define musical timekeeping.

2.3.2 Method

"*Musicians' movements for timekeeping: A link between tapping and musical experience*" (Harris, Manning, & Schutz, n.d.) is a study designed to investigate and confirm the hypothesis that trained participants would be more adept at predicting the placement of a tone or beat in an isochronous sequence than untrained participants. The study also suggested that trained participants would be more accurate than untrained participants when asked to take part in a timing discrimination task. This study drew upon musicians as its trained participants and non-musicians as the untrained participants. It is worth noting that the trained participants were all degree-level percussionists.

The experiment was split into two conditions: both asked participants to judge whether the final tone in a sequence was 'on-time' or not. The first condition allowed participants to move in time with a reference sequence. After a reference sequence of isochronous tones was played, the sequence would stop for one musical bar before the judged tone would sound. This tone would be 'on-time' or 15%/30% of the IOI late or early (the timing of the tone was randomly selected). Participants were asked to tap along with the sequence, hitting a sensor pad with a drumstick and continuing when they predicted the tone should arrive (essentially mimicking the IOI).

The second condition of the experiment repeated the process of the first but without allowing the participants to move. In both instances, participants were asked to judge whether the final tone was 'on-time' i.e. precisely on a down beat.

The results suggest that the trained participants were more adept at accurately predicting the placement of the next isochronous tone and more able to judge when the tone was out of time. The results show that non-trained participants were less likely to be able to judge when a tone was out of time but were still more likely to notice an IOI of +30% than +15%.
The authors of the report conclude that musical training has an influence over timing discrimination tasks and that this training is likely to reduce the level of asynchronous taps produced. They also suggest that the motor skills acquired specifically by percussionists allow for more accurate taps, especially when compared to those of untrained participants.

The suggestion that musicians are more likely to produce less asynchrony in tests of this nature has been made in other studies (Aschersleben, 2002; Repp B. H., 2007) and this experiment is largely an extension of that. The exclusive use of percussionists as research participants could be seen to limit the scope of the study and the results themselves. Unfortunately, the number of participants that took part in this study is not available.

"*Does an auditory distractor sequence affect self-paced tapping?*" (Repp B. , 2006) is a study aimed to investigate the possible effect that a deliberately distracting and asynchronous audio-timing sequence can have on participants who are attempting to tap at a conflicting tempo. Whilst more concerned with the effect that the auditory distractor may have on self-paced tapping, the experiments in the study also examine the effect that these distractors may have on tapping with isochronous sequences, and with and without auditory feedback.
The study briefly discusses alternative investigations that have noted the potential entrainment with visually perceived movement, both in-phase and anti-phase (Richardson, 2005). The work of Richardson *et al.* used paired participants and asked them to swing pendulums together at a preferred tempo and to maintain that tempo, so that any entrainment patterns might be observed. Some trends were observed but the overall conclusion is that this form of entrainment is intermittent and rarely complete – referred to as *relative coordination* (Repp B. , 2006). The use of pendulums in this way is less precise than

other forms of input, however, Richardson *et al.* are less concerned with the precision of input, rather the observation of any impact visually perceived movement may have on entrainment.

In the first of the study's two experiments, participants were asked to tap a digital percussion pad along with a target or *T* sequence of 'freely-decaying piano tones' (fixed at G#5), played back and measured using Max MSP v3.0. After an introduction of six T tones, a *D* (distractor) sequence of tones (either A#5 or E7) would sound. These D tones had an IOI of either 450ms or 550ms, compared to the fixed IOI of 500ms assigned to the T sequence. In addition, the intensity of both sequences would vary, using different MIDI velocities for the tone sequences; in this case, the two MIDI velocities used were either 30 or 60 resulting in a relative difference of approximately 10dB (Repp B. , 2006). This resulted in a possible 16 combinations – two tempi of the D sequence, two pitches of the D sequence and two differing intensities of T and D sequences. There were eight participants in experiment 1 (including the author), all of whom had experience of synchronisation experiments and were of a high standard of musical training.

Each tap was measured for its proximity to the target isochronous event. In this case, taps that 'lead' the beat would be given a negative value. The standard deviation for asynchronies were calculated for each trial and then averaged out over the trial repetitions. These results were then subjected to ANOVA with repeated measures with the variables of tempo, pitch and intensity (Repp B. , 2006).

The results of this experiment showed that the largest effect on variability was when the T sequence was quieter than the D sequence. Variability was less when the T sequence was louder than the D sequence. Both results were described as significant and had a *p value* of $p<.0001$. No other effects were described as significant, including the tempo or pitch of the D sequence.

Experiment 2 was designed to investigate the effect of a distractor when the participants were not provided with a target or reference sequence. This experiment used eight participants (six of whom were involved in experiment 1) and used similar equipment and materials.

This experiment asked participants to tap in time with an initial target sequence, which would have an IOI of either 400ms (fast tempo) or 600ms (slow tempo). Participants were asked to continue their tapping as the T sequence stopped. After a gap of either 4000ms or 6000ms respectively, the D sequence would begin for 20 tones. The sequence would have IOIs of -10%, -5%, 0, 5% or 10% e.g. -10% of a T sequence with an IOI of 400ms would be 360ms. Both T and D sequences had the same MIDI velocity for the produced tones. As there were two T tempi and 5 D tempi (in addition to a no-D trial), 12 different trial types were produced. However, two additional conditions were integrated to the experiment – feedback and no-feedback.

The same 12 trials were completed by participants (with the order of the 12 trials randomised), with feedback from the digital percussion pad and without. These two conditions were tested in separate sessions, usually a week apart. The auditory feedback from the percussion pad produced the same tone and velocity as the T sequence tones.

The author of the report carried out similar statistical analysis on these results to those of experiment 1. The results suggest that participants sped up slightly once the T sequence had stopped, with the ITIs generally shortening on average. At the faster tempo, the presence of the D sequence appeared to have little effect but did affect the mean ITI at the slower tempo. Again, ANOVA with repeated measures confirmed this (p<.007).

The study also investigates any correlation between the tempo of the D sequence and the mean ITI. The author admits that these results are difficult to interpret, but they would suggest that '*the phase and period of the taps were not entrained to those of the D-tempi*' (Repp B. , 2006).

The results of this study suggest that auditory distractors influence timekeeping accuracy. In particular, the effect would seem more pronounced when the auditory distractor is in competition with a reference or target sequence. The results also suggest that without a reference sequence, the auditory distractor may have an effect at slightly slower tempi. However, as both experiments involved a small number of participants, it is perhaps difficult

to come to these conclusions with any real certainty. It is also possible that the introduction of untrained participants would change the results of these experiments further.

In "*Synchronization with competing visual and auditory rhythms: Bouncing ball meets metronome*" (Hove, Iversen, Zhang, & Repp, 2013), the authors investigate the influence auditory and visual distractors may have on a participants' ability to synchronise with a target pattern, whilst audio or visual distractors were played at various off-sets in-tempo. Hove *et al.* cite the previous work of Bermant & Welch (1976), Bertelson & Ascherleben (1998), Bertelson & Radeau (1981), Vroomen, Bertelson, & de Gelder (2001) and Warren, Welch, & McCarthey (1981) in support of the statement that when visual and auditory stimuli are used to convey localisation, the visual stimuli will assume dominance, whereas the auditory stimuli are rarely dominant. This is an example of the "Ventriloquist Effect", an auditory illusion whereby sounds will "*appear to emanate from plausible visual objects, regardless of the actual source of the sound*" (APA, 2018). The authors also tell us that when the two differing stimuli (audio and visual) are used to convey temporal information, the opposite effect is usually observed, with the audio stimuli assuming dominance over the visual. This is sometimes referred to as "Temporal Ventriloquism". Again, the authors refer to a number of previous studies to support their statement (Burr, Banks, & Morrone, 2009; Fendrich & Corballis, 2001; Morein-Zamir, Soto-Faraco, & Kingstone, 2003). In this study, the authors aim to examine the differences between two competing schools of thought. "Modality appropriateness hypothesis" suggests that audio stimuli will more dominant in its influence in temporal processes and that visual stimuli will be more dominant in spatial processes. However, the more contemporary "optimal integration hypothesis" suggests a more nuanced solution, defined by the precision and clarity of the relative stimuli in both temporal and spatial processes.

Hove *et al.* (2013) tested a total of 29 participants, divided into two categories: music experts (12) and visual experts (17). The music experts were musicians who regularly practicised their respective instruments, were studying music an university level and had acheived an excellent standard of musical performance. The visual experts comprised a mixture of video gamers who were experienced in games that required high levels of manual dexterity and timing (e.g. racing games) and sportsmen and women who played sports on a weekly basis that required

high levels of hand-eye coordination and manual dexterity. The participants were asked to maintain a target pattern (led by either an auditory or visual pattern) whilst either an auditory or visual distractor was also present – this distractor was not part of a regular pattern and would vary in its position from the target pattern. The participants were asked to perform this a number of times, with differrent variations i.e. auditory target and visual distractor, visual target and auditory distractor, both stimuli paired exactly.

The experiment tested 29 participants, which is a comparitively large number in sensorimotor tasks. The distance of the participants' taps from the intended rhyhmic pattern were collected and recorded via a drum pad and into a custom-designed MAX MSP patch. The results of the experiment were assessed and analysed by using ANOVA with repeated measures and yielded no statisically significant findings in terms of the dominance of one distractor type over another, although there is some suggestion that the characterisitics of the pool of participants may have some influence on the results. Some of the participants had taken part in sensorimotor experiments previously, and this may have improved their abilities before this particular test. It is also very difficult to arbitrarily split the particpant pool into two distinct groups; some of the musicians (if not all) are likely to have some level of skill in the visual distractor task as they are probably well-versed in following conductors. Conversely, some of the visual experts are likely to have some musical experience, regardless of what level of expertise. Nonetheless, Hove *et al*. are able to make this statement:

> "*a distracting spatiotemporal visual rhythm can be as effective as a distracting auditory rhythm in its capacity to perturb synchronous movement, but its effectiveness also depends on modality-specific expertise*" (Hove, Iversen, Zhang, & Repp, 2013, p. 388).

It is important to note that this was specifically an investigation into audio and visual distractors; effectively a conflict task. However, the authors discuss the design of their visual distractor and their reasoning for it. The visual target or distractor was a computer generated "bouncing ball" that offered some movement leading up to and away from the target beat. The authors cite Iversen *et al.* (2015) as a benchmark for the entrainment of participants with a visual metronome. Iversen *et al.* were able to conclude that a "bouncing ball" i.e. a visual

metronome with movement rather than a simple visual flash, "…*can be as effective as an auditory metronome in entraining participants' movements…*" (Hove, Iversen, Zhang, & Repp, 2013, p. 395). The authors acknowledge that in a previous experiment, Hove, Spivey, & Krumhansl (2010), used a bouncing ball visual metronome but that this might have been less effective as it was presented without any tempo-related acceleration or deceleration leading up to or away from the target beat. It was also presented at a faster tempo, which may negatively influence a participants ability to synchronise with the visual metronome.

"*Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli*" (Jäncke , Loose, Lutz , Specht, & Shah, 2000) is a research report that was designed to further investigate the work of two other studies in the field of finger tapping, "activation and continuation" conditions (i.e. the introduction and removal of a rhythmic stimulus), and brain imaging studies - Rao, *et al.* (1997) and Penhune, Zattore, & Evans (1998). In describing their chosen method of testing, Jäncke *et al*. (2000) discuss the limitations of the two preceding studies and how their research might address the gaps left. Jäncke *et al.* (2000) discuss the results that parts of the brain were active during the "activation" phase in both studies and remained active during the "continuation" phase in the case of Rao *et al.* (1997) (this study used auditory stimulus only), although in the research conducted by Penhune *et al*. (1998), there was unfortunately no continuation phase, despite the implementation of auditory and visual stimuli. Jäncke *et al*. (2000) suggest that these findings support the notion that the brain provides auditory pacing stimuli, even when no external stimuli exist; effectively an internal metronome. Jäncke *et al*. (2000) designed a test that would investigate the processes involved in the brain when test subjects were asked to tap along with the sequence when separately exposed to auditory and visual rhythmic stimuli, and when the test subjects tapped along to the stimuli when it was present and when it was removed.

The results of the research suggested that tapping was more variable in the visual tests, when compared to the auditory tests. The results also reported that there were some parts of the brain that were active during all conditions, there were parts of the brain that were more active during the visual conditions and other parts that responded during the auditory conditions. Ultimately, the researchers concluded that the ability to tap along in synchrony

with auditory or visual stimuli relies on different sub-structures and motor control modes of the brain.

Jäncke *et al*. (2000) were looking specifically at the activation of the regions of the brain in different conditions, using MRI (Magnetic Resonance Imaging). As such, their methodology maintained certain elements that might not suit testing in another context, or with a different hypothesis in mind. For example, 8 subjects were tested in the research process, all of whom were right-handed and none of whom were asked about previous musical experience. This number could be considered quite low in a different research context, as it might be difficult to draw significant statistical meaning from such a small group. The test subjects were also asked to perform the tests in the same order which, in the context of brain imaging, makes more sense than if it were a larger study that was concerned with timekeeping performance. The research does contain some records of ITI, although this is only really used as secondary, and more contextual information when discussing the results of the brain imaging. It is important to note that the ITI results of each participant are combined for the different conditions (audio activation, audio continuation, visual activation and visual continuation) but that there is no condition where the stimuli are re-introduced.

There have been studies that investigate the impact gamification can have on instructing musicians in musical timekeeping. In one such example, "*Multimodal Metronome — Rhythm game for musical instruments*" (Hoang & Cohen, 2022), the authors examined the effectiveness of a timekeeping game that provides users with auditory, visual and haptic feedback and stimuli. Although an early prototype, Hoang & Cohen were aiming to emulate and expand upon the concepts developed by games such as Guitar Hero (Harmonix & RedOctane, 2005), Beat Saber (Ilavský & Hrinčár, 2018) and Just Dance (Ubisoft, 2009), which effectively reward users if their timekeeping is accurate. The movement of each user and their Joy-Con controller is used as an input signal, and the software would record the number of "right" and "wrong" attempts to synchronise with an isochronous pulse. The input signals were recorded into Unity (Unity Technologies, 2023) and the haptic feedback was accessed through the Nintendo Switch operating system. Interestingly, the authors state that:

> "*To make it easier for players to track strike progress, some extra features indicate entrainment, such as a green light that illuminates when the player is on the right beat ("in the pocket" or "in the groove"), turning red when they're on the wrong beat*" (Hoang & Cohen, 2022, pp. 7).

The authors provide no details as to the window of the "right beat"; they only show that it is measured in milliseconds. The concept of *groove* is not explored in the paper, so it is difficult to ascertain the specific parameters the authors are using to define "in the groove" or whether a user has successfully entrained with the target pattern.

"*Ensemble Musicians' Synchronization with Conductors' Gestures: An Automated Feature-Extraction Analysis*" (Luck & Toivainen, 2006) is a study of a musical ensemble's synchronisation in a real-world scenario. The research investigated the accuracy of an ensemble that consisted of 26 orchestral musicians and 16 choral singers, all with a good level of musical experience. The researchers used optical tracking data of a conductor and cross-correlated 12 variables in the movement data of the conductor with the spectral flux of an audio recording of the ensemble to calculate synchronisation accuracy.

Luck & Toivainen explain that studies of this nature tend to offer different results from laboratory-based testing of simple tapping exercises, as the rhythmic complexity is far greater in an orchestral musical piece. However, these types of research are concentrated on isolating which movement type or speed of the conductor allows for greater accuracy in a large ensemble. Indeed, the authors report that there are variable rates of accuracy in individual, isolated testing of musicians versus the results of an ensemble. They find that in the four short excerpts that they analysed, the highest rate of synchronisation came from the two excerpts with "high clarity" of the conductor's movement (although the authors admit that the definition of "clarity" in this context was subjective and based on individual musicians' interpretation of the beat). It is worth noting that the four excerpts were similar in tempo, with no increase or decrease in speed and the excerpts were between 8 and 11 seconds in length. It is difficult to draw comprehensive conclusions about training musicians to keep time from excerpts of this nature, although the connections to group entrainment are very relevant. In fact, the authors state:

> "*We might suppose that musicians would synchronize primarily with their fellow musicians, while following the conductor in a somewhat looser fashion. Support for this comes from the many anecdotal accounts suggesting that musicians tend to "lag behind" the conductor's temporal gestures, while still maintaining a high-quality performance (i.e., the musicians are highly synchronized with each other)*". (Luck & Toivainen, 2006, p. 189).

"*Temporal control mechanism of repetitive tapping with simple rhythmic patterns*" (Yamada & Yonera, 2001) describes the results from the researcher's investigation into the concept of memory mechanism and its influence on the "temporal control" participants display in a series of tests. This effectively confirms that the interval of an ITI tap is determined by the preceding 20 taps, although in this case, the participants are asked to perform a simple two or three-beat pattern. The patterns are made up of long-time and short-time values (see Fig. 2.1).

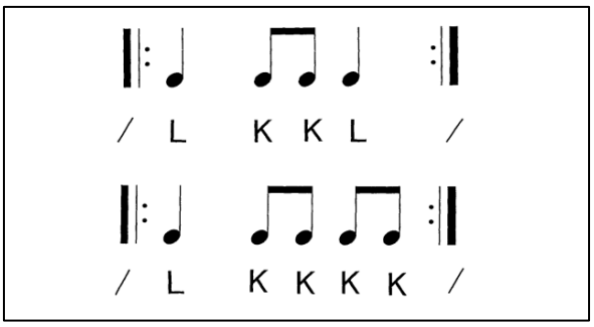

Fig. 2.1 An example of short, two or three-beat rhythms where L (*lang* in German) is the long-time value and K (*kurz* in German) is the short-time value (Yamada & Yonera, 2001).

The research is presented as the collected results from three test phases and determines that the point at which the memory mechanism switches between the long-time value and the short-time value is around a tap interval of 350ms (170bpm) for the short-term value or 700ms (85bpm) for the long-term value.

This is a tapping experiment that investigates differing rhythmic patterns rather than a simple isochronous pattern. The tests use a variety of tempos, with intervals from 185ms to 1000ms. The authors determine, using ANOVA, that tempo and the individual are statistically

insignificant in terms of their influence over the approximate 20-beat window that defines memory mechanism. The three tests provide the participants with constant auditory stimuli rather than introducing then removing it – it is possible that the removal of the auditory stimulus would influence the tap interval at which the memory mechanism switches, or indeed the number of preceding taps that is defined as memory mechanism. Test 1 uses five participants; Test 2 uses five participants and Test 3 uses 10 participants. However, with the repetition of some participants between tests, there is only a total of 12 musically trained participants.

"*Processes underlying adaptation to tempo changes in sensorimotor synchronization*" (Repp B. H., 2001) discusses the results of two experiments designed to explore a participants' ability to adapt to tempo changes when performing a tapping exercise alongside a simple isochronous auditory stimulus. The experiments were designed to investigate the time it takes for the phase of the participants' taps (i.e., 'in-phase' or 'antiphase') to adapt once the tempo change has been implemented in the audio sequence and to also investigate the period of time it takes for participants to adapt the duration of their ITIs to the new tempo. Each experiment used 500ms as the baseline IOI, with increase or decreases in tempo that ranged from 1% – 3%.

The first experiment was used as a means to confirm the findings of Thaut, Miller, & Schauer (1998) – that is:

> "*In synchronising finger taps with an auditory sequence, a small sudden tempo ('step') change in the sequence tends to be followed by rapid adaptation of the tapping period but slow adaptation of the relative phase of the taps, whereas a larger step change leads to initial period overshoot followed by rapid adaptation of both period and phase*" (Repp B. H., 2001, p. 277).

Repp's first experiment confirmed these findings, and the results of the second experiment also supported them.

The first experiment asked eight participants (half of whom had extensive prior musical training and one of whom was the author of the research paper) to tap a MIDI keyboard along

with an audio sequence, changing the key depending on whether they felt an increase or decrease in tempo. The participants were told that there would be a tempo change at some point, but to only change key when they genuinely heard it. The timing data was collected via a custom-designed MAX MSP patch. A repeated measures ANOVA was used on the ITI data to ascertain the adaptation of the participants' taps to the changes in tempo. In the second experiment, a very similar method was used, but with noticeable differences. Experiment 2 asked participants to continue tapping after the sequence had stopped, in an attempt to ascertain the accuracy of the participants' ITIs (at the end tempo of the sequence) once the metronomic stimulus had disappeared. The end of each sequence was also varied, resulting in sequences that would stop between one and eight taps after the tempo change. The author also included some sequences without tempo changes to try and eliminate any erroneous or 'false alarm' results. There were six participants in total for this experiment, four of whom had taken part in Experiment 1 (again, including the research author).

The results from these experiments showed that decelerations in tempo would appear to be easier to perceive than accelerations. It also showed that the 'continuation' ITIs of participants (those ITIs that were measured once the auditory sequence had stopped) would seemingly correct themselves or "settle" after approximately five taps. It was also concluded that correction of the performed ITIs was faster when a tempo change had been identified, rather than when a tempo change had been missed or misidentified. As the author states, there are problematic issues with this conclusion: the fact that participants were aware of an imminent tempo change may have influenced their performance. When the performance data was analysed for the false alarm conditions, there were missing data points which might make the analysis of the data less reliable. The author also notes that his performance displayed an instantaneous period correction when a tempo change was detected – this pattern was not evident with the other five, less musically experienced participants. The small number of participants may cast doubt on the reliability of the results, or more likely a difficulty in extrapolating any meaningful inference for a wider population.

"*Synchronization Error of Drum Kit Playing with a Metronome at Different Tempi by Professional Drummers*" (Fuji, et al., 2011) is a study that investigates the ability of 15 professional drummers to play a simple beat in time with a digital metronome over three

different tempos. The researchers then measured the synchronisation error of the three limbs that each drummer used to voice the instrument (hi-hat, snare drum and bass drum) and were able to determine the rate of error for each drummer over the three different tempos used (60bpm, 120bpm and 200bpm). The participants were all professional drummers and were of a mixture of approximately 75% right-hand dominant and 25% left-hand dominant, although each drummer was able to set the drum kit up to suit their personal preferences. The drummers were asked to play a beat that corresponded to the isochronous metronome that was played back to them for a period of 60 seconds (see fig 2.2). Each strike of each individual drum or cymbal was recorded through close miking techniques and the waveforms of these recordings were gated and filtered to allow comparison to the waveform of the corresponding metronome beat, allowing for measurement of the distance of the participants' strike from the expected IOI (synchronisation error). A two-way ANOVA was used to analyse the results of the average synchronisation error over the three tempos (as absolute values) to ascertain what factors might influence the accuracy of the timekeeping of each participant.

The researchers proposed that whilst there was a rich seam of research in the field of sensorimotor synchronisation, the vast majority of this research was concentrated on finger-tapping experiments and that the extra motor-skills involved with playing a drum kit with sticks (rather than a simple finger tap) might have an influence on the participants' ability to synchronise with the beat. They also theorised that musical experience or training, tempo and auditory feedback could influence the synchronisation error results of the participants.

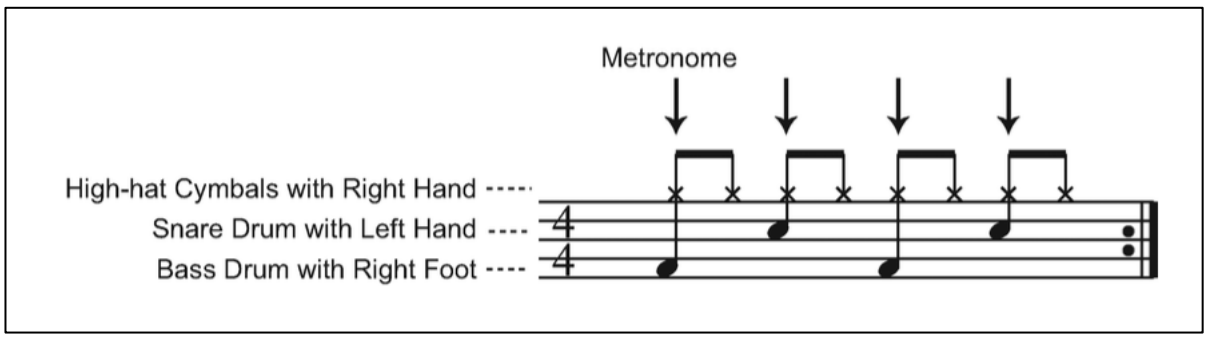

Figure 2.2 The drum score provided to each drummer. The downward arrows show the IOI of the digital metronome (from Fuji, et al., 2011, p. 493)

Fuji *et al.* (2011) concluded that the absolute values of the average synchronisation error were, in general, smaller than the error values of other finger-tapping studies, although this could be partly a result of the previous musical experience of the participants. It is the contention of the authors that this study is further evidence that use of a drum stick rather than the traditional finger-tapping technique will reduce the synchronisation error values. Their previous investigations (Fuji & Oda, 2009a; Fuji & Oda, 2009b) suggest that the use of a drumstick in this situation will have a positive effect, as it promotes a more stable ITI (although it is important to note that this research focused on drummers specifically, so previous experience using a drumstick may affect this outcome). Overall, Fuji *et al.* state that drumstick use is more appropriate in timekeeping tests as "….*holding sticks leads to changes in sensory information such as tactile, auditory, and kinaesthetic feedback information*" (Fuji, et al., 2011, p. 500). They concluded that the statistical relationship in their results between synchronisation error and 'motor effectors' suggested that "*each limb synchronized in relation to the other limbs rather than independently with the metronome*" (Fuji, et al., 2011, p. 491). The results also suggested that at the higher tempo (200bpm), the synchronisation error for all limbs was approximately double that of the error values at the slower tempos (60bpm and 120bpm). The researchers observed differences between the results of dominant hand synchronisation error (hi-hat) and the other two limbs (snare drum and bass drum). At 60bpm and 120bpm, they observed almost no synchrony in the dominant hand, whereas the trailing hand and foot showed 'negative mean synchrony' i.e. slightly ahead of the beat on average. At 200bpm, the results for the trailing hand and foot showed very little asynchrony, but the dominant hand showed evidence of 'positive mean synchrony' i.e. slightly behind the beat on average. Fuji *et al.* (2011) are able to explain this to a degree, citing a number of studies that suggest foot tapping will generally be ahead of a finger tap (Aschersleben & Prinz, 1995; Aschersleben, et al, 2002; Billion, et al, 1996). The researcher's results are consistent with previous studies that suggest the time it takes for sensory information to travel from the ear to the brain is shorter than the neural distance between the foot/hand and the brain (Aschersleben G. , 2002; Fraisse, 1980). However, this generally accepted hypothesis of nerve conduction does not explain the differences in synchronisation error between the two hands (the same neural distance) and the authors are not able to offer an explanation for this.

"*Pinpointing The Beat: Tapping to Expressive Performances*" (Dixon & Goebl, 2002) is a study aimed to investigate the timing of taps when participants are provided with expressive, musical stimuli. In this experiment, participants were required to tap along with three musical excerpts that had been performed and recorded by a pianist prior to the experiment. The authors hypothesized that any timing changes or fluctuations between inter onset intervals that are tapped will provide a smoother curve of variability than those of the performed notes.

The experiment tested 25 musically trained participants, asking them to tap an audio cable in time with the musical excerpt. The use of an audio cable is purported to have eliminated any latency - the electrical noise of the cable was used as the audio feedback for the participants. The musical stimuli provided to the participants (and repeated randomly 18 times for the experiment) were three different sections of a Mozart piano sonata. Over half of the participants were pianists.

The authors measured the timing of the tapped beats (tapped inter-beat interval or t-IBI) and the performed notes or beats (performed inter-beat interval or p-IBI). The time between two successive taps could provide a measure of tempo. The authors also used an averaging process of all tapped notes to provide an overall tempo marking.

The study finds that the tapped beats provide a smoother curve of variability than the performed beats. This supports the original hypothesis and suggests that fluctuations in timing of performed stimuli are not perceived as tempo changes. Only when changes in p-IBI persist do participants perceive a change in overall tempo.

Two further experiments were conducted in the study – a comparative preference test and an experiment using a multi-media computer program (although this second experiment was largely deferred as further work). The comparative preference study confirmed the results of the main experiment of the study – musically trained listeners preferred a set of clicks that displayed a smoothed variability curve (played simultaneously with a performed excerpt).

The study provides an interesting insight into the perception of beat and tempo. It is suggested that perceived beats are not affected by random fluctuations in accuracy but, in fact, beat perception is largely based on anticipation.

Whilst the study observes these trends, the authors (by their own admission) provide little in the way of explanation. The study uses participants that are trained musicians, and, to an extent, this may limit the conclusions that can be drawn from the study. The additional experiments (comparative preference and multimedia tests) are also limited and require further work.

2.3.3 Tempo

In "*Preferred Tempo Reconsidered*" (Moelants, 2002), the study considers the preferred (or perhaps, optimal or natural) tempo for humans. The author suggests that whilst 100bpm has been regarded as the de facto preferred tempo, it should be significantly higher – in the order of 120bpm.

The study reviews relevant literature and uses data from the author's own experiments to confirm this hypothesis.

The study asked 34 musically trained participants to tap a preferred tempo (defined as a 'comfortable rate'), before and after an experiment in tempo synchronization. Whilst these 68 results provided a wide distribution of tempi, there was an obvious peak around the region of 450/500ms. This test cannot be considered conclusive, but it does add some weight to the additional literature considered by the study.

The author discusses several scientifically established phenomena that support the need to reassess the preferred tempo. Initially, three separate laboratory experiments are considered. These relate to natural walking speed, variability in finger tapping experiments and the natural speed of repetitive applause. The results of all these experiments lend themselves to the suggestion that preferred tempo is in the region of 120bpm. It is important to note that the author acknowledges the potential problems with these results e.g. natural walking speed may differ according to age or gender. The study also investigates the

distribution of tempi in recorded music. This investigation used an Internet-based library of dance music (utilizing 'bpm lists'). This provided a large body of test material and a relevant genre to test preferred tempo through movement (in this case dancers). The analysis of this material found prevalence in tempo around the region of 120bpm.

In both these areas of study, the author notes a correlation between preferred tempo and 'octave' relationships i.e. a connection between 120bpm and the factors or multiples thereof.

2.3.4 Metronome Removal

"*Effects of practice on variability in an isochronous serial interval production task: Asymptotical levels of tapping variability after training are similar to those of musicians*" (Madison, Holm, & Karampela, 2013) is a study aimed to establish that practice could influence the variability of timekeeping of participants in a tapping experiment, and to investigate whether this practice would reach a point at which no further improvement upon the variability could be discerned. Ultimately, the findings of the study show that practice can decrease the variability of timekeeping, both locally, and the general drift over entire sequences, although there is no discussion of the long-term effects on timekeeping. The study suggests that this decrease in variability stops after approximately the first hour of practice, regardless of the type of task the participant is asked to perform or the type of sensory feedback the participant is given. The authors indicate that these results are likely to relate to motor implementation rather than cognitive timing processes (Madison *et al.* 2013).

The study consisted of two distinct experiments. Experiment 1 required participants to tap a regular, steady pattern – initially with a metronome and then without, for 70 events or beats each time. This is described as isochronous serial interval production (ISIP) in the study. The participants were required to complete this task in four different response modes: a finger tap, finger waggling, drumstick and wearing a custom-made wrist cuff. The decision to use these differing response modes is explained by the authors as an attempt to illustrate the variance in response times between traditional response modes; the study contains data from previous studies that suggest a finger tapping response provides slower response times (and potentially more variability) than a drumstick response mode (Fujii, 2009; Madison &

Delignières, 2009). The finger waggling and wrist cuff response modes represented further efforts to reduce the tactile information that came with other response modes.

For the first experiment, eight participants were recruited. All participants were between the ages of 25 and 36 and declared themselves not to be professional musicians. The participants were asked to tap along with a metronome in differing response modes and conditions – the distance between the set audio events varied from 500ms to 574ms. These inter onset intervals (IOI) were chosen to provide easier intervals for non-musicians to tap along to. The authors of the study suggested that any IOI smaller than this would prove difficult for untrained participants.

Experiment 2 used similar techniques but only implemented full sensory feedback and only the drumstick response mode. However, the IOIs were varied and ranged from 500ms to 1624ms. The participants were asked to perform this task 18 times with varying IOI, compared to the three differing IOI in experiment 1. This allowed the authors to test and compare the levels of variability between ITI and drift of the entire sequence. As the results and data for both experiments were recorded using a custom-built computer program and trigger-to-MIDI interface, it was possible for the authors to compare and amalgamate the test results for analysis. For the results of experiment 1, the study used a repeated measures ANOVA. This provided results for local variability, response mode and sensory feedback that were statistically significant.

The overall results suggest that practice can influence the variability between ITI but less so on drift. The authors of the study suggest this effect is largely connected with the improvement and increased familiarity of motor response, and that practice is unlikely to have affected the intrinsic timing abilities of participants.

The experiments were conducted separately and over an extended period (approximately one month), which suggests that the effects of practice on variability could be measured with a degree of ‘real-world’ accuracy. However, the small number of participants (and the ambiguous nature of their previous experience) renders the findings of the study suggestive, rather than conclusive.

"*Sensorimotor synchronization and perception of timing: Effects of music training and task experience*" (Repp B. H., 2010) assesses the basic synchronisation skills of a group of 31 students. Nine of these participants are university-level music students and are classed as 'musical experts', with the remaining participants classified as either 'amateur' (have some musical training) or 'novice' (no musical training). The author determined that there were three specific ways in which to test these basic synchronisation skills: a phase correction test, a period correction test, and a tempo continuation test. In the phase correction test, participants were asked to perform an isochronous pattern along with an auditory metronomic pattern. The phase shift of this target pattern was implemented four beats before the end of the sequence and varied between -50ms and 50ms from the established phase. In the tempo continuation test, participants were played a target isochronous pattern and asked to synchronise to it. After a set period of beats, the metronome was removed, and the ITI of each participant was recorded. Similarly, in the period correction test, the metronome was removed after the IOI of the final four beats of the target pattern had been altered by a duration between -50ms to 50ms. In all, there were 165 short trials for participants to complete. In all cases, the participants tapped a drum pad, and their timing data was collected via a MAX MSP patch that had been designed for the experiment, although the author acknowledges that there was a measurable delay between physical taps and the registering of those taps in the MAX patch. These delays were subtracted from the participants' ITI data.

The author used a repeated measures ANOVA to analyse the averages of each test (i.e. variance from target pattern for the phase correction and ITI duration for the tempo continuation and period correction tests) and was able to draw the following conclusions:

- In the phase correction tests, the novices displayed an almost instantaneous phase correction, whilst the amateurs and experts displayed a slower response on average. However, Repp (2010) concludes that there is no statistically significant relationship between phase correction and musical training and instead surmises that performance is negatively affected by familiarity with synchronisation tasks, rather than musical experience.

- The participants were asked to comment after the trials on whether they could detect the phase shifts in each test. The musicians did considerably better than the other participants in detecting phase shifts in the trials, and the amateurs were more accurate in their observations than the novices. The author notes that the amateurs and novices appeared to be more accurate in their observation of positive phase shifts (increase in IOI) than negative phase shifts (decrease in IOI).

- In the tempo continuation test, musicians showed lower variability than the remaining participants. The amateur participants showed slightly lower variability than the novices, but this wasn't statistically significant. It is important to note that the variability of ITIs was calculated by averaging the middle three taps from the final five taps of each participant, only capturing a small window of data immediately after the target pattern had been removed.

- For the period correction test, the same method of analysis was used as in the tempo continuation test, although the target tempo was based on only the last four IOIs of the target pattern. The musicians were again adept at period correction, but surprisingly, the non-musicians displayed a near-perfect period correction on average, which disagrees with some of the findings in the authors' earlier work (Repp B. H., 2001; Repp & Keller, 2004).

- The author also notes that the non-musicians appear to show more accuracy in detecting the legthening of a IOI rather than a shortening (i.e. they were able to detect a decleration in tempo more easily than an acceleration in tempo).

2.3.5 Entrainment and Group Testing

In "*Interaction in musical time*" (Himberg, 2014), one purpose of the study was to investigate the difference between the timekeeping synchronicity of an individual and that of a group or pair. The study showed that human-to-human tappers achieved better synchronicity than human-to-computer tappers, although the human-to-human pair drifted in tempo. Himburg

attributes this phenomenon to 'mutual adaptation', suggesting that this could not happen in the interaction between an individual and a computer-based stimulus. A second experiment investigated the 'rhythmic entrainment' of participants (with varying levels of expertise) from varied ethno-musical backgrounds. This experiment used motion capture to study the movement of participants, and subsequently analyse how mutual adaptation facilitated synchronicity between them. This concept of mutual adaptation is supported by the work of Repp & Doggett (2007), in which they identified that larger onset intervals in target patterns resulted in reactive responses from participants rather than anticipatory responses. Human-to-computer tappers are likely to react to, rather than anticipate, an external, computer-generated target pattern. Human-to-human tappers, therefore, will react to each other's' patterns and 'mutually adapt' over time. It is noteworthy, however, that when target onset intervals were increased (to intervals ranging from 1000ms to 3500ms) it was observed that non-musicians produced fewer reactive responses than musicians.

Over the course of two sessions, a total of 32 participants were involved in the experiment (seven pairs in the first session, nine pairs in the second session). No information is given regarding the prior training or expertise the participants may have had, although the nature of the experiment suggests that each participant had some musical experience.

Each participant was provided with a MIDI drum pad to tap - allowing for measurement of the impact but also audible feedback for each participant. Each participant listened to a metronome for a limited number of bars and then tapped along. There were three different types of trial: synchronised, alternating, and rhythmic. The participants did not know if they were tapping with a human partner or a computer. The computer tapper was given four different conditions, varying in accuracy and duration. This variance provided seven different conditions under which participants might be asked to tap along.

Each individual tapper was unaware of whether the other tapper was their human partner or the computer-based tapper i.e. one human tapper could hear themselves and their partner, whilst the other human partner would hear themselves and the computer-based tapper.

The results of these tests were analysed to establish any possible variance between human-to-human and human-to-computer tappers. Only the period between the cessation of the metronome and the termination of the test was analysed. The measurement and analysis varied depending on the type of test: synchronised, alternating, or rhythmic. For example, when analysing synchrony, the phase values of a participant's results were compared to that of their (human or computer) partner. No consideration was given to general tempo drift. The other conditions did consider tempo drift but were also concerned with grouping the results into categories that matched participants that tapped along to a human or a computer partner.

The author of this study clearly feels that previous experiments have taken an old-fashioned approach to measuring musical timing. However, this study seems more concerned with investigating entrainment or rhythmic synchronisation that with absolute metronomic accuracy. In fact, the author states that tempo and rhythmic accuracy is at its highest when a participant plays with a predictable, regimented computer metronome. Interestingly, the highest level of synchronisation or entrainment occurs with a human partner, although this does incur some tempo drift. As this study is not concerned with the accuracy of participants matching a metronomic audio event as much as it is with the entrainment of trial partners, it is the data gathering and analysis methods that are of relevance to **RQ2**: *"What effect does playing in a group, versus individually, have on musical timekeeping?"*.

"*Modelling single-person and multi-person event-based synchronisation*" (Elliott, Chua, & Wing, 2016) is a summary of research in single-person timing to simple metronomes cues, inter-personal synchronisation between pairs or larger groups, and tapping experiments that implement tempo and phase shifted cues. The authors discuss the dual measurement of phase correction and period correction. These terms refer to the adjustments made by participants when they themselves make timing errors or changes in the phase of an external stimulus occur, or when errors in the consistency of ITIs are made by participants or changes in the tempo (period) of the external stimulus occur. Tapping experiments and the use of isochronous metronomes are discussed with some of the earliest examples of individual timing experiments (Stevens, 1886) as context, but one of the key conclusions drawn is that:

> "*In terms of paced tapping, it is the central timekeeper interval, and its variability, that determine synchronisation accuracy with the metronome. Timekeeper variability tends to increase with longer interval durations, whereas motor variability, remains at a relatively small value*". (Elliott, Chua, & Wing, 2016, p. 168).

There is discussion about the use of changes of phase and IOI period with auditory stimulus to assess the ability of participants to adjust or correct their own phase or ITI duration. Perhaps one of the most interesting points raised here is that any correction made by participants is seemingly consistent across feedback or 'effector' method i.e. there appears to be no difference in the results whether the participants are finger-tapping, moving upper limbs or moving lower limbs in the timing task. The authors also address the issue of whether a correction of phase is also a correction of ITI. They conclude that the work of Repp (2001) may answer that question to an extent, effectively suggesting that corrections made by participants are less noticeable when the tempo of the auditory stimulus remains constant before it is removed:

> "*The period change observed in the subsequent finger tap intervals suggested that phase correction resulted in an adjustment to the central timekeeper interval. Differences in the involvement of period change in the phase shift paradigm and the constant metronome paradigm might in part account for the correction gain differences observed in (Repp, Keller, & Jacoby, 2012)*" (Elliott, Chua, & Wing, 2016, pp. 169-170).

Elliott *et al*. broaden the discussion of synchronisation research to include two-person synchronisation. They cite four studies that investigate the nature of two-person synchronisation through a variety of methods. Goebl & Palmer (2009) used paired participants to perform different parts of a simple piano duet at 133bpm, with the participants' note strike recorded through a MIDI piano. Their results showed that the adaptation to a consistent tempo was more accurate when both participants could hear each other, rather than when only one could hear both contributions. In this condition (with only one 'hearing' partner) the accuracy was more influenced by the participant who could hear only themselves. Konvalinka, Vuust, Roepstorff, & Firth (2010) yielded very similar results

from their research, which only differed through the use of finger tapping as a means of input. In discussing the work of these two studies, Elliott *et al*. are able to draw the conclusion that as a general rule, two-person synchronisation uses the bi-directional information of the previous note or tap onset from each partner to correct asynchrony and ITI of the current note or tap onset.

As the authors go on to describe, Vorberg (2007) has developed a formal model of 2-person synchronisation. In Vorberg's study, the digital metronome used this model to synchronise with a human partner, effectively emulating the the variance expected from two human participants. The variance of correction of the computer model could be adjusted and manipulated by the researcher to investigate the limits of effective synchrony (the model can be seen in fig 2.3).

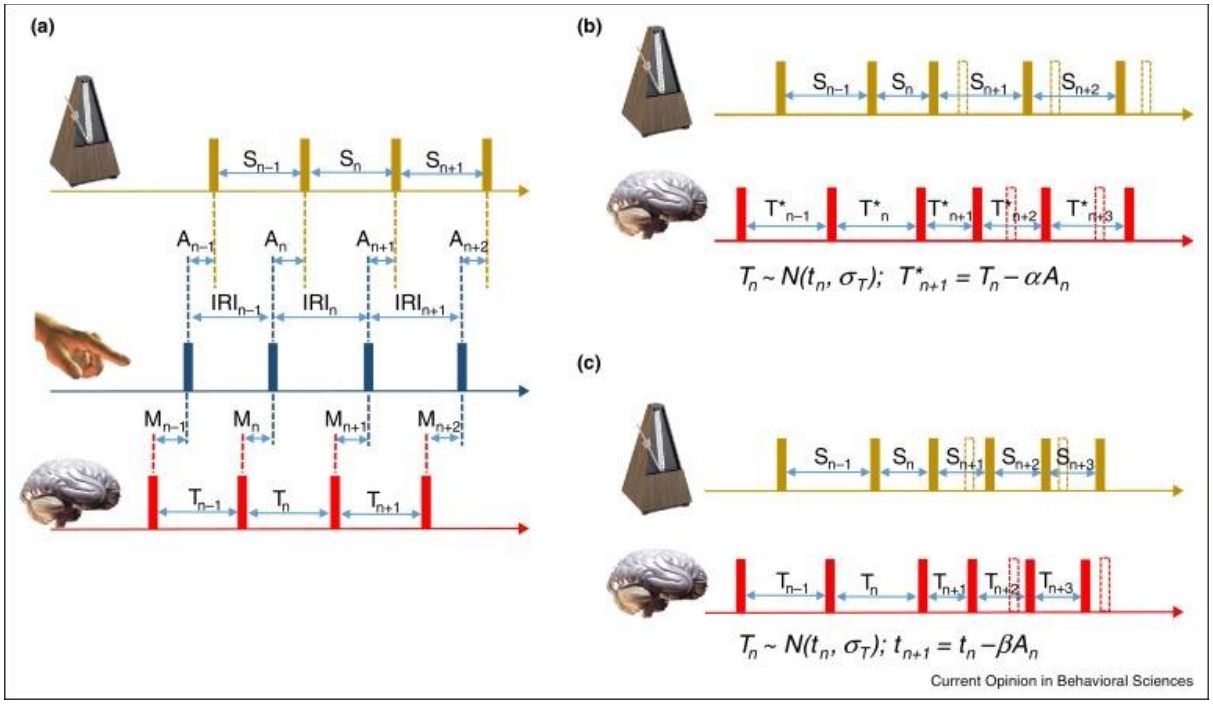

Fig 2.3 A first-order linear phase correction model, developed by Vorberg (2007)

"*where α is the correction gain, A_n is the current event asynchrony, T_n is the time interval generated by an assumed internal timekeeper, M_n is the current motor implementation delay, and S_n is the current metronome interval*" (from Elliott, Chua, & Wing, 2016, p. 168).

This model was further manipulated and investigated by Repp & Keller (2008) in their work, which supported the accuracy of the Vorberg model, as well as the concept that there is a

specific range of adaptation or correction that either individuals or groups must stay within to successfully entrain. Elliott *et al.* conclude that "*regardless of the number of people synchronising, the sum of the correction gains must remain within this range to achieve stable synchrony*" (Elliott, Chua, & Wing, 2016, p. 171). This statement applies only to the participants' phase correction (in-phase or antiphase), and not period correction (ITI).

Finally, the authors of the report discuss multi-person synchronisation and cite three separate studies that investigate the timing relationship between groups of participants. The first example, Wing & Woodburn (1995), examines the hypothesis that rowers on the same side of a boat would synchronise the catches of their oars, as they must maintain physical separation from each other as the oar hits the water. Wing and Woodburn discovered that in actual fact, it was corresponding pairs of rowers from each side of the boat (right and left) that achieved synchrony.

Wing, Endo, Bradbury, & Vorberg, (2014) apply this concept of paired analysis in a more musical context. Using pairwise analysis of a string quartet, Wing *et al.* were able to draw the conclusion that as the size of the ensemble grows, the optimal gain for individual musicians decreases (i.e. the amount of adjustmnent a musician can make to achieve synchrony with other musicians is reduced).

As a further part of their study, two string quartets were tasked with performing a short extract a number of times and the phase correction of each individual was calculated. In one group, it was clear that the first violinist lead the ensemble, as that individual made less correction than the other musicians i.e. the remaining three musicians treated the first violinist as the dominant timekeeper. This conformed to the traditional role of a first violin in a quartet and to the expectations of the researchers.

The second groups results were different – there was no dominant timekeeper, and as a result all of the phase corrections of each musician were more or less equal to each other. Elliott *et al*. conclude that these results are likely due to the physical arrangement of the quartets (in a circle with other musicians in sight) and the likelihood that the first violin in group 1 adopted a more traditional playing style that lead the group, whereas the first violin in group 2 was likely a more democratic member of their respective quartet.

The third example study of multi-person synchronisation referred to the work of Honisch *et al*. (2016). In this study, a group of six participants were tasked with using visual cues to try and entrain a tempo within a circle. A designated leader would be the only participant to hear an isochronous auditory sequence and would convey the tempo with arm movements to the participants either side of them. Honisch *et al*. discovered that the resultant corrections made were inconsistent with their expectations and that this was likely to be due to the physical arrangement of the group (all participants facing outward, with only two other participants within their view).

These examples of multi-person synchronisation are largely concerned with the social interaction between participants and Elliott *et al*. cite that as a growing area of interest for research. Each of these examples use groups of a size that is above the norm, but only a limited number of groups. It would be useful to observe the consistency of the findings of these studies if a larger number of groups were used.

"*Interpersonal Entrainment in Music Performance: Theory, Method, and Model*" (Clayton, et al., 2020) is a comprehensive study of literature and research in the area of musical entrainment. The authors use a combination of analysis of existing research and their own analytical data of existing musical extracts to develop a model for measuring and assessing entrainment in musical performance. Their work discusses the variety of ways in which entrainment can be measured and they broaden that discussion to include inter-personal dynamics, social interaction and ethnographic differences in musical cultures.

Clayton et al are clear that the simplest way to begin analysing synchronisation between two musicians is to use "*Discrete Data Analysis*" (Clayton, *et al*., 2020, p. 155), which is effectively the measure of the difference in distance from a musician's input and either a known temporal event or another musician's input. The authors also suggest that circular statistics are a common method of processing and assessing the relationship between pairs of musicians. The authors state that phase analysis has been thought of as better suited for the assessment of group entrainment

> *"…partly because exploring the stabilization of phase is more consistent with a dynamical systems model of entrainment than calculating the variability of asynchronies. However, using relative phase data for comparison between multiple genres is problematic: the phase calculations depend on the specification of a reference period, and different kinds of music have different types of metrical structure that make it impossible to establish a single objective definition of this period"*. (Clayton, *et al*., 2020, p. 156).

In this instance, the authors have highlighted the difficulty in assessing entrainment in a real-world scenario, with more complex rhythmic input than existing sensorimotor tests that require the reproduction of simple isochronous patterns. Clayton et al discuss a number of other methods of analysis, but these methods are primarily used to ascertain the social and inter-personal effects of entrainment in a musical performance e.g. leadership or dominance.

The study discusses the nature of the analysis conducted on the musical extracts chosen for investigation. In these instances, one of the primary strands of analysis is "*Onset-based Comparative Analysis*", described as "*…calculating time differences between the onsets of nominally simultaneous auditory events. In the simplest model of SMS between two individuals*…" (Clayton, *et al*., 2020, p. 157). This method of analysis is designed to measure the entrainment of two or more musicians but could easily be expanded to include a target pattern i.e. metronome (see Fig. 2.4). In fact, the authors list discrete instrument/event onsets as one of the most common methods of data collection in interpersonal musical entrainment studies, alongside audio waveform recordings.

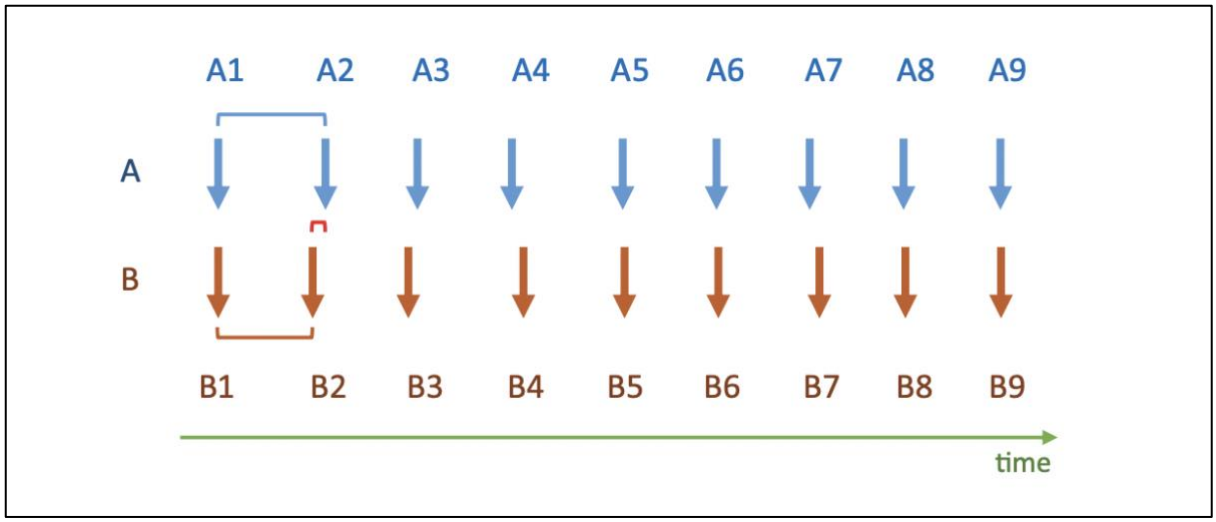

Fig 2.4 "*Events produced by two individuals have onset times represented by the arrows in rows A and B. The blue and brown brackets indicate the inter-onset intervals between the first pair in each sequence; the red bracket indicates the asynchrony between onsets A2 and B2*" (from Clayton, *et al*., 2020, p. 158).

Clayton *et al.* assess and compare the onset timings between instrument types, with a mixture of instruments including a number of instruments less familiar in traditional Western music. In their study of the six ensemble extracts, percussion instruments were generally closer to perfect asynchrony than other instrument types, although the authors acknowledge that these results may be skewed by the sample size and nature of the groups analysed. For example, 'lead' instruments will tend to be ahead of the beat – in some of the musical extracts included for analysis, the percussion instrument should be classed as the lead instrument, as this is ethnographically appropriate. The pairwise comparison of the instruments showed that percussion instruments tended to produce more closely synchronised results:

> "*We have clearly seen that pairwise synchronization between drums or percussion instruments is tighter than that involving melodic instruments, while pairs including plucked string instruments are tighter than those involving bowed instruments... This progression is from short envelopes with clearly defined onsets to more sustained sounds with less defined onsets*". (Clayton, *et al*., 2020, p. 168).

This result does suggest that for timing and synchronisation tests (and in particular, entrainment), the use of percussion instruments is likely to produce the most accurate results, as the percussive nature of hitting or striking an instrument is more equitable across mon-

musicians and musicians, when compared to more instrument-specific movement like bowing or plucking. The study has used more rhythmically complex patterns as a means of measurement, rather than an isochronous pattern that may be more familiar in other sensorimotor synchronidsation tests. As a result, the authors have also been able to evaluate the effect of sub-divisions of meter (what might be otherwise defined as cross-rhythms) have on synchronisation and entrainment when producing these conclusions.

Overall, the model developed by Clayton *et al*. is one that encompasses a wide spectrum of research strands. The definition of musical performance is not limited to instrumentalists. The study includes an investigation into the entrainment of vocalists and dancers, and has specifically targeted cultural and social differences across music genres to highlight where these differences may influence musical entrainment.

2.4 Summary

Research in the field of sensorimotor synchronisation and entrainment contains a number of different *foci*, despite its seemingly narrow scope. The emphasis in the majority of finger-tapping or isochronous pattern reproduction experiments is on in-phase synchronization with a target pattern (audio or visual), rather than any real investigation into the consistency of a participant's ITI. Most literature refers to these two abilities as both sides of the same coin, but there is a discrepancy in the volume of investigation between "hitting the fence post" of a target pattern and the ability to produce a constant, isochronous pattern. The investigation of which factors influence this ability to produce consistent ITIs will address **RQ1:** "*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping*".

There have been studies that address the idea of continuation, and, within these, there has been some investigation of a participant's ability to produce a consistent ITI. However, these studies only remove the target pattern or metronome and do not reintroduce it. The reintroduction of a metronome could provide further information about the factors that influence a participant's synchronisation or tempo continuation skills. The studies that have removed the metronome have generally measured the continuation of ITIs for a short period after the target pattern has stopped. There is definite scope to increase this period and

observe the effect an extended duration of metronome-absence may have. These gaps or opportunities for further investigation would address **RQ1**: "*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping".*

There are studies that address the differences in participants' performance between auditory and visual metronomes. The long-held belief was that auditory metronomes stimulated an improved response when asking participants to perform a temporal reproduction task. However, there are some studies that now suggest that a visual metronome that includes a non-linear representation of temporal movement, rather than a simple timed flash, can stimulate similar results to that of an auditory metronome. It may be that a familiarity with one mode or the other would influence a participant, and it may be that tempo (particularly in a visual condition) has an influence on ITI consistency. There appears to be an absence of research that addresses audio/visual metronomes in combination over tempo, with removal and reintroduction. Testing of this nature would address **RQ1:** "*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*" and **RQ3:** "*What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping.".*

These research questions are not mutually exclusive to one particular area of the proposed research. Indeed, it is likely that experimental work will address multiple research questions and influence test design over the duration of the thesis. The existing research contains a number of consistencies that will positively influence the experimental design for the thesis. There is a clear consensus that synchronisation with target patterns and ITI are two of the main factors that define effective synchronisation and timekeeping, certainly in the sense of sensorimotor tapping exercises. From a more fundamental point of view, the averaging of ITI data and the use of parametric statistical tests (such as ANOVA) are common approaches to carrying out experimental work in this field. There are other practical elements that are consistent across the current research methodologies, including finger-tapping, use of drumsticks in synchronisation experiments, the use of MAX MSP as a data recording and playback platform, and the use of audio waveform recordings as a temporal measurement tool. When discussing synchronisation, most studies use negative or positive mean asynchrony as a measure of accuracy. In terms of ITI, the averaging of intervals and

expressions as absolute values is considered the norm. Use of this averaging in conjunction with the calculation of ITI as a percentage of tempo will allow the measurement of musical timekeeping to be kept the same over tempo and be regarded as a valid comparison.

In terms of group performance and entrainment, there are studies that are primarily focused on the social interaction of a group or ensemble. These inter-personal dynamics are likely to play their part in the entrainment of a group performing a timekeeping task but there is not a vast amount of research on the topic of group entrainment with differing metronome types or the removal of a metronome during a synchronisation test. This leaves an opportunity to explore the measurable performance of groups of participants, utilising the methodology established in existing research studies, to assess the averaged ITIs of these participants under variable test conditions. Specifically, this gap in existing research can be addressed by **RQ2:** "*What effect does playing in a group, versus individually, have on musical timekeeping*?".

From a more theoretical perspective, the collection of ITI data using differing metronome conditions, types, and tempi may present the opportunity to investigate the concept of groove in musical timekeeping. Whilst musicologists and ethnomusicologists don't always agree on the definition of groove, it would appear to be accepted that microtiming deviations or variations are a factor in "what makes groove, groove". It is possible to measure these microtiming deviations through the collection of ITI data. If we assume that musicians can adjust their microtimings within a performance to create a feel or groove, perhaps deliberately arriving early or late to a beat window, then it follows that the measurement of pure asynchrony ("or hitting the fenceposts") may not be the only parameter that should be measured when assessing good timekeeping. A performer could maintain a consistent ITI whilst also being consistently early or late to a beat window. It is also relevant to observe if non-musicians are capable of this too, whether consciously or subconsciously. Group performance may have an effect on groove, as the process of mutual adaptation may take place and create a groove, demonstrated through closely aligned group entrainment.

3. Methodology

3.1 Introduction

This chapter will outline the methodology that underpins the thesis and addresses the research questions specified in Chapter 1. The purpose of this chapter is to establish the core test methodologies that were employed in the testing phases of the research and will act as a guide for replication of the work or as a basis for further research.

One goal of the research is to establish what factors may influence a person's ability to accurately produce consistent Inter-Tap Intervals, and to investigate which factors or conditions may improve this ability. In broader terms, the results of these tests inform the overall research ambition; that is, to try to preliminarily identify practices or procedures that may positively influence timekeeping in a real-world, musical scenario, whether as an individual or as part of an ensemble. The research questions are designed to investigate individual factors that may combine to provide a framework that enables the assessment and design of a structured regime for practice or performance for musicians to improve their timekeeping.

3.2 Research Aim

As stated in Chapter 1, the Research Aim of this thesis is to perform a technical exploration of different metronome configurations and develop preliminary recommendations for musical timekeeping education and assessment.

The framework from which the Research Aim will be addressed will be centred around these research questions:

- **RQ1:** *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*

- **RQ2:** *What effect does playing in a group, versus individually, have on musical timekeeping?*

- **RQ3:** *What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?*

- **RQ4:** *What implications do the findings of the previous research questions have for musical timekeeping education and assessment?*

These research questions will provide a platform to explore the overall research aim of the thesis. They provide focal points for each test phase and offer a structured approach to identifying the key factors that may influence timekeeping abilities. Some of the research questions relate to established, common practices in the field of sensorimotor synchronisation and inter-personal entrainment, but it is the combination of these questions and the related findings that provide a unique contribution to existing knowledge in this area.

3.3 Study Design

It is important to determine that the correct methodology and framework for analysis has been selected for the test phases in this thesis. Experimental work allows for direct observation of any changes in participants' ITI when presented with differing metronome configurations. This empirical real-world data is central to establishing statistically significant trends found within the results of the test phases. This data is also crucial in establishing any causal relationship between participants' performance and differing metronome conditions or configurations. This research is intended to generate empirical findings that inform preliminary recommendations for teaching and practice; to do this, data collection is essential. Whilst an observational study of musicians in a more authentic performance setting might provide the opportunity to detect entrainment and timing patterns, it would be difficult to study the causal effects of differing metronome conditions, as control over the test variables would be limited. Case studies would provide a platform from which to study the development of individuals or groups of participants over time, however, the results may not inform any findings that could be expanded to form recommendations for timekeeping tuition or practice, as it would not be possible to generalise these results. A longitudinal study of a consistent set of participants with varying metronome instruction may provide insight into the evolution of their synchronisation abilities, but this process would require a significant

and sustained commitment from participants and might still require some experimental manipulation. Computational modelling would potentially allow for the creation of a mathematical model of synchronisation or potential ITI variance, but without the input of several participants, this could oversimplify the dynamics of the human response to metronome configurations. In this context, experimental work with a focus on direct observation and real-world outcomes is the most relevant study design.

Alongside the experimental work designed for this research, participants were asked to complete a short 5-point Likert scale questionnaire after each experiment. These responses provide insight into the participants' perception of their own timekeeping during the test phases. Whilst a questionnaire of this type does not yield the specific quantitative data needed to test the differing metronome configurations, it does provide us with an idea of the participants' subjective experiences which in turn gives context for the results of the ITI data collected.

The study design for this thesis and its associated test phases represents a true experimental design, rather than quasi-experimental or correlational, in that it offers control over the order and number of independent variables, a randomisation of test order and, ultimately, the measurement of a known variable (Campbell & Stanley, 2015).

True experimental design is a suitable model for the experimental phases described in the thesis, but this model does give rise to the possibility that the causal inferences derived from the results and findings are applicable to the test environment more than in a real-world setting.

It is important to ensure that the data collected in the test phases is relevant and can be used meaningfully to synthesise any recommendations for teaching and assessment. The collection of ITI data is a valid and effective metric for evaluating timekeeping accuracy and ability, as it specifically quantifies the temporal precision of a participant, which in turn reflects a musician's ability to maintain a steady and consistent tempo – in the case of the experimental work for this thesis, producing an isochronous pattern. This ability can be correlated with the

quality of musical performance, as musicians who are able to maintain steady and stable timekeeping are likely to produce more rhythmically coherent performances.

The measurement of ITI through trigger-to-MIDI processing, waveform audio recording or input capture and measurement allows for the assessment of timekeeping accuracy as it provides detailed information and is particularly sensitive to micro-timing deviations, particularly those that are not perceivable to the ear. This objective and quantifiable data can be normalised across differing tempi, allowing for statistical analysis and, subsequently, comparison. This comparison will enable an analysis of the effect varying tempo has on a performer's ability to produce a consistent ITI.

ITI provides a metric that is consistent across the differing contexts of the experimental work in this thesis. Whether testing an individual performing on their own or as part of a group, the data collection remains regular, enabling comparison between individual and ensemble timekeeping. As such, it is an effective means of observing the effects of group dynamics on individual timekeeping. It also remains a valid means of assessing timekeeping irrespective of the metronome type. Therefore, it is a useful measurement for the comparison between differing metronome configurations e.g. audio and visual metronomes.

The use of ITI as a measurement of musical timekeeping is also well-established in research. Elliott, Chua, & Wing, 2016; Himberg, 2014; Madison, Holm, & Karampela, 2013 and Repp & Keller, 2008; are examples of research in music psychology, cognitive science and sensorimotor control that have used ITI as a means of measurement, analysis and comparison. The widespread use of ITI in peer-reviewed studies emphasises its validity and reliability as a means of data collection and analysis.

3.4 Participants

The individual studies in the thesis were intended to investigate the timekeeping and sensorimotor skills of a wide range of individuals. Specifically, there was no intention to limit the pool of participants to expert or experienced individuals i.e. there was no deliberate

action to select participants with prior musical experience over those without any such experience.

There were no limitations to the participant pool in terms of demographic characteristics and a pool of participants with a wide range of ages, experience and background were recruited for the test phases.

The only criteria for exclusion for any participants related to persons with hearing or visual impairments that may have prevented them from being able to take part in the tests, simply due to the nature of the tasks involved. However, this did not occur at any point during the test phases. Participants were required to be over the age of 18 and able to provide informed consent.

Participants were recruited from the researcher's network of contacts and from the pool of students and staff at Wrexham University and The Liverpool Institute of Performing Arts. Whilst this was a pool of convenience to some extent and therefore could potentially be biased toward the researcher's subject speciality, there was also the opportunity to recruit participants from other disciplines by using a gatekeeper. The gatekeeper in this instance was the Head of Faculty who was able to provide access to students and staff from all three faculties in The Liverpool Institute of Performing Arts. This provided balance to the participant profile for the tests and is in keeping with the recruitment policy utilised by other studies of this nature (as discussed in Chapter 2). Each test phase incorporated a minimum of approximately 16 participants. This number was targeted to provide results that are meaningful and statistically significant, although it was deemed prudent to increase the minimum value for some test phases in order to deliver this statistical significance, due to the number of variables being measured. This minimum number is in keeping with the general number of participants used in other studies of this nature (Repp B. H., 2010; Fuji & Oda, 2009; Repp B., 2006). This approximate number of participants provided opportunity to conduct the research within an appropriate timescale.

In their entirety, the four experiment phases (including the pilot study discussed in Chapter 4) included 105 unique participants. Of these participants, 71 were male and 34 were female. The average age of participants across the four experiments was 27 years old.

3.5 Framework of Analysis

To ensure consistency in the capture, processing and analysis of all experimental data in the experimental phases of the thesis, it is prudent to establish a framework of analysis. The table below illustrates the Research Questions and objectives addressed in each test phase and describes the data collected and how that data is analysed.

Test Phase	Research Question	Objective	Data Collected	Data Analysis
Pilot Study	**RQ3**: What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?	To investigate what impact differing amounts of rhythmic information in a metronome has on a participants' ability to produce an isochronous pattern.	MIDI/Trigger Timing data. This data is used to calculate the ITI for each participant. The data is captured through a MAX/MSP patch.	Normalisation of the ITI data to ensure a valid comparison across tempi. A 2-way ANOVA with repeated measures to establish results or trends that are statistically significant.

Test Phase	Research Question	Objective	Data Collected	Data Analysis
Experiment 1	**RQ1**: What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?	To investigate any impact the removal and reintroduction of a metronome has on a participants' ability to produce an isochronous pattern	MIDI/Trigger Timing data. This data is used to calculate the ITI for each participant. The data is captured	Normalisation of the ITI data to ensure a valid comparison across tempi.

	RQ2: What effect does playing in a group, versus individually, have on musical timekeeping?	at differing tempi and to measure the difference, if any, in the ability to produce an isochronous pattern when performing the same task as part of a group.	through a MAX/MSP patch.	A 2-way ANOVA with repeated measures to establish results or trends that are statistically significant.

Test Phase	**Research Question**	**Objective**	**Data Collected**	**Data Analysis**
Experiment 2	**RQ1**: What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping? **RQ2**: What effect does playing in a group, versus individually, have on musical timekeeping? **RQ3**: What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?	To investigate the impact of group performance may have on participants' ability to produce a consistent isochronous pattern under differing test conditions and to observe any impact changes in tempo, rhythmic information in the metronome and presence of metronome may have on participants ability to produce a consistent isochronous pattern.	Audio waveform recordings of each participant. The gating and filtering of these recordings enables calculation of the ITIs for each participant. The audio waveform data is captured in ProTools and processed through a MatLab script.	Normalisation of the ITI data to ensure a valid comparison across tempi. A 2-way ANOVA with repeated measures to establish results or trends that are statistically significant.

Test Phase	Research Question	Objective	Data Collected	Data Analysis
Experiment 3	**RQ1**: What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping? **RQ3**: What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?	To investigate any impact the removal and reintroduction of a metronome has on a participants' ability to produce an isochronous pattern at differing tempi, using differing combinations of audio and visual metronomic information.	Trigger data captured through Unity. This timing data is used to calculate the ITI of each participant.	Normalisation of the ITI data to ensure a valid comparison across tempi. A 2-way ANOVA with repeated measures to establish results or trends that are statistically significant.

This framework of analysis provides the means to measure and analyse how different metronome configurations may affect sensorimotor synchronisation in participants and, particularly, how their ability to produce a consistent ITI is affected. The statistical analysis of the empirical data collected in the test phases and the observation of the responses to post-test questionnaires provide a platform from which to synthesise answers to **RQ4**: *What implications do the findings of the previous research questions have for musical timekeeping education and assessment*?

3.6 Materials

The materials used in the test phases evolved over the duration of the experimental period. This evolution was informed by the successes and failures of each preceding test phase and influenced by the requirements for each individual study. The pilot study used a bespoke tapping sensor pad (via a trigger to MIDI interface) and custom-designed MAX MSP patch to capture timing data, similar to the design used in Hove et al. (2013), Repp (2006) and Repp (2001). The same concept was used in the next test phase, with Piezo sensors attached to a semi-muted cowbell to transmit the participants' timing data; the partial muting of the cowbell allowed for auditory feedback that was at a comparable level to the headphone output. This configuration worked effectively for individual participants, but a trial-run of

group testing revealed that the trigger to MIDI interface and MAX MSP would be unsuitable for capturing the timing data for a group of participants performing simultaneously. As noted in pre-existing research of this nature, MAX MSP does incur some slight latency, but this latency is consistent and was accounted for in the analysis of the results.

For the next test phase, the groups of participants struck a cowbell in the same fashion as the previous test, but the timing data was recorded via close mics into ProTools, via a Focusrite Saffire Pro 40 audio interface. The waveform recordings of each participant strike and metronome event were then processed and compared using a custom-designed script in Matlab, utilising a model based on Fuji *et al.* (2011). Unlike the previous test that utilised MAX MSP, there was no latency in the timing data recorded.

For the final test phase, participants were asked to strike a cowbell to a target pattern that was audio only, visual only or a combination of audio and visual. The timing data was recorded via a Piezo sensor attached to the cowbell that was in turn connected to an Arduino Mega. This timing data was recorded and processed by a custom-designed programme in Unity. This programme also generated the audio and visual stimuli for the participants. No noticeable timing latency was detected in this process.

In all test phases, the participants were provided with a pair of Beyer Dynamic DT 770 Pro studio headphones, fed by a Behringer headphone amplifier. The group test differed slightly, as the audio target pattern was played through two JBL SRX 715 speakers (powered by a Crown 3000 stereo amplifier).

3.7 Procedures

3.7.1 Process

For each test phase, participants were provided with a Participant Information Sheet that explained the tasks involved in the relevant experiment (see Appendix C). The researcher also gave a detailed explanation to each individual and there was a short practice period before the formal testing commenced.

The number of tasks in each test phase varied depending on the objectives of each test, but individual participants were required for approximately 20 minutes on average. The order in which participants completed each test condition was randomised to ensure any possible effects fatigue might have on the overall results were negated.

In all of the three main experiments, participants were asked to tap or strike a fixed cowbell with a drumstick in time with an accompanying metronome. The metronome varied in type across the test phases (for example, a visual metronome was used in Experiment 3), and the *metronome state* was altered (i.e*. introduced, removed* and *reintroduced*) in some of the test phases. Participants were asked to maintain an isochronous pattern on the cowbell regardless of the *metronome state*. All of the tests were conducted at three different tempi: 80bpm, 120bpm and 160bpm. The individual timing data for each tap or strike the participants performed was recorded and analysed after the testing was complete.

In some of the test phases, participants were asked to complete a short Likert-style questionnaire once they had completed the timing tasks. This questionnaire comprised a small number of statements aimed to ascertain each participants' perception of their own timekeeping performance during the tasks.

3.7.2 Environment

The experimental settings for each phase utilised three separate spaces. The television studio in Wrexham University provided a well-lit, acoustically controlled test environment. The studio is well-insulated and had a low ambient SPL (sound pressure level). Similarly, two rehearsal rooms in The Liverpool Institute for the Performing Arts were acoustically treated spaces that provided comfortable test conditions with a low ambient SPL.

3.7.3 Research Ethics

Participants were asked to complete a short form that detailed their consent to take part in the test process, consent to have their anonymised timing data and image recorded, and that they had been provided with a detailed explanation of the tasks involved (see Appendix C). For those participants that expressed an interest in the overall research process, an

explanation of the research aim was provided after their contribution had been completed, so that any effects of demand characteristics were minimised. On the consent form, participants were asked to provide their age, gender, and an outline of their musical experience, although it was stated that they were under no obligation to provide this information. It was made clear to the participants that their contributions were entirely at their own discretion and that they were entitled to withdraw at any point without providing a reason. It was also made expressly clear that any withdrawal from the test process would not adversely affect the research project in any way.

Ethical approval for all the test phases was given by the Research Ethics Sub-Committee of Wrexham University.

3.8 Data Analysis

For the data analysis of each test phase, a two-way ANOVA with repeated measures is used. This is consistent with the data analysis methods seen in Hove *et al.*, (2013), Madison *et al.*, (2013), *Fuji et al.*, (2011), Repp (2006), and Repp (2001). This allows for the average ITI of each participant to be analysed during the different conditions (e.g. metronome type, tempo, and presence of metronome). Each data set has been normalised according to tempo and expressed as a percentage of that tempo as an absolute value. Normalising the data in this fashion enables a fair comparison between test conditions, specifically in terms of tempo variations. The precedent for this type of analysis has been set by existing research (as discussed in Chapter 2) and, given the experimental design and its adoption of previously established test methodologies, it is appropriate for the analysis of these data sets.

Some of the test phases include results from a Likert-style questionnaire, intended to glean insight into the perception of each participants' timekeeping performance in different test conditions. Whilst the results from these questionnaires provide limited, subjective quantitative data, it is possible to use Kendall's Co-efficient of Concordance to analyse the internal consistency of the responses. This does not provide results related to timekeeping performance but adds robustness to the contextual information that the responses may offer.

3.9 Potential Limitations

The experimental design follows the key concepts established by existing research in the field of sensorimotor timekeeping tasks and has broadened the test design beyond the recognised finger-tapping procedures to include a more musically percussive input method i.e., using a drum stick to strike a cowbell. The findings of the thesis could therefore be limited, or rather directly applicable to, percussion instruments or instrumentalists.

As acknowledged by existing literature, the ability of a participant to reproduce a simple, isochronous pattern may not be directly correlate with a musicians' ability to reproduce more complex rhythmic patterns in quite the same way. The results and findings should be treated as an indicator, rather than an absolute in this instance. Likewise, every effort has been made to ensure that the number of participants is large enough to provide meaningful insight into the topic, and that the experiential characteristics of those participants is as broad as possible. It is important to note that an increase in participant numbers and the likely increase in diversification of musical experience would add more granularity to the results and findings.

3.10 Summary

The methodology and framework of analysis discussed in this chapter reflects a strategy that is in keeping with other studies of a similar nature. The research questions that are outlined are designed to confirm concepts that have been established in previous work in the field of sensorimotor synchronisation and group entrainment, and to investigate new combinations of those concepts. The design is also structured to allow for new, untested concepts to be included in the research activity.

Participant numbers are consistent with, or exceed, the general number recruited for these types of studies, and the experiential characteristics of the recruited participants are deliberately as broad as possible.

The test design is consistent with existing models, although it does explore combinations of test conditions that have not previously been tested together: the removal and reintroduction of a metronome, metronome type, and differing tempi.

The analysis of the averaged participant ITIs (expressed as an absolute percentage of tempo) using an ANOVA with repeated measures is consistent with current practice.

There are potential limitations to the extent of generalisation that can be made when applying the findings to situations outside laboratory settings, but these results can be seen as a clear indication rather than an absolute confirmation of their validity.

4. Stimulus to Research - A Pilot Study

4.1.1 Pilot Study

The idea for this test design was born out of the researcher's experiences as a musician. The idea that an increase in rhythmic information through subdivisions of a target tempo would improve timekeeping accuracy led the researcher to design a sensorimotor test, using similar test methodologies established in existing research. For this test (Owens, 2015), participants were tasked with tapping a sensor pad along with a target pattern. This target pattern was presented to them in two different states: isochronous and cross-rhythmic. The participants were also presented with tempo variations of these two metronome states: 60bpm, 120bpm and 180bpm. The test design was targeted at collecting the timing data of each participant, specifically ITI measurements.

4.1.2 Participants

This experiment was performed by 22 participants (20 male, 2 female), with an average age of 37. 16 of the participants identified themselves as musicians (regularly played an instrument for five years or more). Musicians and non-musicians were not segregated in any way for this experiment. Convenience sampling was used to select the participants for this experiment. The participants were a mixture of undergraduate Music Technology, Sound Technology and TV Production Technology students from the University, with additional participants from the researcher's network of contacts.

4.1.3 Stimuli

The test used six audio clips (three isochronous and three cross-rhythmic) at three differing tempos (60bpm, 120bpm and 180bpm). The participants were asked to tap along to each of these clips twice, in a random order, which resulted in Inter-tap interval data from twelve clips in total for each participant (see Fig 4.2).

	60	120	180
	Cross-rhythmic	Cross-rhythmic	Cross-rhythmic
	Isochronous	Isochronous	Isochronous
4 beats intro	32 beats with metronome	32 beats with metronome	32 beats with metronome

Fig. 4.1 A representation of all combinations of test conditions and variables for pilot study.

The isochronous metronome consisted of a simple isochronous pattern, using a stock audio sample provided in the Logic Pro X software. The cross-rhythmic metronome included the isochronous pattern but added a semiquaver pattern (at a higher pitch and different timbre) and a syncopated pattern (at a lower pitch and different timbre).

The volume of the headphone output was limited to a safe standard in accordance with The Control of Noise at Work Regulations 2005 (Health and Safety Executive, 2021), but each participant was able to alter the volume within those limitations.

4.1.4 Equipment

The participants listened to the stimuli through Sennheiser HD 201 headphones and were asked to tap a sensor pad in time with the metronome. The sensor pad was constructed from a 3mm thick wooden disk, soundproofing foam, and a 27 mm piezo sensor (Fig. 4.3). The piezo sensor was connected to an Alesis Trigger I/O, which in turn was connected via USB to MAX/MSP (v.6.1) (see Appendix A). The audio clips and auditory feedback for participants' taps were hosted in the custom-designed Max patch for the study.

Fig. 4.2 A participant using the sensor pad in the test environment.

4.1.5 Procedure

Participants were given a four-beat introduction to each audio clip. The first four and last four taps were discounted from the data analysis. The tapping data from each participant was recorded through the MAX MSP patch and saved as a plain text for easy import and analysis. Where actual taps fell within a given range of the expected beats (50% of the nearest expected Inter Onset Interval), they were assigned as the attempted tap for the nearest expected beat. Retriggers that fell within a given range (≤ 80ms) were discounted from the results, and only the first (or main) tap was counted and assigned.

4.1.6 ITI Data Analysis

The participant ITI data of the pilot study can be categorised into two separate phases, with two separate conditions: Tempo and Metronome type, analysed using a two-way ANOVA with repeated measures for statistical significance.

In terms of the factor of tempo, Mauchly's Test of Sphericity indicated that the assumption of Sphericity should be rejected, $\chi 2(2) = 10.720$, $p < 0.05$. Subsequently, the ANOVA with a Greenhouse-Geisser correction determined no significant effect of tempo upon participants' average ITI: $F(1.257, 0.001) = 0.019$, $p > 0.05$.

With regards to the metronome type, since there are only two conditions of this variable, Sphericity is not meaningfully testable and so is assumed. To this extent, the ANOVA

determined that there was no significant effect of metronome type upon participants' average ITI: $F(1, 0.001) = 0.913$, $p > 0.05$.

In terms of the factor of the interaction between tempo and metronome type, Mauchly's Test of Sphericity indicated that the assumption of Sphericity should be rejected, $\chi2(2) = 7.615$, $p < 0.05$. Subsequently, an ANOVA with a Greenhouse-Geisser correction determined that there was no significant interaction effect of tempo and metronome type upon participants' average ITI: $F(1.361, 0.002) = 1.453$, $p > 0.05$).

Based on evaluation of the results from this experiment, it can be concluded that there was no statistical significance in the change of participants' ITI between metronome type, and that there was no statistical significance in the change of ITI over tempo.

4.1.7 Limitations

The three tempi chosen for the study were multiples of 60bpm. The fastest tempo participants were asked to tap along with was 180bpm. The tempo of 180bpm gives an isochronous pattern with an IOI of 333ms. Participants reported difficulty in synchronising with both metronome types at this tempo. As Madison *et al*. (2013) suggest, metronomes with an IOI of less than 500ms (i.e. faster than 120bpm), may prove to be harder for untrained participants to tap along with.

The test was designed as a means of gathering timing data from individuals, under differing conditions. The test design was not designed to gather data from multiple participants performing as a group. The personal professional experience of the researcher would suggest that the testing of groups of participants could provide different outcomes to the statistical analysis of individual participant ITI data. The differences in ITI produced by a participant in an individual setting, compared to the ITI produced in a group setting are further investigated in Chapter 6 of this thesis.

4.1.8 Conclusions

Following similar procedures to that of Clayton *et al.* (2020), this test design included increased rhythmic information as a test variable. This ITI data was then used retrospectively to investigate whether 'enforced' explicit counting influenced participants ability to reproduce consistent ITIs.

The primary function of this prior work was to design a test that could capture the timing data of participants in a sensorimotor synchronisation test. The data analysis was performed after the realisation that the yielded timing data might provide insight into the ITI of participants under different test conditions. As such, the design of the pilot study, its procedure and stimuli in particular, could be adjusted and enhanced to provide ITI data under a wider variety of test conditions.

Analysis of the participants' timing data from this pilot study indicated no link between the consistency of ITI and the type of metronomic or rhythmic information provided. However, this analysis does not provide any insight into whether that information impacts a participants' ability to stay perfectly synchronised with an isochronous or cross-rhythmic target pattern. If we consider the subjective terms 'feel' or groove' and assume that some timekeepers deliberately wish to be consistently ahead or behind the target beat, it is possible that a participant (and/or musician) may maintain an ITI that has a consistent duration with that of the target IOI, but their taps do not meet the onset of the metronome pulses. By the measure of asynchrony, this would be deemed 'out of time'. Therefore, ITI may be a measure of timekeeping accuracy that is overlooked in its relevance and importance to musicality.

This analysis provided an insight into ITI over differing metronome types and tempo conditions. Participants provided timing data that was influenced by an unbroken rhythmic stimulus, in all variations of the test. This timing data did not provide insight into the ability of participants to maintain a consistency in their ITI durations if the rhythmic stimulus is removed after its introduction. As the pilot study design was aimed at gathering individual participant timing data, it did not provide insight into a participant's ability to maintain consistent ITI durations when provided with differing metronome types when part of a group.

5. Experiment 1: Individual study with an Intermittent Isochronous Metronome

5.1 Introduction

This experiment is designed to address the following Research Questions:

- **RQ1:** *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*

- **RQ2**: *What effect does playing in a group versus individually have on musical timekeeping?*

The designs of further experiments in this thesis are informed by this first experiment.

This experiment investigates the relationship between differing states of metronomic audio stimuli, in the role of a click track, and the effect that the stimuli may have on the participants' ability to maintain a consistent Inter-tap Interval (ITI), by asking participants to strike a cowbell along with a metronome.

In this chapter, the results of the experiment are discussed, comparing the IOIs of the metronome and the ITIs of the participant. Taking averages of these intervals over a selected number of beats for the purpose of comparison across experimental conditions, has allowed conclusions to be drawn as to the influence of tempo and presence of the metronome on the participants' ability to sustain a regular ITI duration.

This experiment is concerned only with ITI. As such, the effect of the differing metronome states is only discussed in terms of their influence on participants' ITIs and not in terms of their influence on participants' ability to synchronise accurately in phase with the beats, or IOIs.

5.2 Background and Rationale

There is a solid body of work in existence that employs experiments that measure the ability of individuals to keep time. Repp (2010) and (2006) have served as a template for the key aspects of this experiment, particularly the procedure for tapping along to a target isochronous pattern and the concept of continuation after the removal of the target pattern, or metronome. For this experiment, certain adaptations have been made:

- the finger tapping that is a common mode of input for participants has been replaced by a drumstick and cowbell for participants to strike. This is in line with the findings of several studies (Madison *et al*., 2013; Fuji & Oda, 2009; Madison & Delignières, 2009) and is designed to reduce variability and improves response times.

- the participants played an isochronous pattern along with a target pattern. That target pattern (metronome) was removed after 48 beats. Unlike other studies of this nature, the metronome was then reintroduced after a certain point (16 beats), and continued for a further 48 beats. The resultant effect that reintroduction had on participant ITIs was measured.

- Taking into consideration the work of Madison *et al*. (2020), auditory feedback was included and the effect of increased audio information on participants' averaged ITI was recorded.

The selection of the various tempi used in the experiment was influenced by studies in the area of preferred tempo and research that has investigated possible physical limitations to sensorimotor synchronisation. Moelants (2002) suggests the preferred tempo for humans is in the region of 120bpm, leading to a target IOI of 500ms. Moelants also noted that "*the 'octave' 81-162bpm (370-740ms) is found as optimum*".

This 'harmonic' relationship between tempo preference and sub-divisions or multiples of 120bpm may go some way to support the findings of Grondin, Meilleur-Wells & Lachance (1999). Their research indicates, in general terms, that an interval of around 1.18 seconds is

the point at which a person's ability to predict timed events begins to deteriorate, without explicit counting of sub-divisions of the interval.

5.3 Experiment

5.3.1 Research Objectives

This experiment was intended to investigate the effect on the consistency of participants' ITI when provided with an intermittent metronome. Three different metronome tempo conditions were used to analyse the average ITIs of participants at discrete tempo intervals. The removal and reintroduction of the metronome was designed to analyse participants' average ITIs during three different metronome states (*present*, *removed* and *reintroduced*).

The experiment was also intended to measure and investigate any noticeable entrainment effect that group playing might have on the consistency of participants' ITIs. Consequently, the experiment required participants to strike a cowbell with a drumstick to allow for interaction between the participants in the group phase of testing. Unfortunately, due to a technical issue, ITI data for the group test was unavailable. The ITI data from the individual test remained unaffected.

The test design in this chapter was tailored to meet the specific research objectives established for the experiment. The design follows the overall Methodology found in Chapter 3.

5.3.2 Participants

This experiment was undertaken by a total of 16 participants (10 male, 6 female) with a mean age of 21. Seven of the participants identified themselves as musicians (regularly played an instrument for 5 years or more). Musicians and non-musicians were not segregated in any way for this experiment. Convenience sampling was used to select the participants for this experiment, and the participants were recruited through university email and word-of-mouth. The participants were a mixture of undergraduate Music Technology, Sound Technology and TV Production Technology students from Wrexham University.

5.3.3 Stimuli

This experiment used three audio clips at three differing tempos (80bpm, 120bpm& 160bpm) which were replayed in a random order. The metronome for the experiment used a stock woodblock sample sourced from Apple's Logic Pro X (v10.2.4)

5.3.4 Equipment

The participants heard the stimuli through two JBL SRX 715 speakers (powered by a Crown 3000 stereo amplifier). The audio feed for the amp was provided directly from the Apple MacBook Pro headphone output (via the 3.5mm headphone output). The audio clips for the experiment were hosted in a MAX MSP patch specifically designed for the experiment. Participants were asked to tap a cowbell with a drumstick. The cowbell was fitted with a piezo sensor that was in turn connected to an Alesis Trigger I/O. This trigger-to-MIDI converter was connected via USB to MAX/MSP (v.6.1) (see Appendix B). The experiment took place in the Television studio on the University campus, providing an acoustically controlled environment.

The volume of the speaker output was limited to a safe standard in accordance with The Control of Noise at Work Regulations 2005 (Health and Safety Executive, 2021).

Sound level measurements were taken to ensure that the volume of the physical cowbell strikes did not exceed safe levels.

5.3.5 Procedure

Before the experiment began, the participants were given a briefing on the requirements of the test. The participants were asked to strike a cowbell in time with three audio clips, each lasting 100 beats. The clips were played at random and at the three different tempi. Participants were given a practice attempt before the experiment began at a 100bpm tempo condition. After 48 beats (not including the four-beat introduction) the metronome fell silent, and the participants were asked to continue striking the cowbell at the same tempo. After 16 beats, the metronome was reintroduced, and the participants were asked to continue to try and keep time with the metronome (see Fig. 5.1).

The first eight and last eight beats were discounted from the analysis of the results. The tapping data from each participant was recorded through the MAX MSP patch and saved as a plain text file for easy import and analysis. Where actual taps fell within a given range of the expected beats (50% of the nearest expected Inter Onset Interval), they were assigned as the attempted tap for the nearest expected beat. Retriggers that fell within a given range (≤ 80ms) were discounted from the results, and the first (or main) tap was counted and assigned.

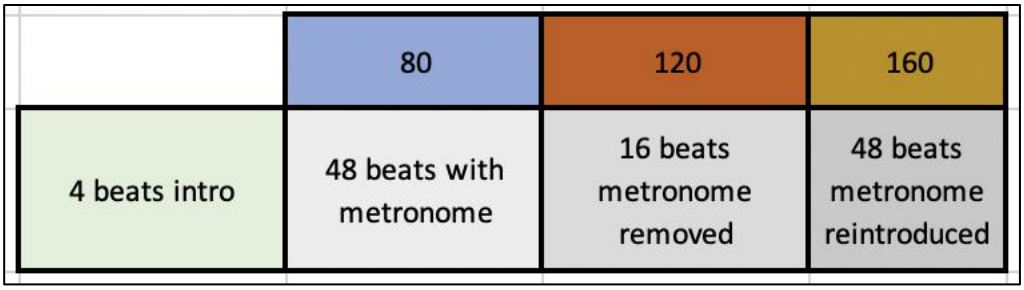

Fig. 5.1 A representation of test conditions for Experiment 1.

At the end of each test, the participants were asked to complete a short questionnaire, requesting responses that used a 5-point Likert Scale for four statements. These statements were:

1. **My timekeeping accuracy was influenced by other participants;**
2. **My timekeeping was more accurate when I played individually;**
3. **My timekeeping was accurate when I played as part of a group;**
4. **My timekeeping was accurate when the metronome was present;**
5. **My timekeeping was accurate when the metronome was absent;**

The Likert Scale for statement 1:

1----------2- ---------- 3 ---------- 4 ---------- 5

Decreased a lot **Decreased a little** **Not at all** **Increased a little** **Increased a lot**

The Likert Scale for statements 2, 3 & 4:

1----------2- ---------- 3 ---------- 4 ---------- 5

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

5.4 Analysis and Results

5.4.1 Analysis

In this study, the data analysis compares the IOIs of the metronome and the ITIs of the participant. Taking averages of these intervals over a selected number of beats for the purpose of comparison across experimental conditions, allows conclusions to be drawn as to the influence of tempo, and metronome state on the participants' ability to sustain a consistent ITI.

To analyse the results of each participant with consistency between tempo conditions, we determine metronome IOI duration in seconds based upon the tempo of the metronome in bpm as follows:

$$\tau_{BPM} = \frac{60}{BPM} \qquad (Equation\ 5.1)$$

Each individual participant's strike is recorded relative to the beginning of the metronome sequence, forming an array of times $\mathrm{X} = \mathrm{x}_1, \mathrm{x}_2 \ldots \mathrm{x}_\mathrm{n}$, where $\mathrm{x} \in \mathbb{R}_{>0}$. From this, the mean ITI can be calculated:

$$\bar{\Delta} = \frac{x_n}{n} \qquad (Equation\ 5.2)$$

A normalised mean ITI is determined relative to the IOI at the tempo concerned:

$$\bar{\Delta}_{BPM} = \left| 1 - \frac{\bar{\Delta}}{\tau_{BPM}} \right| \qquad (Equation\ 5.3)$$

To ensure the results of ITI were comparable over the changing tempi in the tests, these formulae were used to normalise the average ITI of each individual test result.

5.4.2 Results

5.4.2.1 ITI Data Analysis

The results of the experiment can be categorised into three separate phases, or metronome states: *present*; *removed*; and *reintroduced* with three separate tempo conditions (see Fig. 5.2 – 5.4). Data collected was subsequently analysed for statistical significance using a two-way ANOVA with repeated measures.

In terms of the factor of tempo, Mauchly's Test of Sphericity indicated that the assumption of Sphericity had not been violated, $\chi2(2) = 0.616$, $p = 0.753$. Subsequently, the ANOVA test determined that participants' mean ITI measures differed statistically significantly between the three tempi tested ($F(2, 0.009) = 7.530$, $p < 0.003$). Post-hoc tests using the Bonferroni correction indicated that there are statistically significant differences in mean ITI measures between tempos of 80bpm and 120bpm ($p < 0.01$) but not between tempos of 80bpm and 160bpm ($p = 0.367$) or tempos of 120bpm and 160bpm ($p = 0.176$) (see Fig. 5.3).

In terms of the factor of stage of test (*metronome state*), Mauchly's Test of Sphericity indicated that the assumption of Sphericity had not been violated, $\chi2(2) = 5.96$, $p = 0.51$. Subsequently, ANOVA testing determined that participants' mean ITI measures differed statistically significantly between the three states tested ($F(2, 0.015) = 21.662$, $p < 0.00001$). Post- hoc tests using the Bonferroni correction indicated that there are statistically significant differences in mean ITI measures between all combinations of metronome condition, specifically: the conditions of metronome *present* and metronome *removed* ($p < 0.001$); between metronome *present* and metronome *reintroduced* ($p < 0.01$); and between metronome *removed* and metronome *reintroduced* ($p < 0.02$) (see Fig. 5.2).

In terms of the interaction between the *tempo* and stage of test factors (*metronome state*), Mauchly's Test of Sphericity indicated that the assumption of Sphericity should be rejected, $\chi2(9) = 0.059$, $p < 0.05$. Subsequently, the ANOVA test with a Greenhouse-Geisser correction determined that the interaction between *tempo* and *state* (metronome condition) does not

significantly affect mean ITI measures ($F(1.899, 0.030) = 2.992$, $p > 0.05$) (see Fig. 5.4). Based on evaluation of the results from this experiment, the following statements can be made:

- There was statistical significance in the change of ITI between metronome states.
- There was statistical significance in the change of ITI over tempi.
- There was no statistical significance in the length of ITI between tempo and presence of metronome.

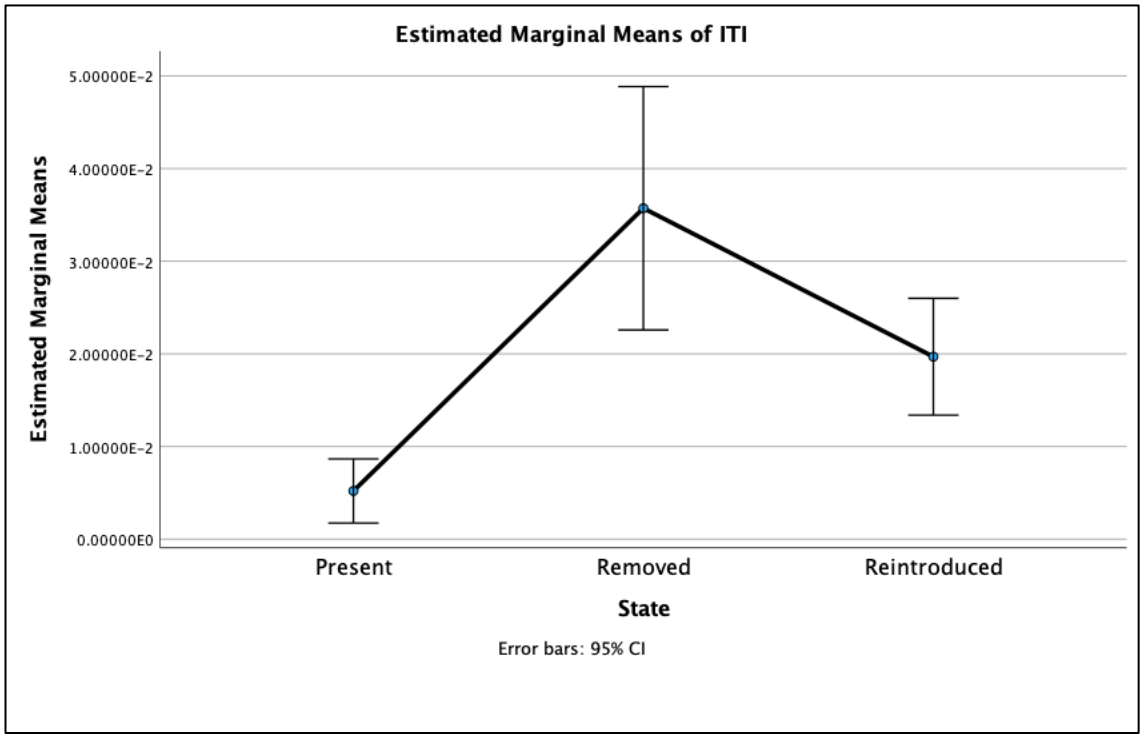

Fig. 5.2 Mean ITI across the three metronome states for Experiment 1.

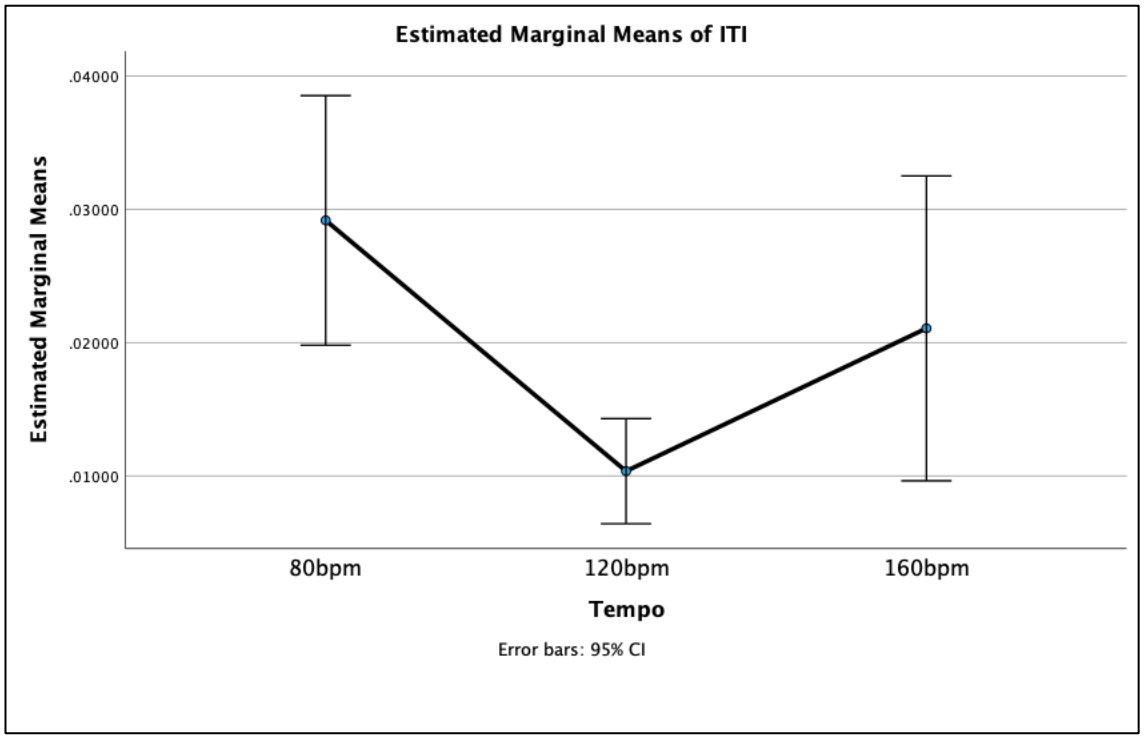

Fig. 5.3 Mean ITI across the three tempi for Experiment 1.

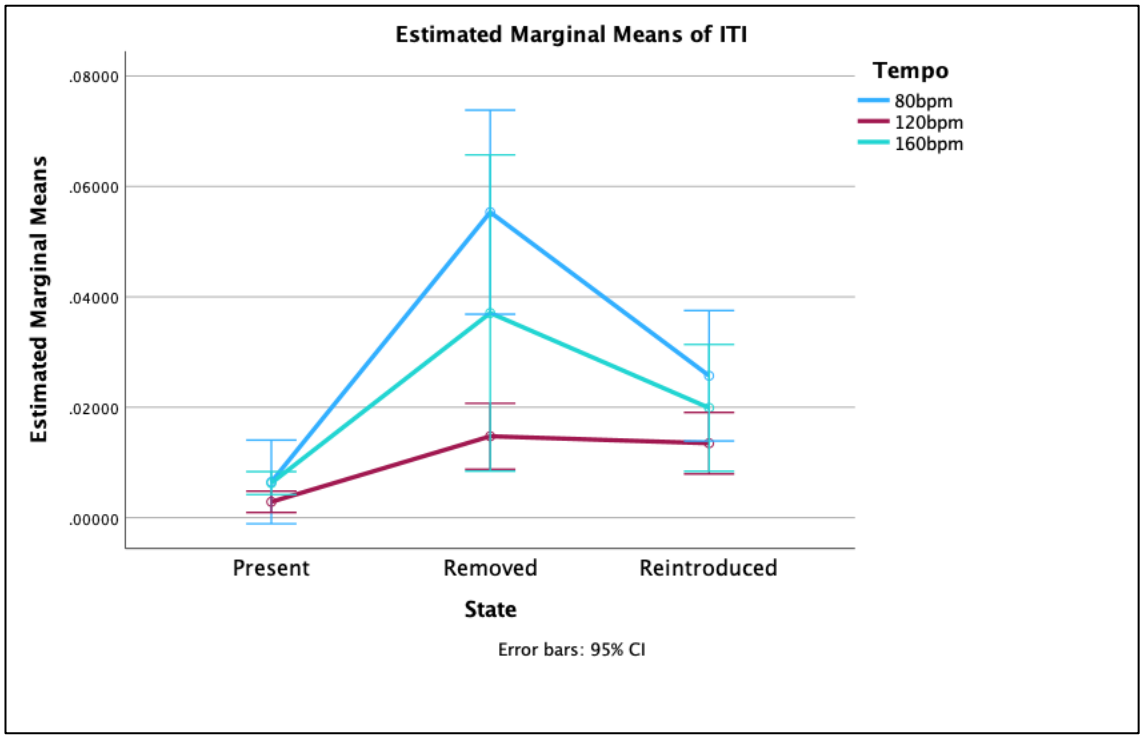

Fig. 5.4 A comparison of mean ITI across tempo and metronome state for Experiment 1.

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5.4.2.2 Questionnaire Response Analysis

For the complete set of participants' responses to the post-experiment questionnaire, Kendall's *W* was run to determine if there was agreement between the perceptions of timekeeping performance with different metronome types and different metronome states. The participants' perception of their performance under these conditions was determined according to a five-point Likert Scale from 1 (Decreased a lot or Strongly Disagree) to 5 (Increased a lot or Strongly Agree). The consistency of responses from the 16 participants were statistically significant $W = .451$, $p < .001$.

In this instance, we can accept the hypothesis that the entire collection of responses displays an internal consistency.

Whilst the test of Kendall's coefficient of concordance refers to the overall response of each participant, the distribution of each group of responses to the individual questions of the post-experiment questionnaire are shown in the figures below (Fig. 5.5 – Fig. 5.9). These responses were collected after the participants completed the individual test phase and the group test (that was unsuccessful because of a technical failure). However, post-experiment responses are included as they contain statements referring to individual performance and provide context to the participants' perception of their timekeeping during the individual test.

In Fig. 5.5, the overall responses do not show clearly whether participants felt that their timekeeping was influenced by other participants in a group, as the responses are relatively evenly distributed.

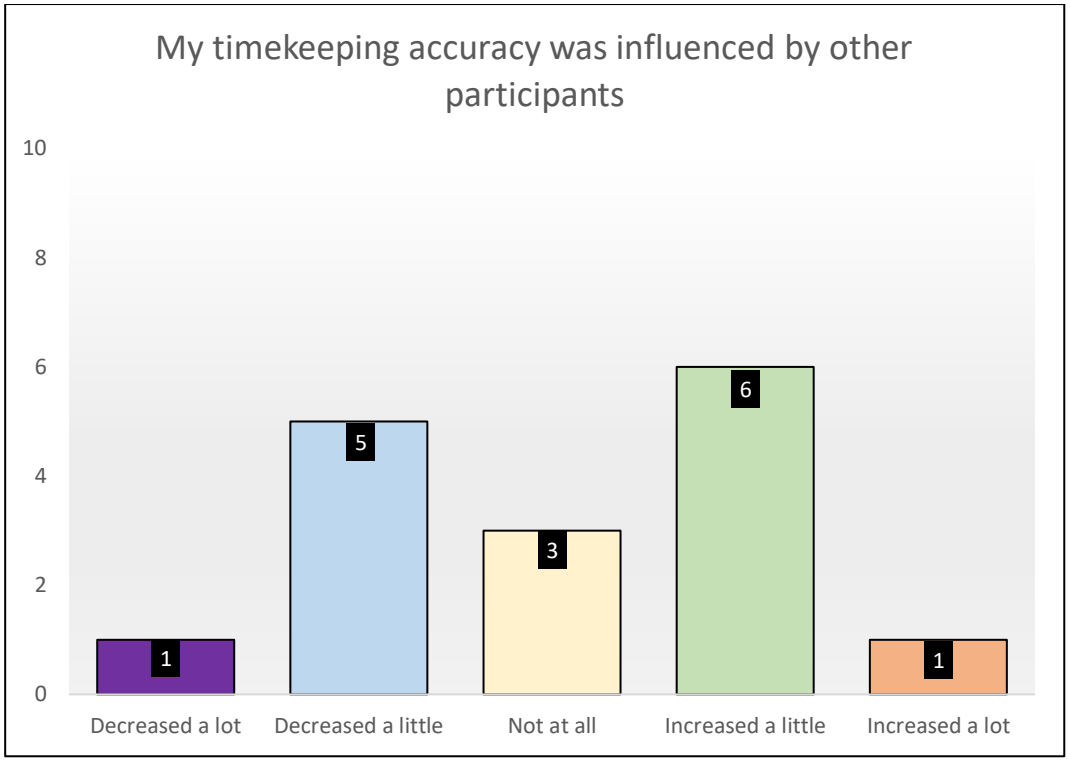

Fig. 5.5 The overall response to Statement 1: "*My timekeeping accuracy was influenced by other participants".*

In response to whether the participants perceived their timekeeping to be more accurate when performing as an individual, Fig. 5.6 shows that over half the participants agreed with that statement.

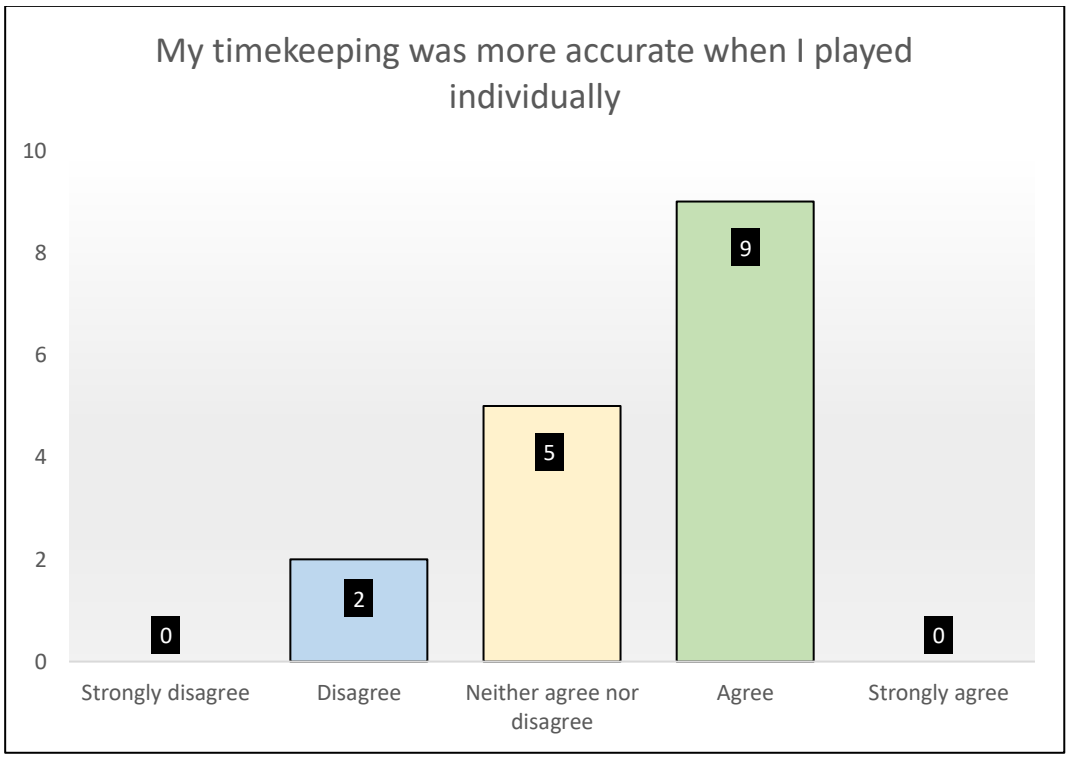

Fig. 5.6 The overall response to Statement 2: "*My timekeeping was more accurate when I played individually".*

This perception is confirmed to an extent by the responses to "*my timekeeping was accurate when I played as part of a group*", as these display a majority response that disagrees with that statement.

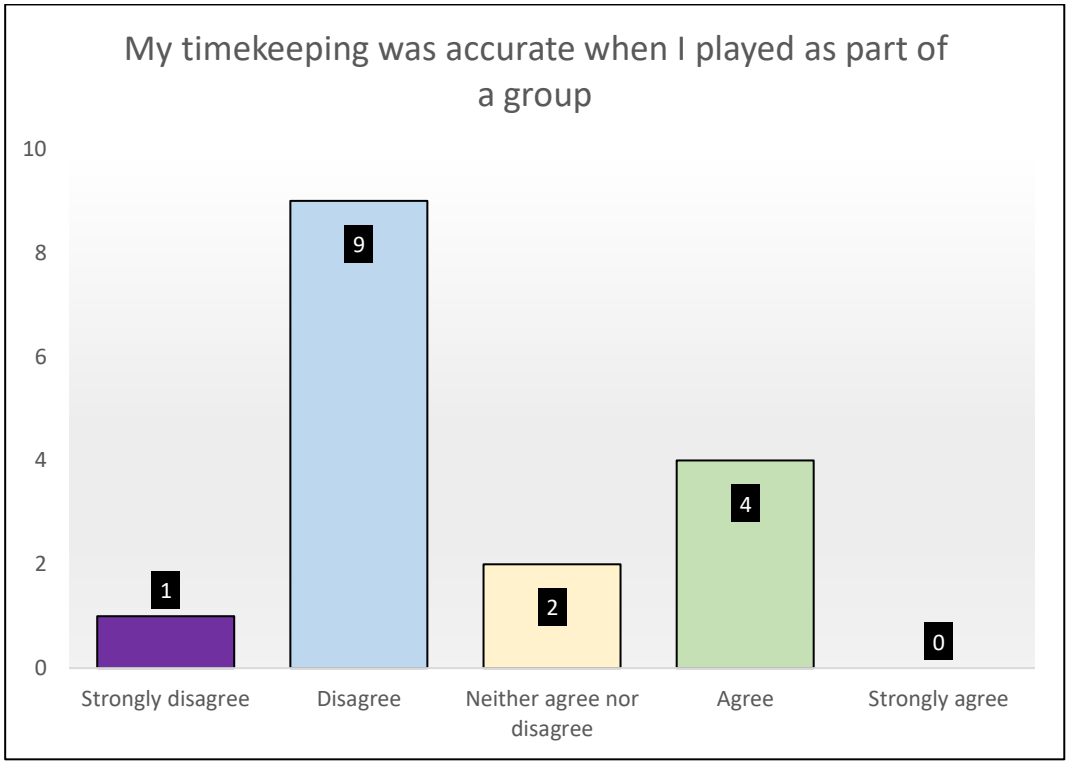

Fig. 5.7 The overall response to Statement 3: "*My timekeeping was accurate when I played as part of a group".*

What can be clearly seen is that the participants felt that their timekeeping was accurate when the metronome was present, as shown in Fig. 5.8, with all but one of the participants either agreeing or strongly agreeing with that statement.

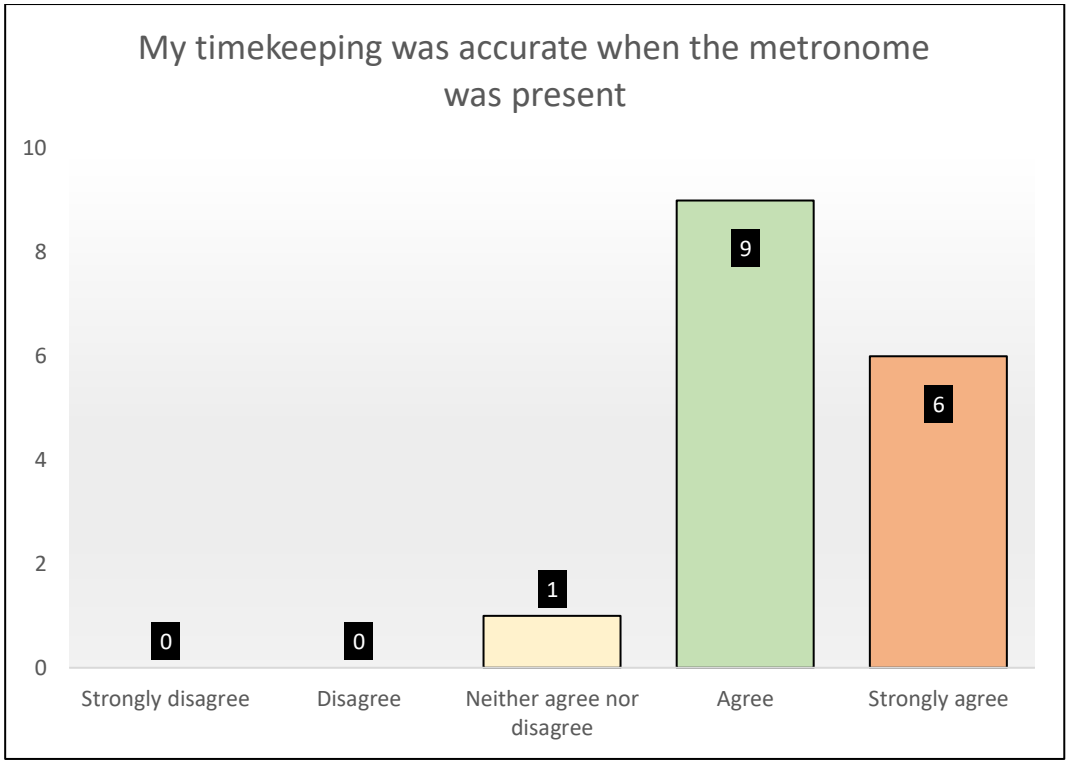

Fig. 5.8 The overall response to Statement 4: "*My timekeeping was accurate when the metronome was present".*

The perception amongst participants of their timekeeping accuracy when the metronome was absent, is less clear. Fig. 5.9 shows that the distribution of the responses is slightly weighted toward disagreement.

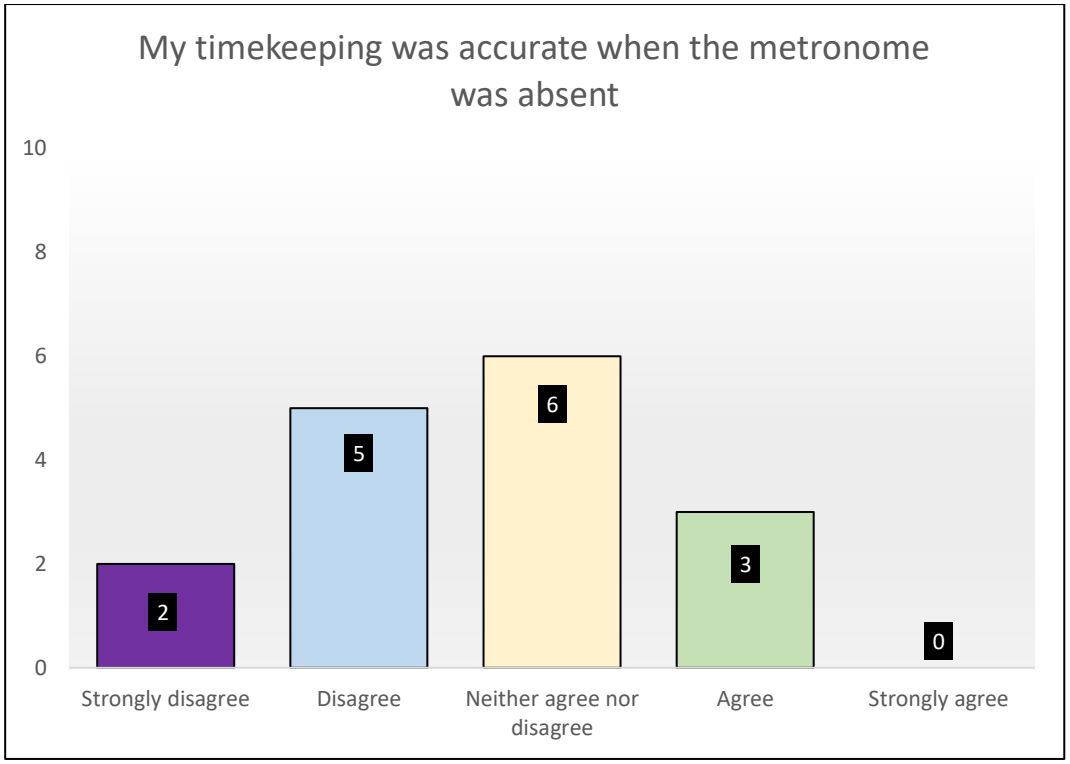

Fig. 5.9 The overall response to Statement 5: "*My timekeeping was accurate when the metronome was absent".*

5.5 Limitations

As outlined earlier, this experiment was initially designed to test two participation conditions and their possible effect upon ITI: individual and group participation. Unfortunately, the resonant frequencies from multiple participants resulted in retriggers that obscured the group data. It was also noted that the trigger to MIDI interface and interconnections struggled to process multiple inputs at near-simultaneous occurrences, due to large data transmission rates. In order to enable the testing of group participation, an alternative method of recording participants' strikes should be used. To facilitate the capture of multiple near-simultaneous strikes, it is prudent to use audio capture data (rather than trigger to Midi data) and process the timing information after the test phase. The use of close mic techniques and a suitable DAW are appropriate for the audio capture, and a bespoke script in appropriate software (MatLab or similar) will enable the timing data for participants' strikes to be analysed, using audio waveform analysis.

The ITI data from the individual test phase was unaffected and produced interpretable results, however the group phase did not provide useable ITI results, although anecdotal observations

made by the researcher of the group test phase suggest a potential impact on entrainment. This was most notable in the impact the reintroduction of the metronome had on group entrainment.

The participant numbers were in-keeping with other studies of this nature, but a larger number of participants may add robustness to the statistical analysis.

The findings from the pilot study analysis discussed in Chapter 4 of this thesis suggest there is no link between ITI and the type of metronomic or rhythmic information provided to the participant. However, this has only been tested on an individual basis, and could yield differing results if participants were tested when performing as part of a group.

5.6 Conclusions

This chapter investigated the effect that removing the metronome has on a participant's ability to maintain a mean ITI consistent with the IOI of the metronome. It also assessed the effect that reintroducing the metronome after its absence might have on the participants' ability to produce consistent ITIs. The results show that there was a definite decrease in the consistency of ITI when the metronome was removed. At all tempi, participants initially produce ITIs that are relatively near the target IOI. Once the metronome is removed, ITIs drift in consistency, most notably at 80bpm. It also suggests that the reintroduction of the metronome does not immediately reinstate the consistency of ITI that was present in the condition before its removal, although the largest recovery toward the target ITI is at 80bpm, where the drift in ITI is most noticeable during the *removed* state. This improvement could be due to the larger intervals between IOIs (and therefore more time to readjust) once the metronome is reintroduced. As the average ITI consistency is at its worst at the slowest tempo, it is another indication that ITI and timekeeping accuracy (in terms of matching isochronous metronomic information) are not necessarily linked.

The tempo that yielded the most consistent ITIs (that is, closest to target IOI and with least variance) was 120bpm. This result lends support to the concept of 'preferred tempo' that is suggested by Moelants (2002). It is difficult to conclusively determine if this result is

connected to Moelants' theory, as there is still some dispute amongst researchers concerning other factors that might have an influence on preferred tempo, such as musical experience and age. A study by Drake, Jones, & Baruch (2000) indicated that musical experience affected preferred tempo, whilst other studies provide evidence that musical experience has no effect, but age may mean that older participants would tap a slower preferred tempo in test conditions (Hammerschmidt, Frieler, & Wollner, 2021).

The responses to the post-experiment questionaire offer insight into the perception the participants had of their own timekeeping performance. It would appear that they generally felt that their timekeeping was best in an individual setting and when the metronome was present. Their perception of timekeeping accuray when the metronome is removed is less clear, but would suggest the participants found the absence of the metronome to have either no effect or a negative effect on their timekeeping. However, it is important to remember that these participants are likely to consider timekeeping from a purely synchronisation point of view, rather than framing the statements in the context of producing consistent, isochronous intervals. Whilst the group test failed to produce useable ITI data, it is interesting to consider the participants' repsonses to the statement that addresses the group test phase specifically. Three quarters of them perceived the group condition to either have no effect or a negative effect on the accuracy of their timekeeping.

In answer to **RQ1**: '*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping'?*, this chapter has demonstrated that the removal and reintroduction of a metronome causes the average ITI of participants to drift futher from the target IOI of the metronome, compared to when the metronome is originally introduced. It demonstrates that tempo is a influence on average ITI and that the slower tempo induces ITIs furthest from the target IOI of the metronome. However, these results only apply to an individual interacting with a metronome.

Whilst **RQ2**: "*What effect does playing in a group, versus individually, have on musical timekeeping?*" cannot be addressed by the quantitative data collected in this chapter, the response of the participants to the post-experiment questionnaire provides insight into the

perception of timekeeping when playing as a group. The responses suggest that participants perceived their timekeeping to be more accurate when playing as an individual.

Chapter 6 investigates the influence the changes in metronome state and tempo have over participants' ITI in a group setting, and collects responses from participants to ascertain their perception of timekeeping accuracy in a group test environment.

6. Experiment 2: Group Study with Cross-rhythmic and Isochronous Metronomes

6.1 Introduction

This experiment is specifically designed to address the following Research Questions:

- **RQ1**: *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*

- **RQ2**: *What effect does playing in a group, versus individually, have on musical timekeeping?*

- **RQ3**: *What influence does differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?*

This test phase represents the second stage of the overall series of experiments. As with its predecessor, this test will analyse participants' ITI averages during differing test conditions. Whereas the preceding test focussed on individual participants that were attempting to entrain with a computer-generated audio metronome, this test investigates the influence different metronome conditions, different tempi and whether the removal of the metronome will influence the average ITIs of groups of performing participants.

6.2 Background and Rationale

There are well-established processes and procedures for measuring a participant's sensory-motor response to audio stimuli (Madison, Karempala, Ullén, & Holm, 2013) (Repp, 2002). These tend to use the audio stimuli to prompt participants to tap or strike a sensor (typically a pad or object fitted with a sensor, or which has been close miked). The point of interest for these investigations can vary; in some cases, it may take the form of psychological or neuroscientific enquiry, in others, it may be to observe social or inter-personal cues, but there is almost always a clear connection between the ability to reproduce isochronous patterns and the ability to keep time from a musical perspective.

The test methodology used for in this chapter is based on these established ideas. The 36 participants were asked to strike a cowbell with a drumstick, as research suggests that this is a more effective and uniform method (than tapping a sensor pad) in reducing any physical latency from the cognitive process (Fuji & Oda, 2009).

This study represents a development in the test criteria, informed by the observations and results from Chapter 5. The previous chapter investigated the ability of an individual participant to reproduce isochronous patterns when provided with variations in audio stimuli (metronome type, tempo, and metronome state). The experiment described in this chapter has expanded the test criteria to explore group performance, specifically to investigate the potential change in entrainment it may have on the individual participants within those groups. As before, isochronous and cross-rhythmic auditory metronomes were used to try and determine the effect that more or less rhythmic information would have on the participants' ability to produce an accurate and consistent ITI. In Chapter 5, it was found that the metronome condition has a statistically significant effect on the change in ITI. It was also found that tempo had a statistically significant effect on ITI (three tempos were used – 80bpm, 120bpm & 160bpm) but that there was no statistically significant relationship between tempo and the metronome conditions (present, removed or re-introduced). Only individuals were tested, and the results suggested that metronome type (isochronous or cross-rhythmic) had no significant effect on the individual participants' ability to produce accurate, consistent ITIs.

The metronome in this test acted as an 'entrainment partner' for the participants. It posed the question of whether or not these changes in stimuli would have a similar effect on group performance i.e. more than one participant at a time.

Entrainment can be defined as "*the process by which independent rhythmical systems interact with each other*" (Clayton, 2012). In terms of entrainment in music, Clayton specifies one of the distinct features:

> *"Inter-individual/intra-group entrainment concerns co-ordination between the actions of individuals in a group, which is essential for ensemble playing in any musical tradition. This is largely facilitated by the entrainment of attentional rhythms to*

auditory information, although other sense modalities – vision in particular – often also play a part" (Clayton, 2012)

The group setting is designed to simulate ensemble performance, whilst asking participants to perform a relatively simple task. Primarily, the test is designed to observe the differences in ITI when additional auditory information (metronome) is removed and reintroduced. There is the opportunity to observe not only the effect of the metronome as one 'rhythmical system' versus another (the participants), but also the participants themselves as individual 'rhythmical systems' interacting with each other.

Existing studies of this type typically use solo or paired participants alongside the automated stimuli (Himberg, 2014; Luck & Toivainen, 2006; Dixon & Goebl, 2002; Repp B. H., 2001). For this study, the intention is that groups of four participants will be tested. This is designed to simulate smaller musical ensembles, therefore providing insight into the interaction between group members and any influence this group setting has on the participants' individual ITI.

The interaction between performers themselves may influence the group's ability to reproduce an isochronous pattern, and subsequently near-ideal IOIs. Although primarily used in the observation of social interaction, Distraction Theory proposes that subjects who are asked to perform tasks (both simple and complex) are affected by the mere presence of an audience (Baron & Moore, 1978). Although Distraction Theory differs slightly from the original research upon which it was based (Zajonc, 1965), it still explains that an audience will facilitate the process of completing simple tasks and potentially hinder the accuracy of complex task completion. It is possible that a similar phenomenon may be observable in the comparison of individual test findings and group test results. There is research to suggest that participants who took part in tasks with partners or 'co-actors' could be influenced by the ability of the co-actor. Muller, Atzeni & Butera (Muller, Atzeni, & Butera, 2004) conclude that there is some evidence of upward progression, i.e. errors are decreased in the performance of tasks when in the presence of a co-actor with a superior ability at that task. This form of social interaction may have an effect in our experiment, and potentially in musical performance generally.

The ultimate aim of the practical studies in this thesis is to develop recommendations for teaching strategies and assessment. This concept is intended to aid beginner musicians as well more established musicians. Drewing, Aschersleben & Li (Drewing, Aschersleben, & Li, 2006) studied the timekeeping efficacy of participants over a very broad age range and posited that sensorimotor skills and timekeeping improved rapidly during childhood up to teenage years and then tended to remain at that level until old age. Drewing *et al*. suggested that this rapid improvement and sustained ability cannot necessarily be attributed to the development of general cognitive abilities alone, but more likely a combination of the cognitive abilities linked with the specific components attributed to synchronization as influenced by Repp (Repp B. H., 2001) and Krampe (Krampe, 2002) i.e. timekeeping, error correction and sequencing.

The work of Drewing *et al*. was a particular influence on the experimental design for this phase of testing and the for the previous phase of testing. Whilst not identical, as the stimuli involved differed at points, it was important to have an established test methodology in place on which to base the test design.

6.3 Experiment

6.3.1 Research Objectives

Three different tempo conditions were used to analyse the effect the speed of the metronome may have on participants ability to maintain an isochronous pattern. At each tempo, the groups of participants were asked to play along (strike a cowbell) with two metronome types: isochronous or cross-rhythmic. The isochronous metronome provided tempo markers at the expected IOI for each tempo only; the cross-rhythmic metronome provided additional audio information, in the form of increased rhythmic complexity and in terms of frequency content.

The test design in this chapter was tailored to meet the specific research objectives established for the experiment. The design follows the overall Methodology found in Chapter 3.

6.3.2 Participants

In total, 40 participants took part in the experiment, with each test session consisting of four participants (10 test sessions overall). The test phase spanned three days. The recruited participants were students and staff members from several subject disciplines in Wrexham University. 25 participants were male, 15 were female. Participants were asked to classify themselves as 'Musician' or 'Non-Musician' according to the statement "*I have regularly practiced, played or studied and instrument (including voice) for the past 5 years*". Each participant was asked to declare if they suffered from any form of hearing loss or impairment; none of the participants reported any such condition.

Due to a technical error, only partial ITI data was recorded for the first test group. The data from this partially completed test was removed from the ITI analysis, but the responses to the post-experiment questionnaire have been retained and included in the analysis of the participants' perception of their performance.

Out of the 36 participants whose ITI data was analysed, 13 classified themselves as 'Musician', 23 classified themselves as 'Non-Musician'. The four participants whose ITI data was excluded from analysis classified themselves as 'Musician'.

The age of participants ranged from 18 to 62 years old.

6.3.3 Stimuli

The participants were played a stock, cowbell metronome from the ProTools software for the isochronous test conditions. For the cross-rhythmic test condition, each participant was played a combination of three, metrically derived, percussive samples in addition to the isochronous stock cowbell. The additional samples and cowbell were replayed at an identical volume, although they varied in pitch and timbre.

6.3.4 Equipment

Each participant was provided with a cowbell (supported on a double-braced cymbal stand) and a drumstick. Each participant was given a pair of Beyer Dynamic DT 770 studio

headphones and asked to cover one ear (of their choosing) with the headphones and leave one ear uncovered. Each cowbell was close-miked with a Röde NTG-2 shotgun microphone. ProTools (version 12.6) was used to record the individual cowbell strikes, as well as providing the playback of the six audio files (isochronous and cross-rhythmic). Headphone volume was controlled using a Behringer HA8000 V2 headphone amplifier. The volume of the headphone output was limited to a safe standard in accordance with The Control of Noise at Work Regulations 2005 (Health and Safety Executive, 2021), but each participant was able to alter the volume within those limitations.

Sound level measurements were taken to ensure that the volume of the physical cowbell strikes did not exceed safe levels.

The experiment was conducted in an acoustically treated room, with adequate lighting.

6.3.5 Procedure

Before the practical element of the test procedure commenced, participants were asked to complete a short survey that asked for information on demographics and prior musical experience.

Each participant was provided with a drumstick and a secured cowbell, set to a comfortable playing height. The participants were given a short practice period that included an opportunity for them to hear the auditory metronome and strike the cowbell without the ITI data being recorded.

Each group was arranged in a square formation, with participants facing inward at a 45^{o} angle (see Fig. 6.1). The distance between each participant was approximately two metres. This distance was chosen to largely eradicate any effect inter-aural time of arrival or level differences may have on a participant's performance, and to also allow participants to have a clear view of each other. Arranging the participants in this fashion emulates the visual contact of a typical small musical ensemble. Each participant was asked to cover only one ear with the headphones, to allow for auditory feedback from their instrument and from those of the other members of their test group.

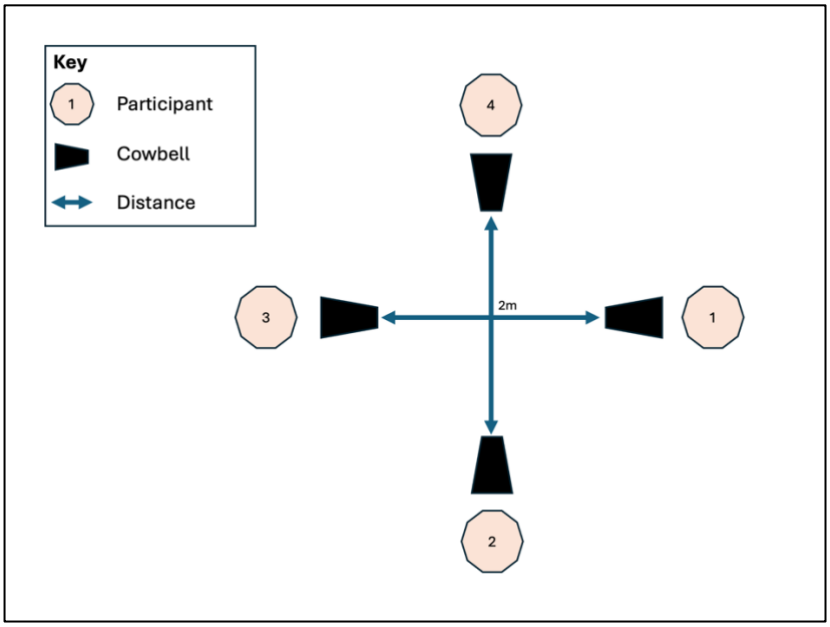

Fig. 6.1 Arrangement of participants for Experiment 2.

In total, participants were played six audio patterns. These patterns were split into three tempos: 80bpm, 120bpm and 160bpm. At each tempo, there were two differing metronome conditions: isochronous and cross-rhythmic (see fig. 6.2). The order in which these patterns were played to each group was randomly assigned.

Each of the six audio patterns followed the same structure: 20 crotchet beats at tempo with the metronome; 16 crotchet beats with the metronome removed; and 20 crotchet beats with the metronome reintroduced. Participants were provided with eight crotchet beats at the beginning and end of each audio sample, which were then discounted from analysis. For each test condition, participants were instructed to strike their cowbells in time with the isochronous pulse in each of the audio samples, regardless of different metronome type (i.e. isochronous or cross-rhythmic). Participants were instructed to continue this pulse when the metronome was removed and when it was reintroduced.

	80	120	160
	Cross-rythmic	Cross-rythmic	Cross-rythmic
	Isochronous	Isochronous	Isochronous
8 beats intro	20 beats with metronome	16 beats metronome removed	20 beats metronome reintroduced

Fig. 6.2 A representation of all combinations of test condition and variables for Experiment 2.

At the end of each test, the participants were asked to complete a short questionnaire, requesting responses that used a five-point Likert Scale for four statements. These statements were:

1. **My timekeeping accuracy was influenced by other participants;**
2. **My timekeeping was accurate when I played as part of a group;**
3. **My timekeeping was accurate when the metronome was present;**
4. **My timekeeping was accurate when the metronome was absent;**

The Likert Scale for statement 1:

1----------2- ---------- 3 ---------- 4 ---------- 5

Decreased a lot **Decreased a little** **Not at all** **Increased a little** **Increased a lot**

The Likert Scale for statements 2, 3 & 4:

1----------2- ---------- 3 ---------- 4 ---------- 5

Strongly disagree **Disagree** **Neither agree nor disagree** **Agree** **Strongly agree**

6.4 Analysis and Results

6.4.1 Analysis

Before the analysis of each participant's audio recordings took place, the individual WAV files were processed to amplify the initial transients of each cowbell strike. This allowed accurate measurement of the onset of each participant's strikes within their own isochronous patterns. The compressed and normalised WAV files of each participant were then analysed using a custom script in Matlab software. The program analysed each file and provided measurements (given in milliseconds) of the distance between each inter onset interval.

By comparing the distances of each individual strike to the expected (or ideal) inter onset interval, it is possible to determine the variance of individual participants' ITIs at the three different tempos and at different points in the isochronous pattern. However, to compare inter-tap interval variance across the three tempos, it was essential to normalise the values. To ensure the results of ITI were comparable over the changing tempi in the tests, the established formula was used to normalise the average ITI of each individual test result, as described in the preceding chapters (equations 5.1, 5.2 & 5.3).

The responses of each participant to the questionnaire were also analysed. The responses were collated as one large group of all 40 participants (this included the responses from the four participants whose ITI data was excluded from analysis).

6.4.2 Results

6.4.2.1 ITI Data Analysis

A two-way repeated measures ANOVA was run to determine the effect of differing metronome types, tempi, and metronome state on the participants' average ITI. For the complete test, there was shown to be no statistically significant two-way interactions between variables. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 2.161$, $p = .339$. Analysis of the complete set of results with studentized residuals showed that there was normality, as assessed by the Shapiro-Wilk test of normality and no outliers, as assessed by no studentized residuals greater than ± 3 standard deviations.

The simple main effect of *metronome type* did not prove to be statistically significant (see Fig. 6.4). *Metronome type*: $F(1.000, 35) = 2.295$, $p = .139$. However, the simple main effects of *tempo* (Fig. 6.3) and *state* (Fig. 6.4) demonstrated a statistically significant difference in ITI across tempo and across metronome state:

In terms of the effects of *tempo*: $F(2, 70) = 4.123$, $p = .020$. Post-hoc tests using the Bonferroni correction for multiple comparisons showed that statistical significance was present between 80bpm and 160bpm ($p = .049$), but not between 80bpm and 120bpm ($p = .164$) or between 120bpm and 160bpm ($p = .954$).

When assessing the effect of *metronome state*: $F(2, 70) = 5.693$, $p = .020$. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 1.788$, $p = .409$). Post-hoc tests using the Bonferroni correction for multiple comparisons showed statistical significance between the *present* state and *reintroduced* state ($p = .009$), but not between the *present* state and *removed* state ($p = .207$) or between the *removed* state and *reintroduced* state ($p = .333$).

A comparison of ITI across tempo and metronome state can be seen in Fig. 6.6.

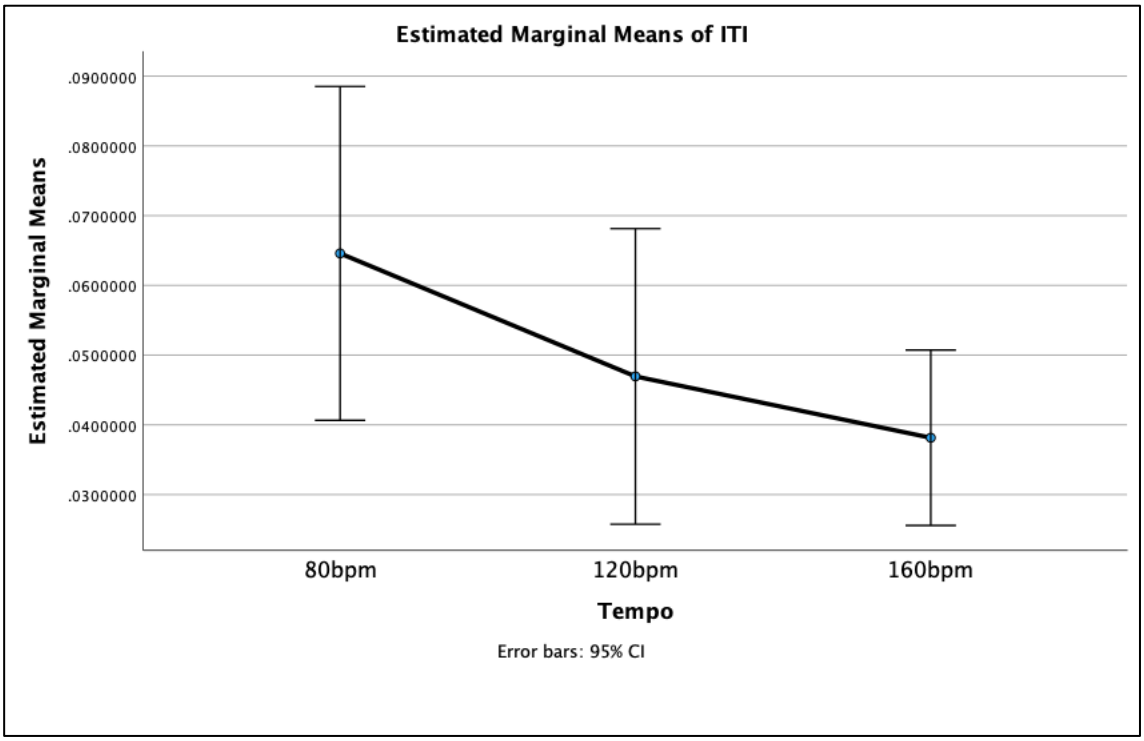

Fig. 6.3 Mean ITI across the three tempi for Experiment 2.

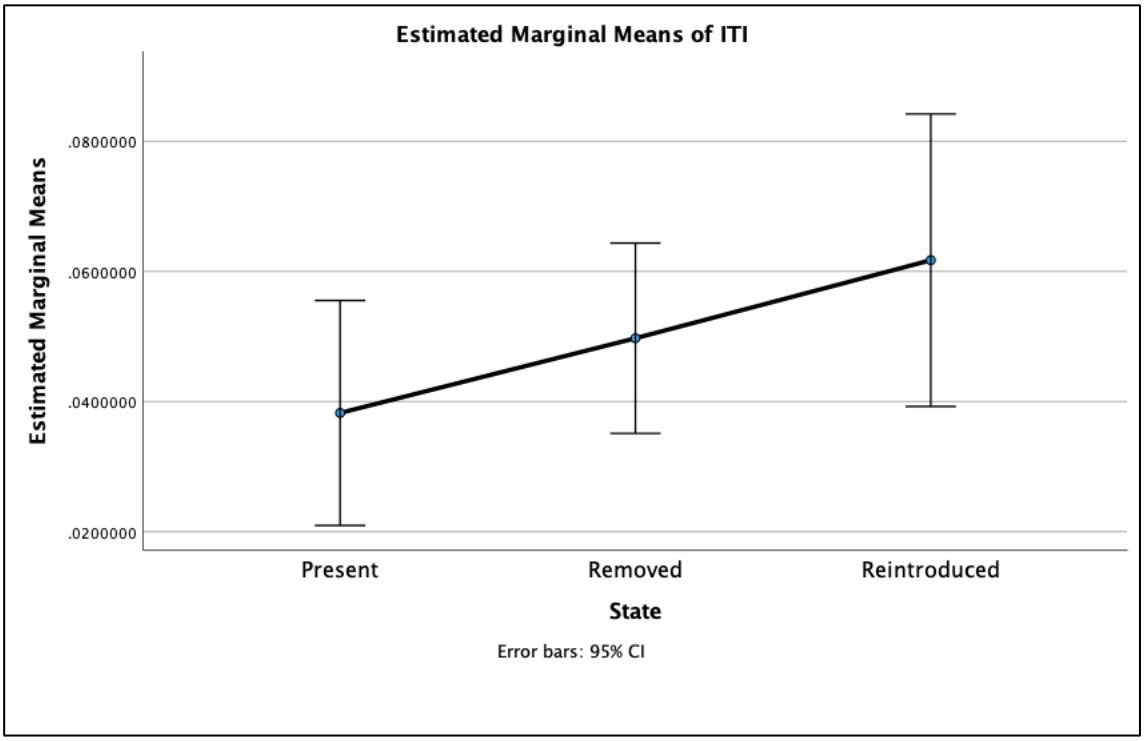

Fig. 6.4 Mean ITI across the three metronome states for Experiment 2.

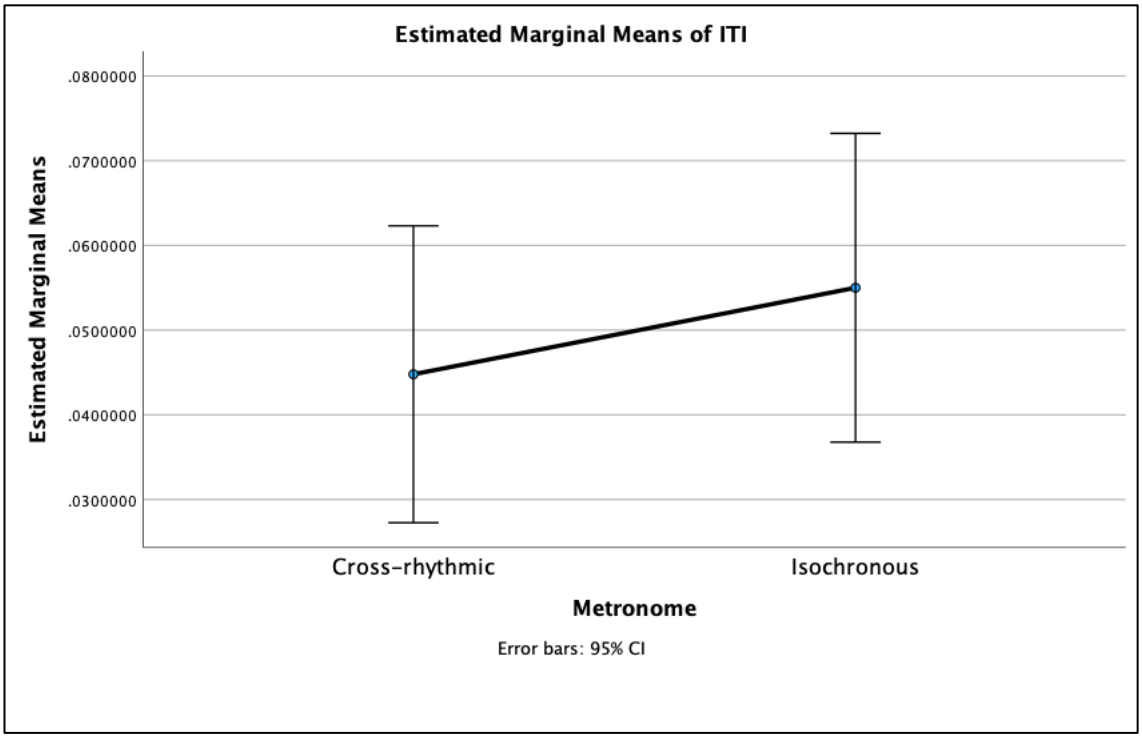

Fig. 6.5 Mean ITI across the two metronome types for Experiment 2.

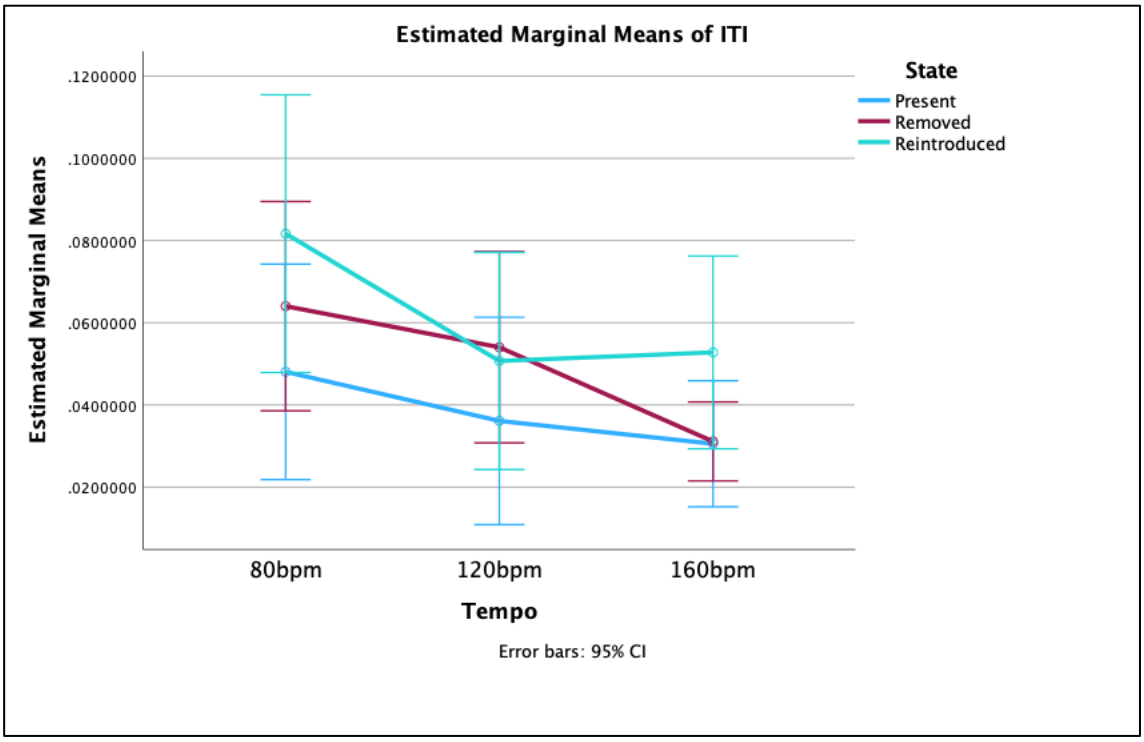

Fig. 6.6 A comparison of mean ITI across tempo and metronome state for Experiment 2.

Statistical analysis of the ITI data revealed that two variables produced significant effects on participants' average ITI. The tempo variable was shown to have significance, demonstrating greater average ITI distance from the target IOI at the slower tempo and larger variance. At the higher tempo, average ITI distance was closer to the target IOI and the level of variance was smaller. The metronome state variable was shown to have significance, specifically when the metronome was reintroduced.

6.4.2.2 Questionnaire Response Analysis

For the complete set of responses to the post-experiment questionnaire, Kendall's *W* was run to determine if there was agreement between the 40 participants' perception of their timekeeping performance with different metronome types and different metronome states. The participants' perception of their performance under these conditions was determined according to a five-point classification system from 1 (Strongly Disagree or Decreased a lot) to 5 (Strongly Agree or Increased a Lot). The consistency of responses from the 40 participants were statistically significant $W = .388$, $p < .001$.

There was a statistically significant consistency between the 40 participants' response to their perception of their timekeeping performance and perceived influence of other participants, so the hypothesis can be accepted that the entire collection of responses displays an internal consistency.

Whilst the test of Kendall's coefficient of concordance refers to the overall response of each participant, the whole group findings for the questionnaire can be collated per statement. These figures display the responses to each statement on the form filled in by each participant once the test was complete. It is this data in its entirety that was analysed by using Kendall's Concordance Coefficient.

Fig. 6.7 shows that only two of the participants felt that their timekeeping was not influenced by other participants. Most of the participants responded that they perceived their timekeeping accuracy to influenced positively by other participants.

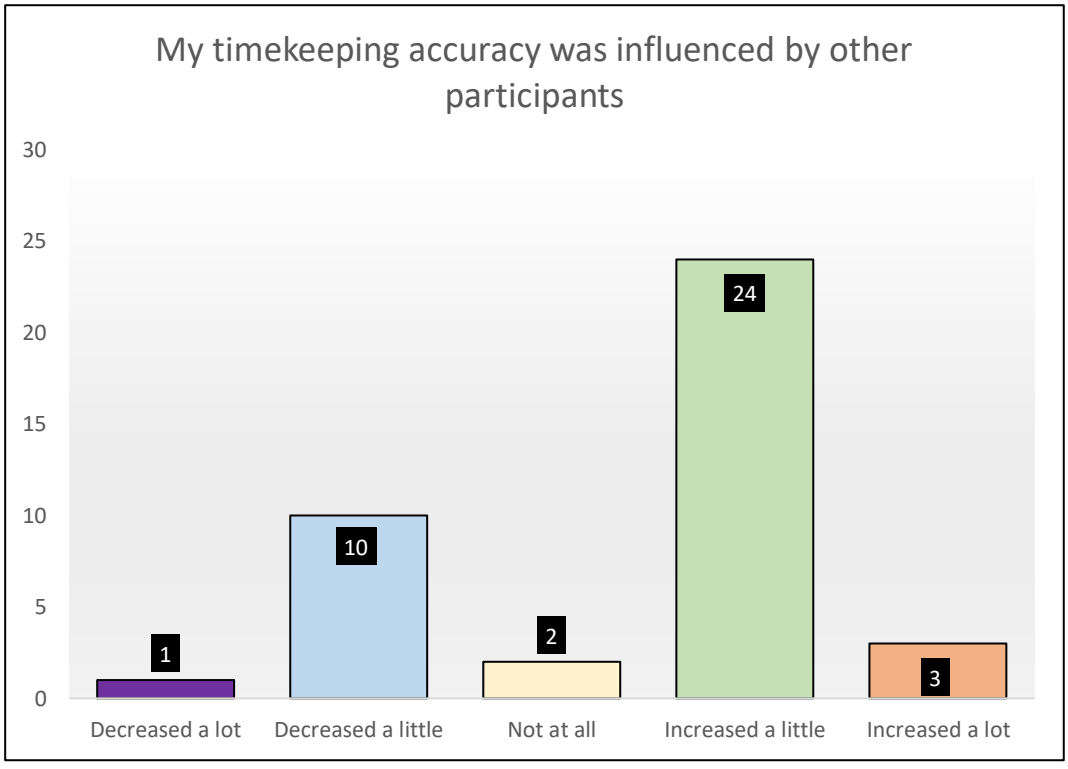

Fig. 6.7 The overall responses to Statement 1: "*My timekeeping accuracy was influenced by other participants".*

However, when the participants were presented with the statement "*My timekeeping was accurate when I played as part of a group*", the responses were much more evenly distributed and do not provide an obvious majority perception of timekeeping accuracy (see Fig. 6.8).

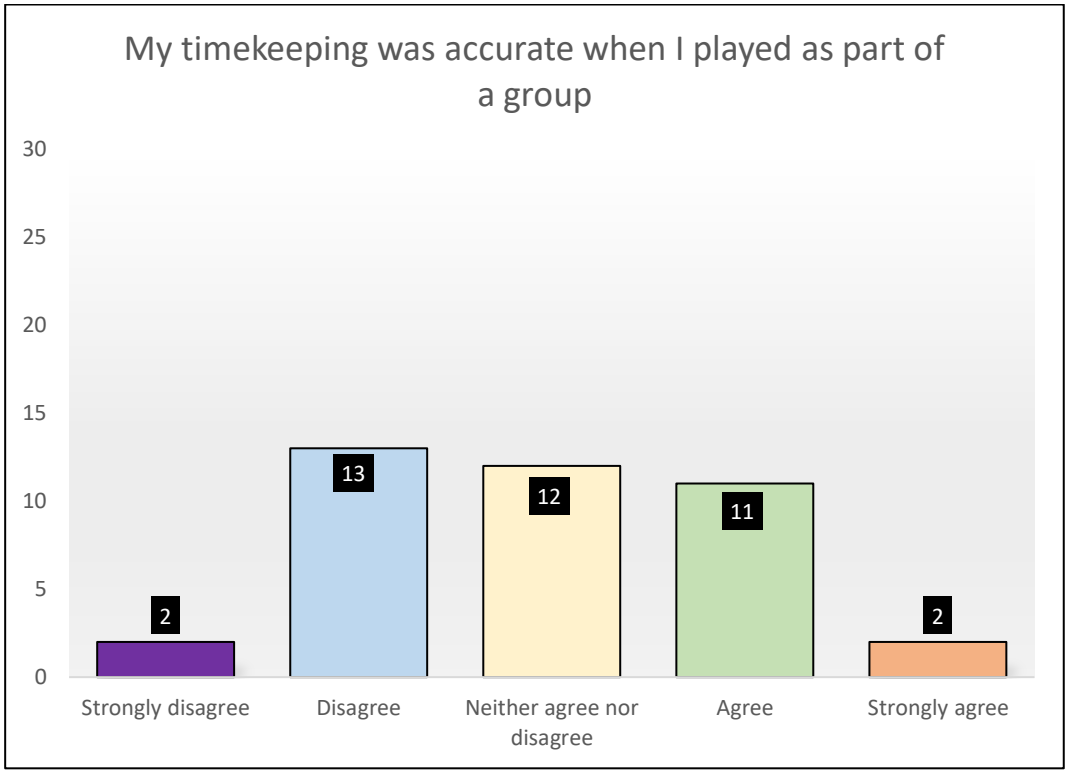

Fig. 6.8 The overall responses to Statement 2: "*My timekeeping was accurate when I played as part of a group".*

In Fig. 6.9 we see a clearly that the vast majority of participants perceived their timekeeping to be accurate when the metronome was present. Fig. 6.10 shows that participants perceived their timekeeping was not accurate when the metronome was removed, however the responses to this statement are more evenly distributed.

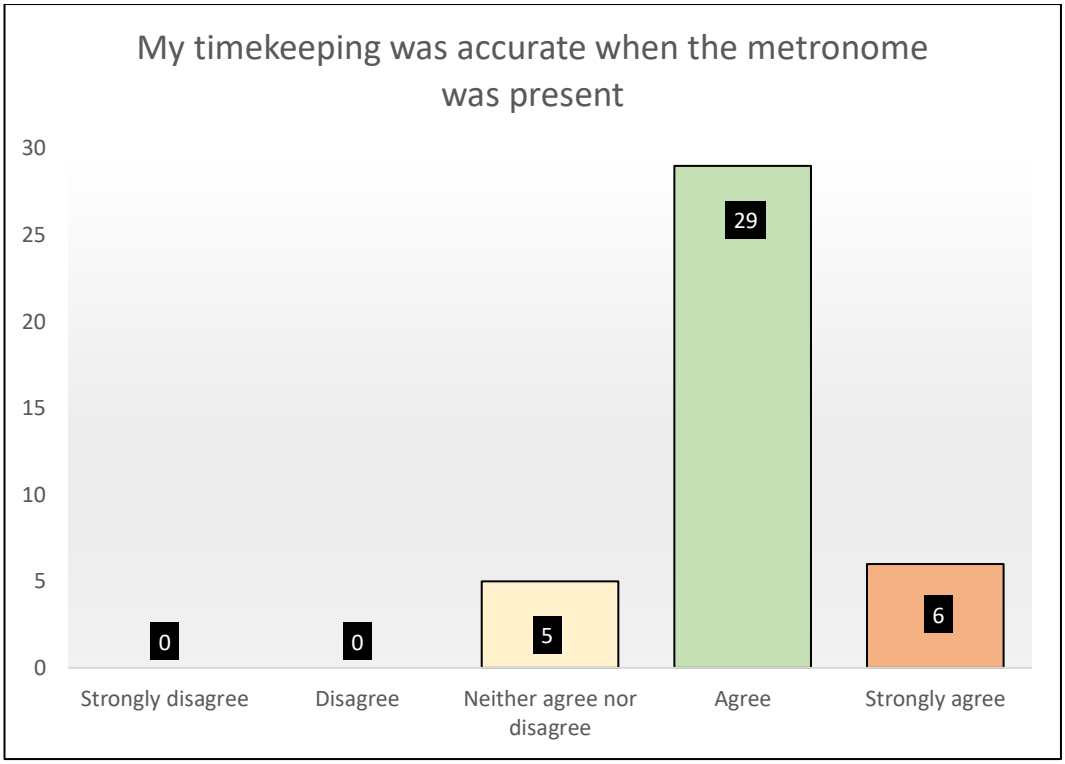

Fig. 6.9 The overall responses to Statement 3: "*My timekeeping was accurate when the metronome was present*".

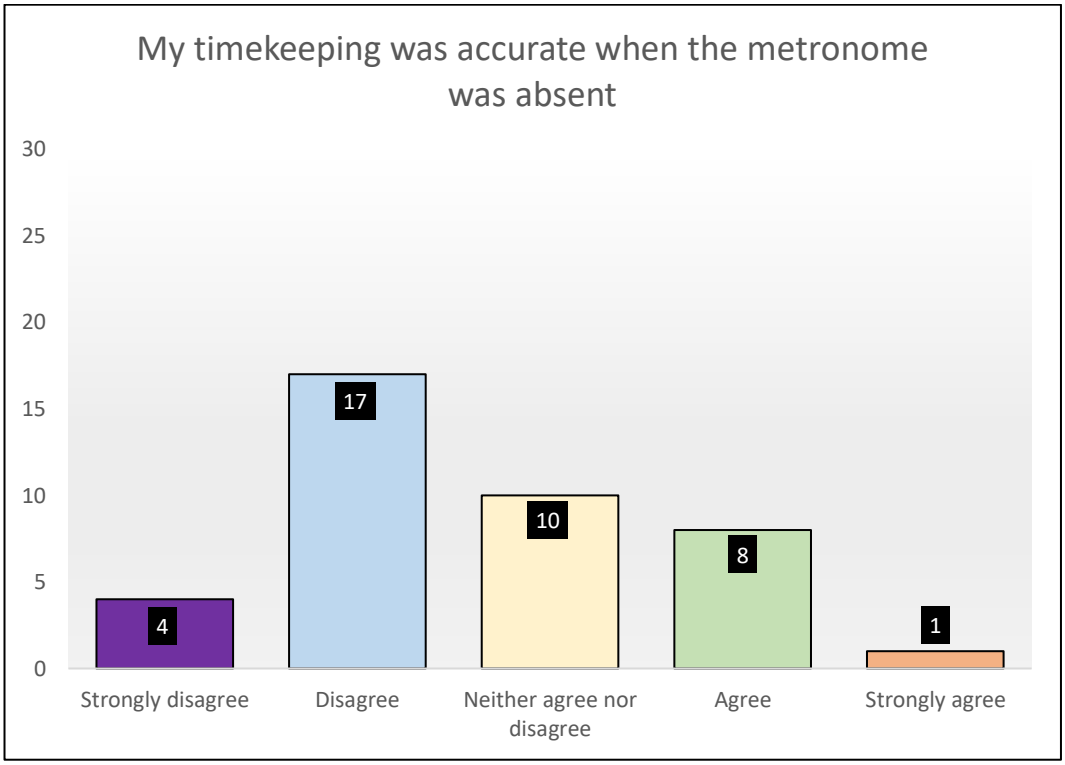

Fig. 6.10 The overall responses to Statement 4: "*My timekeeping was accurate when the metronome was absent*".

6.5 Limitations

The size of the groups was limited to four participants each. When analysed in these small groups, the data was deemed insufficient to allow for meaningful conclusions to be drawn. In that instance, the average ITI of each group over tempo, metronome type and metronome state was used, reducing the granularity of the results. Therefore, the data analysis took all of the 36 participants' ITI information into account, in effect treating them as one large group. It may be beneficial to repeat this experiment on a larger scale, using larger groups than the four participants per group used in this study, however this might present some challenges in itself, such as accurately isolating individual performance data from recordings, ensuring uniformity of auditory playback for each participant, and the logistics of accommodating large groups in a suitable test environment.

As the groups were, in some cases, a combination of musicians and non-musicians it may be a worthwhile exercise to repeat the experiment with exclusively trained and untrained participants in their respective groups.

6.6 Conclusions

The work of this chapter intended to explore any influence on participants' Inter-tap Interval that metronome type, tempo and the removal and reintroduction of an auditory metronome might have. The focus of the experiment was to explore any observable similarities or differences in the results of a group test, compared to that of the individual test examined in Chapter 5.

The analysis of ITI data from the experiment provides two statistically significant results. Tempo and metronome state have a statistically significant impact on participants' average ITI. This is consistent with the results from Chapter 5 and suggests that performing the timekeeping task as part of a group rather than as an individual has no impact on the statistical significance of the metronome type. It should be concluded that there is no discernable difference in the level of influence the two types of auditory metronome (cross-rhythmic and isochronous) have on the ITI produced by participants.

Tempo is demonstrated to have a statistically significant effect on ITI, specifically between the slowest tempo (80bpm) and the fastest tempo (160bpm). ITI duration is furthest from the target duration at 80bpm and closest to the target duration at 160bpm. This is consistent with the findings of Chapter 5 to the extent that the slower tempo produces ITI duration furthest from target duration. However, in this group test, there is no average correction of ITI – the average ITI increases in an almost linear fashion at 80bpm, as the metronome state changes. As groups, average ITI at this tempo lengthens as the metronome is removed and continues to increase as the metronome is reintroduced. At 160bpm, the average ITI lengthens by an almost imperceptible amount when the metronome is removed, and then lengthens much more noticeably when the metronome is reintroduced. This is not the case at 120bpm, where average ITI lengthens as the metronome is removed, but then shortens toward the target ITI as the metronome is reintroduced, although this *reintroduced* state of the 120bpm average ITI data does not fully recover to the levels of the initial *present* state at that tempo (see Fig. 6.11).

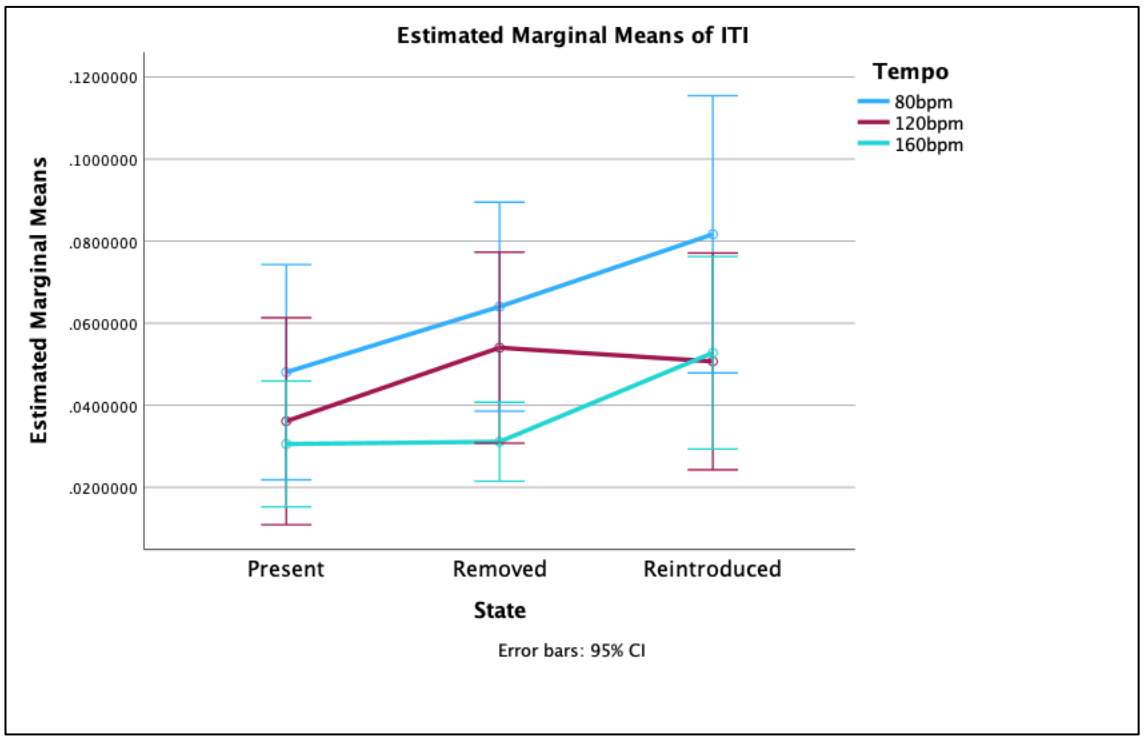

Fig. 6.11 Mean ITI for the three tempi over metronome state.

Metronome state leads to statistically significant differences in average ITI, specifically the combination of the *present* and *reintroduced* states. This is a slightly different outcome to the

results from Chapter 5, where all combinations of metronome states were significant. In this case, the results show that average ITI duration increases in a linear fashion, increasing in length (and distance from target IOI) once the metronome is removed and continuing to increase once the metronome is reintroduced. It is possible to conclude that the improved performance in the *removed* state in this group experiment is due to the presence of other performers, who act as entrainment partners. The synchronized drift in ITI duration during the *removed* state may produce an average ITI that does not stray as far from the target IOI, when compared to the individual results from Chapter 5. It would appear that the reintroduction of a fixed metronome that is temporally at odds with the participants causes a significant amount of confusion, and results in average ITI duration that is even longer than when the metronome was removed. This is not the case at 120bpm; it is possible that this improved performance could be related to tempo, as 120bpm falls within the range of established test methodologies that have investigated 'preferred tempo' (Moelants, 2002). This preference for tempi with a specific range of IOIs or beat duration may afford participants an improved capacity to predict or maintain ITIs when a metronome is removed.

A post-test survey was conducted after each group session. The results from this questionnaire provide insight into the perceptions of the participants' own performance and the factors that they felt influenced their contribution. The questionnaire showed that the majority of participants felt that their accuracy was improved when the metronome was present. A slightly smaller majority felt that their performance was adversely affected when the metronome was absent. Both these results are supported by the statistically significant change in ITI between metronome conditions. The survey results indicate that the participants perceived their timekeeping abilities to have been influenced by performing the task as a group. There was no discernible majority opinion on whether that influence was positive or not.

In answer to **RQ1**: '*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping'?*, this chapter has demonstrated that the removal and reintroduction of a metronome has a significant effect on the average ITI of participants. Once the metronome is reintroduced, average ITI never regains the same level of accuracy as measured when the metronome is first present. This is most clearly indicated

at the slowest tempo of 80bpm, further the supporting the findings in Chapter 5. However, in this group environment, the average ITI that is closest to the target IOI of the metronome is is measured at the fastest tempo of 160bpm. Again, this demonstrates that tempo is a influence on average ITI and that the slower tempo induces the least consistent ITI.

Participants' responses to the post-experiment questionaire clearly indicate that they felt their timekeeping was accurate when the metronome was present, and just over half of the participants felt their timekeeping was not accurate when the metronome was removed.

The results of data analysis in this chapter can address **RQ2**: "*What effect does playing in a group, versus individually, have on musical timekeeping?*". Average ITI moves closer to the target IOI of the metronome as the tempo increases. This trend differs from the results of participants who performed as individuals in Chapter 5, as the average ITI was closest to the target IOI at the median tempo in that experiment.

Average ITI was at its furthest from target IOI when the metronome was reintroduced. As each group member had three co-actors to entrain with when the metronome was removed, this could explain the improved average ITI when compared to the individual results of the same metronome state in Chapter 5. The results of average ITI in the *reintroduced* state could indicate that re-entrainment with a rigid, target pattern is made more difficult by the presence of other group members.

The participants' perception of their timekeeping accuracy as part of a group is not clear. The majority of participants responded that their timekeeping was positively influenced by other group members. However, the statement "*My timekeeping was accurate when I played as part of a group*" yielded responses with a much more even distribution.

In answer to **RQ3**: "*What influence does differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?*", there is no indication that metronome type has any influence over average ITI. Whilst the analysis shows a slight increase in average ITI in the isochronous metronome data when compared to the cross-rhythmic ITI data, it is not significant enough to draw any meaningful conclusions.

Chapter 7 investigates the influence the changes in metronome state and tempo have over participants' ITI in a individual setting. In addition, Chapter 7 introduces a visual metronome condition to examine the influence this differing metronome type has on average ITI, and it includes responses from participants to a post-experiment questionaire designed to ascertain their perception of timekeeping accuracy in this test environment.

7. Experiment 3: Audio Visual Metronome Test

7.1 Introduction

This experiment is specifically designed to address the following Research Questions:

- **RQ1:** *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*

- **RQ3:** *What influence does differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?*

This test phase represents the third stage of the overall series of experiments. As stated previously, the purpose of this test is to investigate the influence that differing metronome conditions may have over ITI. Test participants will be exposed to isochronous metronome figures, both in audio, visual and audio-visual combined forms. The test participants will also be asked to play along with metronome conditions that contain both audio and visual stimuli together.

This experiment expands upon the test methodology developed in previous chapters, incorporating established methodologies and protocols. Based on the results and conclusions from previous experiments, this phase will see individual participants strike a cowbell to produce an isochronous pattern whilst listening to audio stimuli and/or watching visual stimuli. This represents an expansion upon previous tests: the results of the previous chapters suggested that cross-rhythmic auditory metronomes have no significant statistical impact on an individual participant's ability to produce a consistent ITI, therefore, this study will exclusively use isochronous auditory and visual metronomic patterns as stimuli.

7.2 Background and Rationale

Traditional metronomes have employed audible pulses to produce a consistent and precise beat for musicians to practice their timekeeping. Since the invention of the conventional metronome in 1818 by Johan Maelzel (Wyatt, J, 1818), musicians have used metronomes to aid in their ability to keep time whilst performing or practising. Digital metronomes emerged

in the latter half of the twentieth century as technology advanced. Primarily, these metronomes initially provided solely auditory cues and, in many instances, were incorporated into Digital Audio Workstations for recording purposes, or in handheld digital devices for the purpose of practicing an instrument recreationally. More recently, metronomes have been developed for software or mobile applications that can be installed on smart devices such as phones, tablets, and home computers – these applications use a variation of auditory, visual, and tactile cues to assist users in keeping time.

Computer games such as Guitar Hero (Harmonix & RedOctane, 2005) and Beat Saber (Ilavský & Hrinčár, 2018) employ visual cues alongside auditory stimuli to encourage users to participate in what is essentially a timekeeping exercise. In some instances, the gamification of timekeeping tasks has been used to assess and develop metronomic practices, using a combination of auditory, visual, and sometimes tactile cues (Hoang & Cohen, 2022). Visual and tactile cues are beneficial to people who have hearing difficulties or have differing sensory preferences, improving accessibility of the metronomes. Wearable devices have also been created with the ability to produce visual and auditory cues as well as tactile output. These devices can be used in performance or rehearsal settings and provide discrete tempo information for the musicians using them. There are also developments in Augmented Reality (AR) metronomes, such as the work of Pinkl & Cohen (2020) which uses polyrhythmic auditory and visual cues in an AR environment to provide tempo information to the user.

It is the influence of these developments, extending beyond the traditional audio-only metronomic information, that the experimental work of this chapter intends to examine. For the purposes of this study, the visual metronome will be represented by a moving visual cue, similar to the 'Bouncing Ball' metronome described in Hove *et al*. (2012). As those authors discuss, visual metronomes with movement of this type provoke more accurate visuomotor synchronisation from users, over the more traditional stationary, flashing visual stimuli.

7.3 Experiment

7.3.1 Research Objectives

This experiment was designed to test the effects that differing metronome conditions would have on the timekeeping of individual participants, using various combinations of audio and visual metronomic stimuli.

The test design in this chapter was tailored to meet the specific research objectives established for the experiment. The design follows the overall Methodology found in Chapter 3.

7.3.2 Participants

27 people participated in the study. In total, 16 participants were male, 11 were female. There were three days of testing, all contained within a 14-day period. The recruited participants were students and staff members from several subject disciplines in The Liverpool Institute for Performing Arts. Participants were asked to classify themselves as 'Musician' or 'Non-Musician' according to the statement "*I have regularly practiced, played or studied and instrument (including voice) for the past 5 years*". Each participant was asked to declare if they suffered from any form of hearing loss or impairment, or any visual impairment; none of the participants reported any such condition.

Out of the 27 participants, 21 classified themselves as 'Musician', 6 classified themselves as 'non-Musician'.

The age of participants ranged from 18 to 50 years old.

7.3.3 Stimuli

Each participant was given a pair of studio headphones and asked to cover one ear (of their choosing) with the headphones and leave one ear uncovered. The participants were played a stock, cowbell metronome sampled from the Logic Pro X software for the isochronous audio test conditions. For the visual metronome test conditions, each participant was played a moving tempo marker that was precisely the same duration as its audio equivalent (see Fig.

7.1). This visual marker crested at a specific point on the screen at the commencement of each cycle of the IOI. The movement remained the same, regardless of tempo. The volume of the headphone output was limited to a safe standard in accordance with The Control of Noise at Work Regulations 2005 (Health and Safety Executive, 2023), but each participant was able to alter the volume within those limitations.

Sound level measurements were taken to ensure that the volume of the physical cowbell strikes did not exceed safe levels.

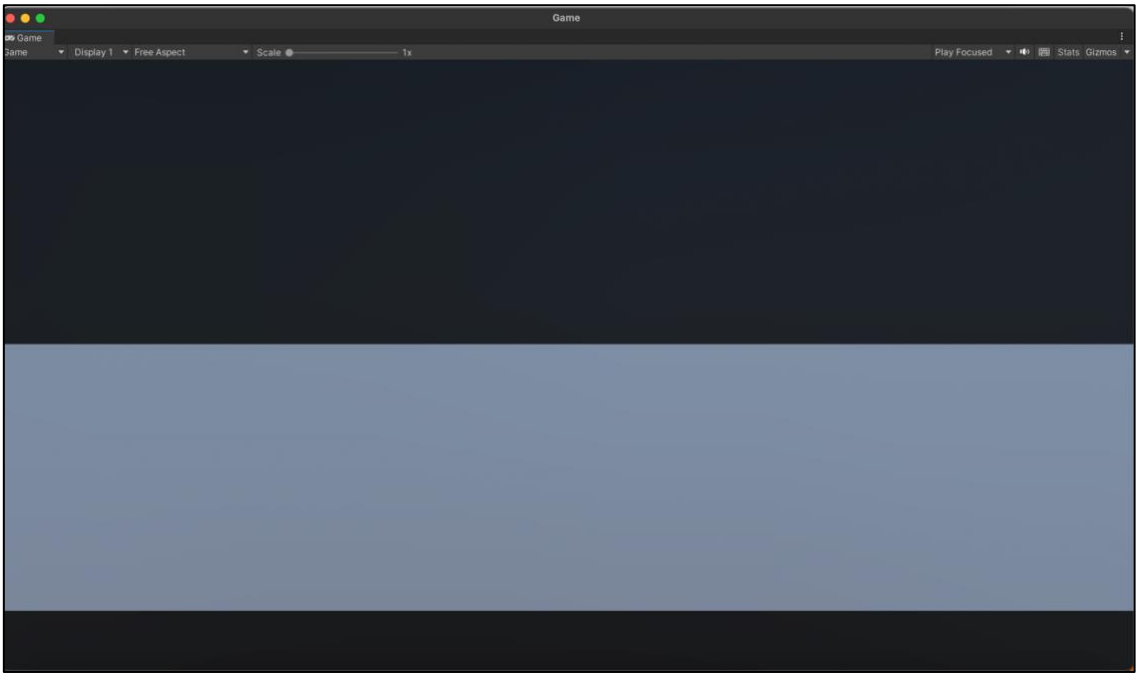

Fig. 7.1 The moving tempo marker used in Experiment 3.

7.3.4 Equipment

Each participant was provided with a cowbell (supported on a double-braced cymbal stand) and a drumstick. The participants were asked to use a pair of Beyer Dynamic DT 770 Pro studio headphones and the volume was controlled using a Behringer xHA8000 V2 headphone amplifier.

A testing application was developed using a hardware and software combination; a piezo sensor for input, connected to an analogue input of an Arduino nano. The input information from the Arduino was then captured by Unity (Unity Technologies, 2023), using the Uduino

plugin from Teyssier (2023). The piezo sensor was attached to a cowbell for test subjects to strike with a drumstick.

Fundamentally, the hardware component served as an interface for providing input information to the Unity environment to be used in combination with audio and visual elements to the user.

The piezo sensor input was assigned to an input variable of the Uduino plugin, allowing this analogue input (A0) to be detected, and latterly recorded, within Unity (see Fig. 7.2).

To record the input as accurately as possible, the update frequency of both the Arduino and Unity were recorded in microsecond intervals, however, the signal decay of the analogue input was longer than this interval. To refine the accuracy of this, a sensitivity limiter was applied, though this resulted in reduced detection of smaller inputs. It was decided that it was preferable to over record the input data and omit all but the first interaction record.

```
test = UduinoManager.Instance.analogRead(AnalogPin.A0, "PinRead");
lightSouce2.intensity = test / 200.0f;

UduinoManager.Instance.SendBundle("PinRead");
```

Fig. 7.2 Unity Arduino (Uduino) configuration for analogue read.

This was achieved with minor modification to the Uduino ‘Read Lights’ script from their tutorials. This script also contained a logging co-routine in order to create and append the log described in **7.3.4.1**.

The software application comprised two key ‘indicator’ components:

1) An audio output, in this instance, a simple, stock woodblock sound was emitted using a ‘Sound Source’ component at appropriate intervals.

This element was able to be negated by an ‘AudioMute’ script that allowed the component to play silently, providing a reference point for a logging script (7.5). This action was triggered at the appropriate time by the researcher with a key press (M).

2) Prefab elongated cube shapes were generated, with rigidbody physics, causing them to drop into view at appropriate intervals. These cubes dropped onto and through a basic collider, which triggered the audio output, from which each interaction could be measured.

This element was able to be negated by a ‘VideoBlank’ script that produced an occlusion to the scene, hiding the generated cubes while still allowing them to provide a reference point for a logging script (**7.3.4.1**). This was triggered at the appropriate time by the researcher with a key press (V).

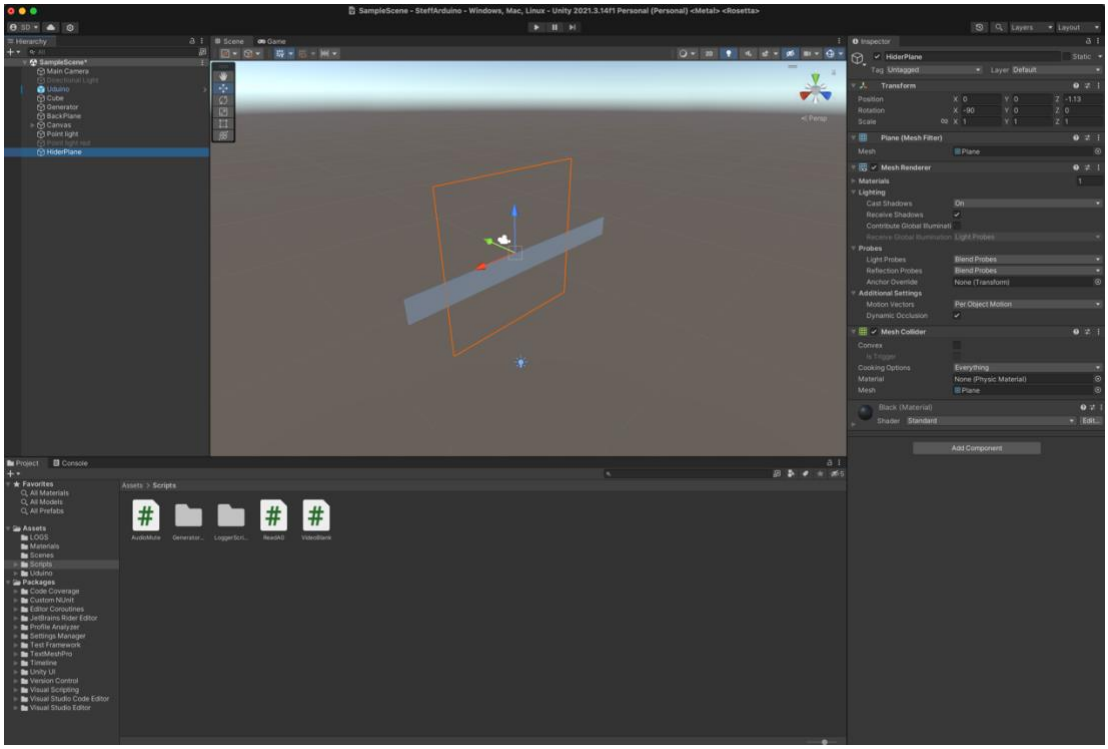

Fig. 7.3 The design view of the Audi-visual Metronome within the Unity Environment.

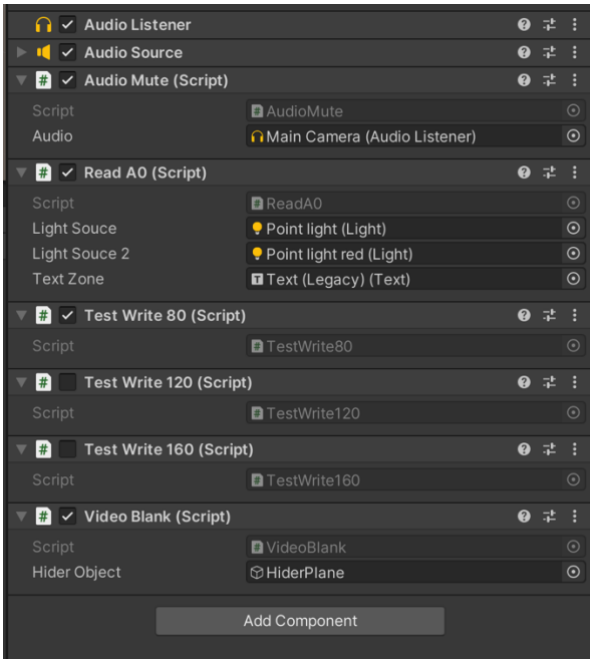

Fig. 7.4 The function select window in Unity.

These indicator components were controlled by scripts that triggered either audio only, visual only, or both components, at predetermined bpm intervals, 80bpm, 120bpm and 160bpm. The appropriate script was enabled prior to each test event.

7.3.4.1 Logging Script

Each instance of the test was recorded using a logging script which used the C# 'StreamWriter' function to create and append information to a log file (see Fig. 7.5).

```
void LogCowbell()
{
    string path = "Assets/LOGS/" + "TestLog" + ".txt";
    StreamWriter sw = new StreamWriter(path, true);
    sw.Write(", , , ,");
    sw.Write("COWBELL, ");
    sw.Write(System.DateTime.Now);
    sw.Write(", ");
    sw.Write(Time.timeSinceLevelLoad);
    sw.WriteLine(";");
    sw.Close();
}
```

Fig. 7.5 The logging script for metronome and cowbell events.

Each test commenced with header information for clearer delineation (Fig. 7.6).

Fig. 7.6 Log file output headings for data text file.

Each cube collision event was recorded as a 'Metronome' event. Each cowbell input was recorded as 'Cowbell' event. Each event record also captured 'Date & Time Now', providing a timestamp accurate to 1s, as well as 'Time Since Level Load', providing a timestamp with microsecond accuracy.

These events were formatted with delimiters ',' for offset and ';' as line breaks in order to produce an easily importable CSV for analysis (Fig. 7.7).

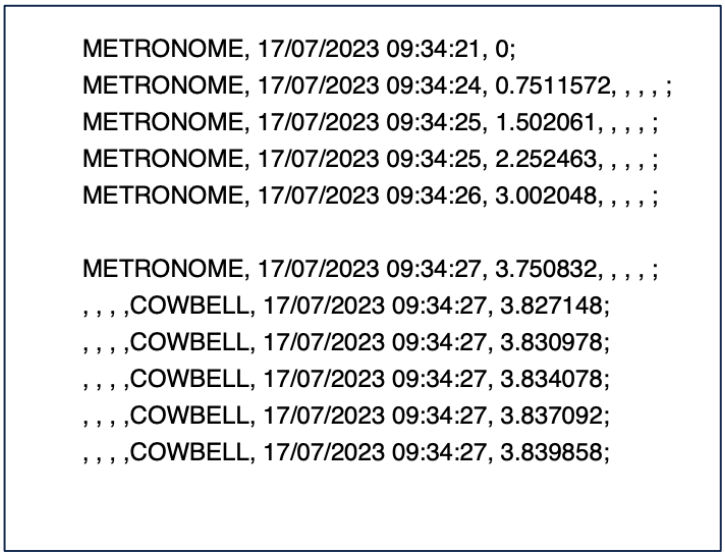

Fig. 7.7 Logging example of metronome and cowbell events.

The logged information was imported into Excel for processing and analysis.

7.3.5 Procedure

Before the practical element of the test procedure commenced, participants were asked to complete a short survey that asked for information on demographics and prior musical experience.

A short practice period was given to the participants that included an opportunity for the participants to listen to an example of the auditory metronome and see an example of the visual metronome. In total, participants were played nine isochronous audio and/or visual patterns. These patterns were split into three tempos: 80bpm, 120bpm and 160bpm. At each tempo, there were differing metronome conditions; audio only, visual only and audio and visual combined (see Fig 7.8). The order in which these patterns were played to each participant was randomly assigned. The three different tempo conditions were used to analyse the effect the speed of the metronome may have on participants ability to maintain an isochronous pattern. At each tempo, participants were asked to play along (strike a cowbell) with an isochronous metronome. The isochronous metronome provided tempo markers at the expected IOI for each tempo; dependant on the metronome type, these markers were in audio and/or visual form.

Each of the nine patterns followed the same structure: 32 crotchet beats at tempo with the metronome; 32 crotchet beats with the metronome removed; and 32 crotchet beats with the metronome reintroduced. Participants were not informed of the duration of each test phase. Participants were provided with four crotchet beats at the beginning and end of each pattern, which were then discounted from analysis. For each test condition, participants were instructed to strike their cowbells in time with the isochronous pulse in each of the audio and/or visual samples and were instructed to continue this pulse when the metronome was removed and when it was reintroduced.

	80	120	160
	Iso with Visual	Iso with Visual	Iso with Visual
	Iso without Visual	Iso without Visual	Iso without Visual
	Visual only (Iso)	Visual only (Iso)	Visual only (Iso)
4 beats intro	32 beats with metronome	32 beats metronome removed	32 beats metronome reintroduced

Fig. 7.8 A representation of all combinations of test conditions and variables for Experiment 3.

At the end of each test, the participants were asked to complete a short questionnaire (see Appendix D), requesting responses that used a five-point Likert Scale for six statements. These statements were:

1. **My timekeeping was accurate when the audio metronome was present;**
2. **My timekeeping was accurate when the audio metronome was absent;**
3. **My timekeeping was accurate when the visual metronome was present;**
4. **My timekeeping was accurate when the visual metronome was absent;**
5. **My timekeeping was accurate when both the visual and audio metronomes were present;**
6. **My timekeeping was accurate when both the visual and audio metronomes were absent;**

The Likert scale for each statement:

1----------2- ---------- 3 ---------- 4 ---------- 5

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

7.4 Analysis and Results

7.4.1 Analysis

The data collected from each of the individual participants' strikes was used to establish an average value for the ITI of each participant at different stages of the tests. Statistical analysis was conducted on all the possible variations of the variables to assess which, if any, factors

played any significant role in affecting participants' ITI. To ensure the results of ITI were comparable over the changing tempi in the tests, the established formula was used to normalise the average ITI of each individual test result, as described in the preceding chapters (equations 5.1, 5.2 & 5.3).

Participants also provided feedback via a short questionnaire after they had completed their tests. The questions were designed to assess the participants' perception of their own performance under the different test conditions. Whilst this feedback is subjective, it was designed to provide some insight to the perceived accuracy of participants versus the actual, objective data.

Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, and a Greenhouse-Geisser correction was applied, $F(1.099, 27.476) = 11.826$, $p = .001$. Analysis of the complete set of results with studentized residuals showed that there was normality, as assessed by the Shapiro-Wilk test of normality and no outliers, as assessed by no studentized residuals greater than ± 3 standard deviations.

A two-way repeated measures ANOVA was run to determine the effect of differing metronome types, tempi, and metronome state on a participants' average ITI. For the complete test, there was shown to be no statistically significant two way interactions between variables. The simple main effects of *tempo* and *metronome type* did not prove to be statistically significant (see Fig 7.9 and Fig. 7.10). *Tempo* $F(1.336, 33.407) = 1.087$, $p = .325$. *Metronome type*: $F(1.159, 28.973) = 2.105$, $p = .156$. However, the simple main effect of *metronome state* did prove to be statistically significant (see Fig 7.11). The main effect of metronome *state* showed that there was a statistically significant difference in ITI between metronome states.

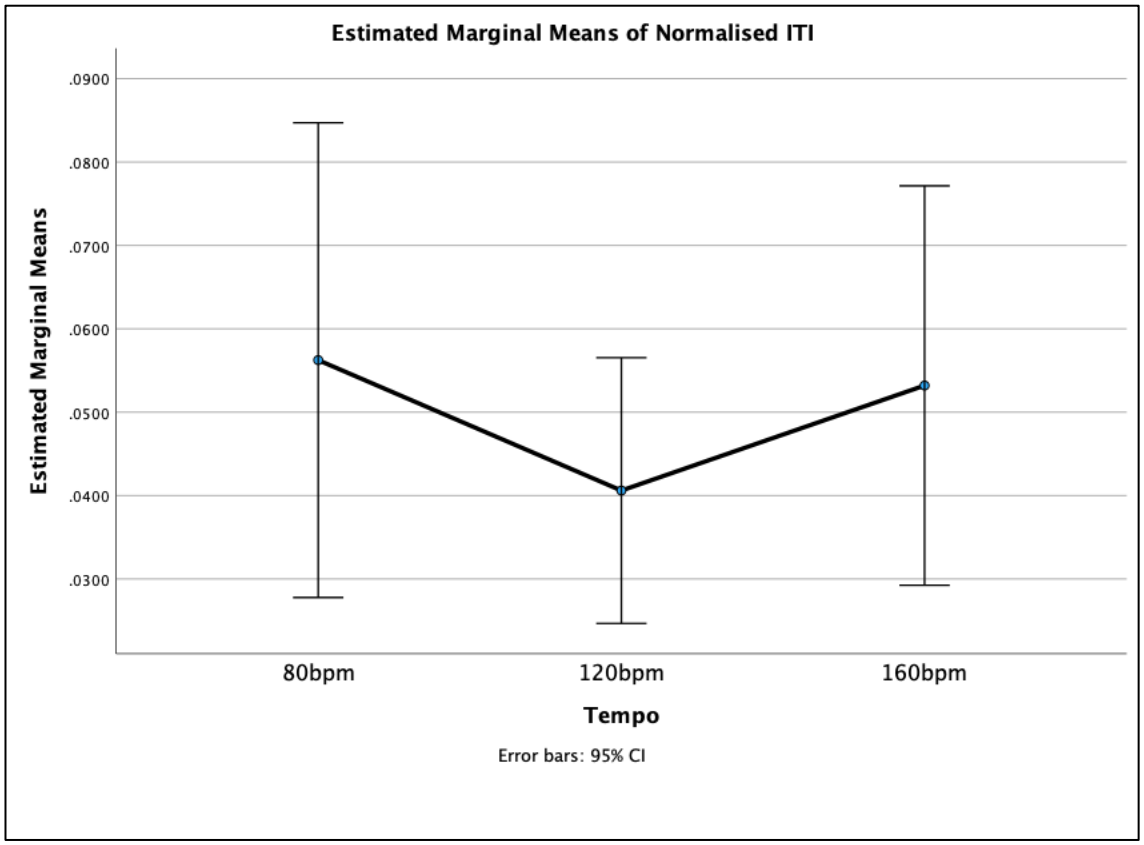

Fig. 7.9 Mean ITI and standard deviation across the three tempi for Experiment 3.

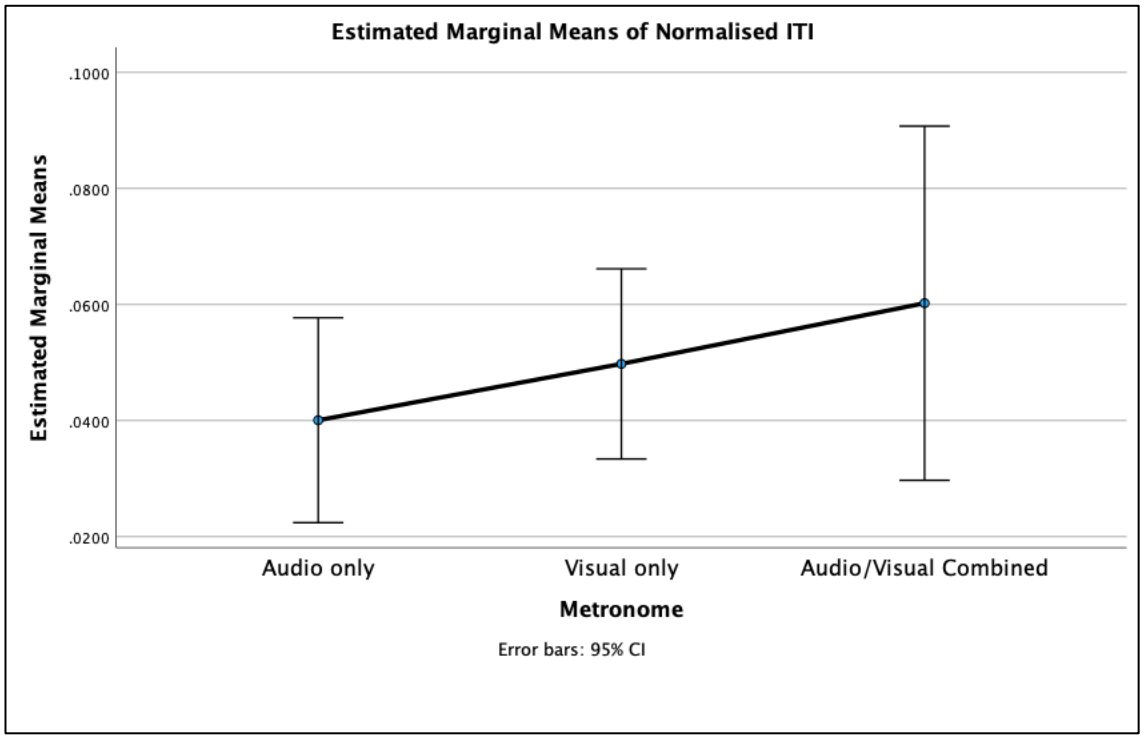

Fig. 7.10 Mean ITI across the three metronome types for Experiment 3.

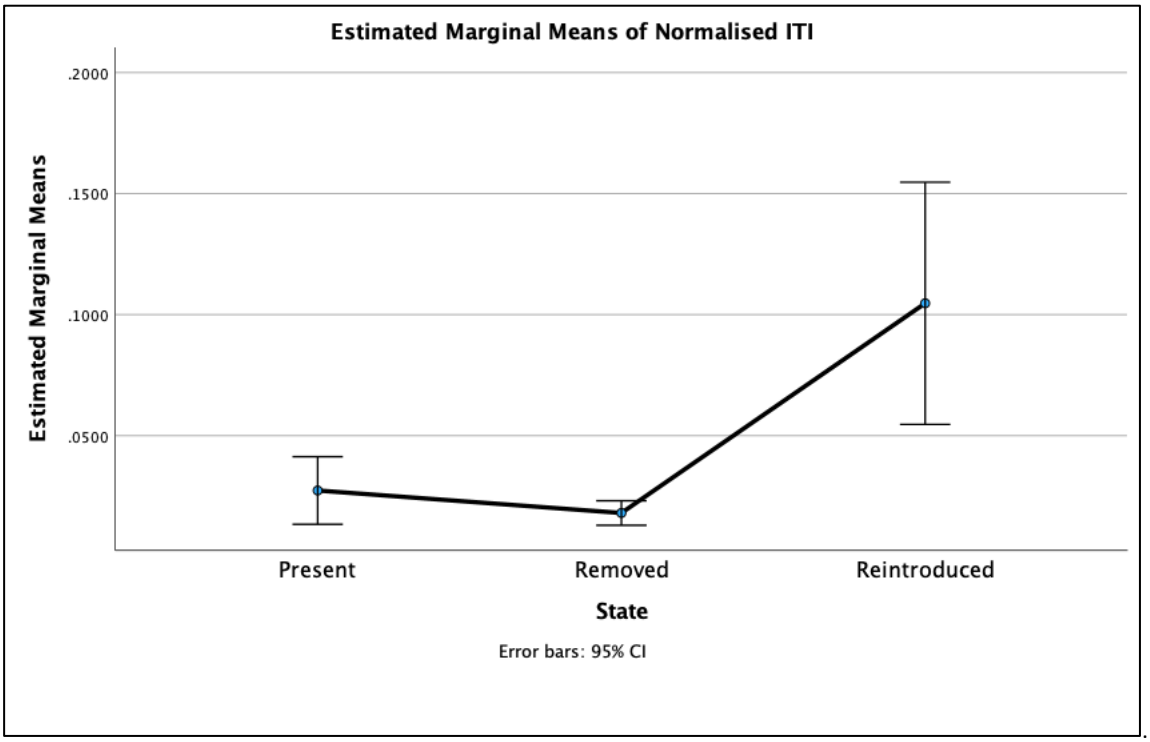

Fig. 7.11 Mean ITI across the three metronome states for Experiment 3.

Statistical analysis of the ITI data revealed that only one variable produced any significant effect on participants' average ITI. The metronome state variable was shown to have significance, specifically when the metronome was reintroduced. This was confirmed by adjustment for multiple pairwise comparisons using the Bonferroni correction. This was true, regardless of tempo or metronome type. The other two states (metronome present and metronome removed) were not statistically significant, regardless of tempo or metronome type.

7.4.2.1 Questionnaire Response Analysis

For the complete set of responses to the post-experiment questionnaire, Kendall's Concordance Coefficient *W* was run to determine if there was inter-rater agreement between the 27 participants' perception of their timekeeping performance with different metronome types and different metronome states. The participants' perception of their performance under these conditions was determined according to a five-point classification system from 1 (Strongly Disagree) to 5 (strongly agree). The consistency of responses from the 27 participants was statistically significant $W = .538$, $p < .001$. Therefore, we can accept the hypothesis that the entire collection of responses displays an internal consistency.

Whilst the test of Kendall's coefficient of concordance refers to the overall response of each participant, each group of responses to the individual questions of the post-experiment questionnaire are included in the figures below. These figures display the responses to each statement on the form filled in by each participant once the test was complete.

Fig. 7.12 shows a clearly that participants perceive their timekeeping to be accurate when the audio metronome was present. In contrast to this, Fig 7.13 shows that the participants felt their timekeeping was not accurate when the audio metronome was removed.

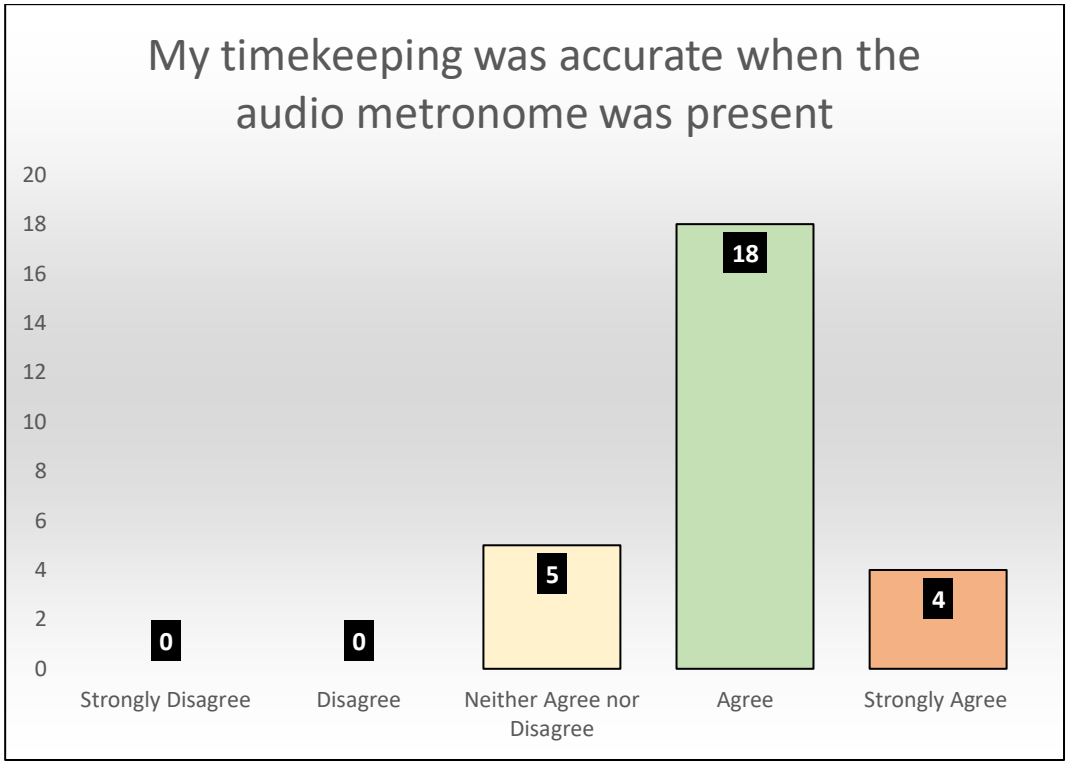

Fig. 7.12 The overall responses to Statement 1: "*My timekeeping was accurate when the audio metronome was present*".

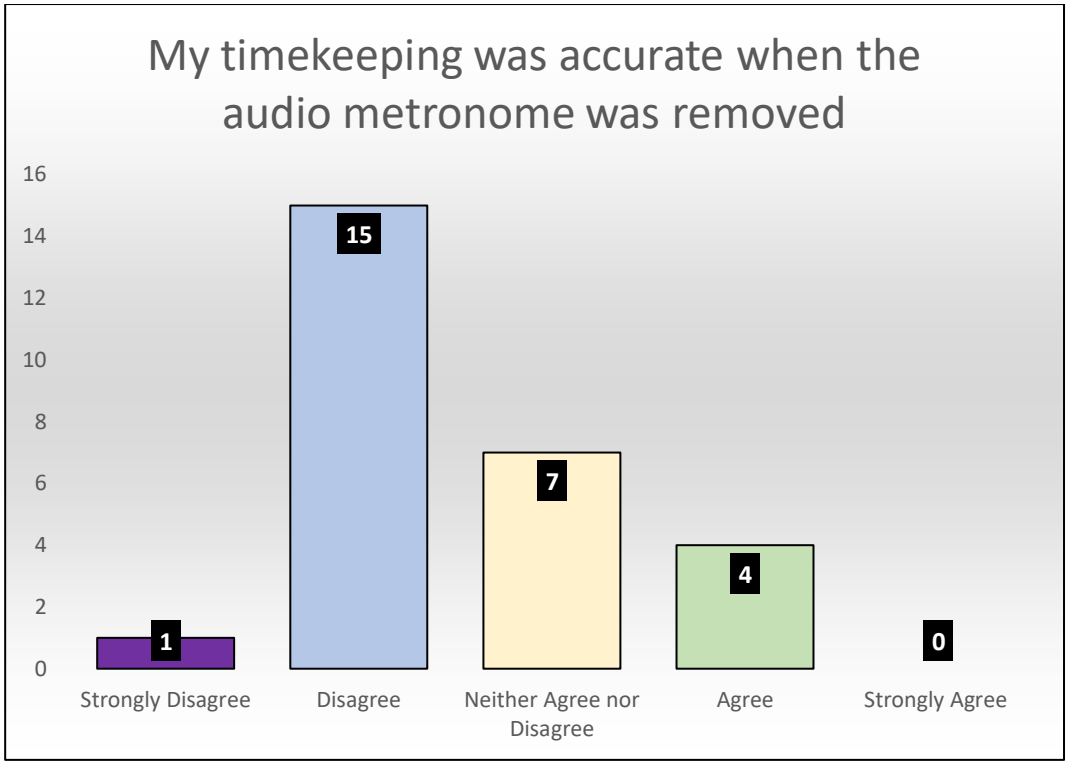

Fig. 7.13 The overall responses to Statement 2: "My timekeeping was accurate when the audio metronome was absent".

Fig. 7.14 shows that the majority of the participants believed that the visual metronome had either a positive influence on their timekeeping, or that they did not perceive it to have any influence. However, Fig 7.15 shows that the majority of participants believed that the removal of the visual metronome resulted in their timekeeping getting worse.

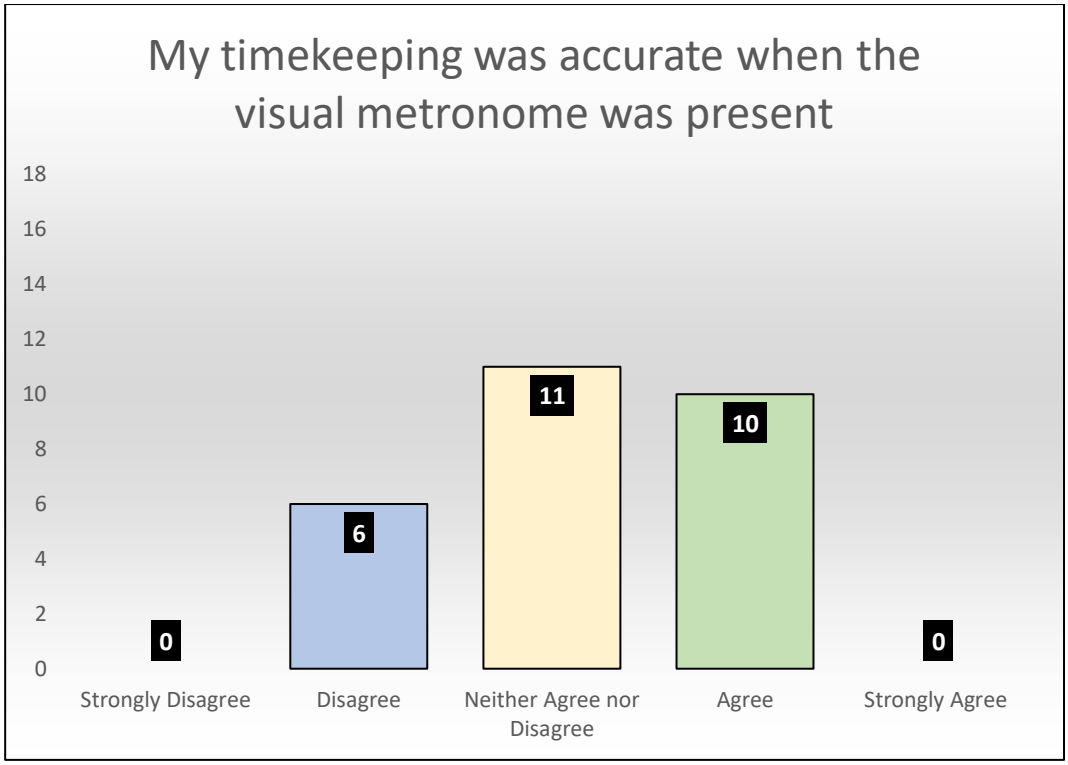

Fig. 7.14 The overall responses to Statement 3: "*My timekeeping was accurate when the visual metronome was present*".

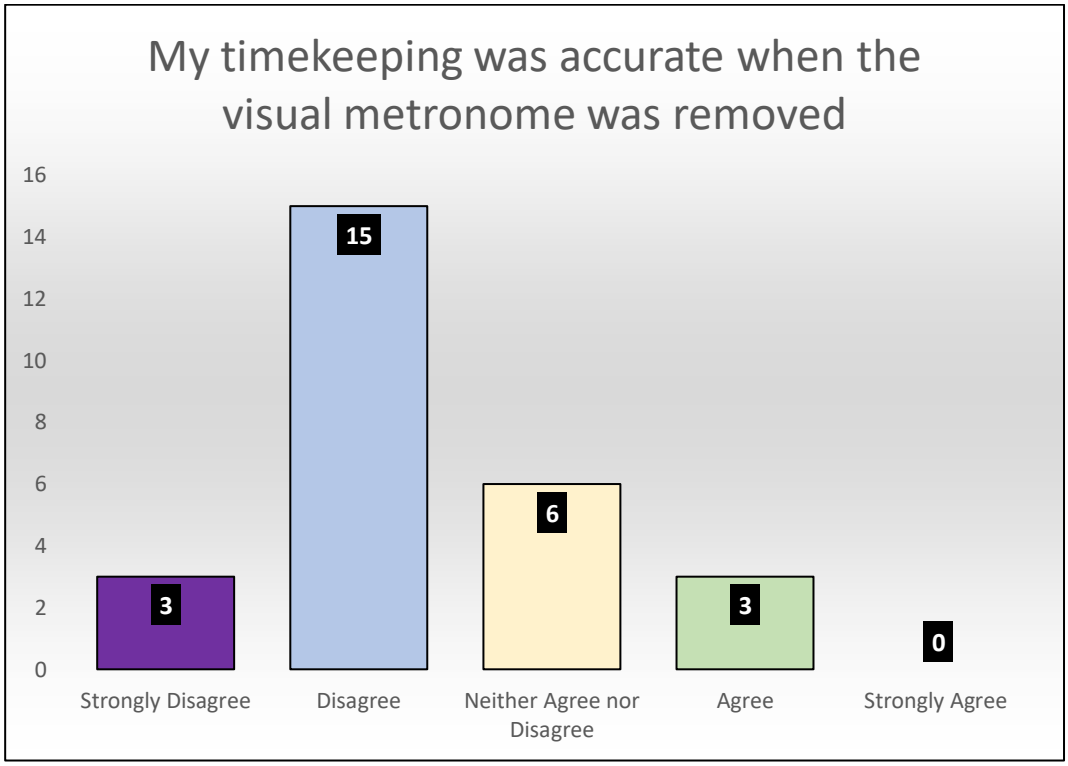

Fig. 7.15 The overall responses to Statement 4: "*My timekeeping was accurate when the visual metronome was removed*".

The responses to the post-experiment questionnaire indicate that most participants believed that their timekeeping was accurate when the combined audio/visual metronome was present (see Fig. 7.16) but that their timekeeping was not accurate when the combined audio/visual metronome was removed (see Fig. 7.17).

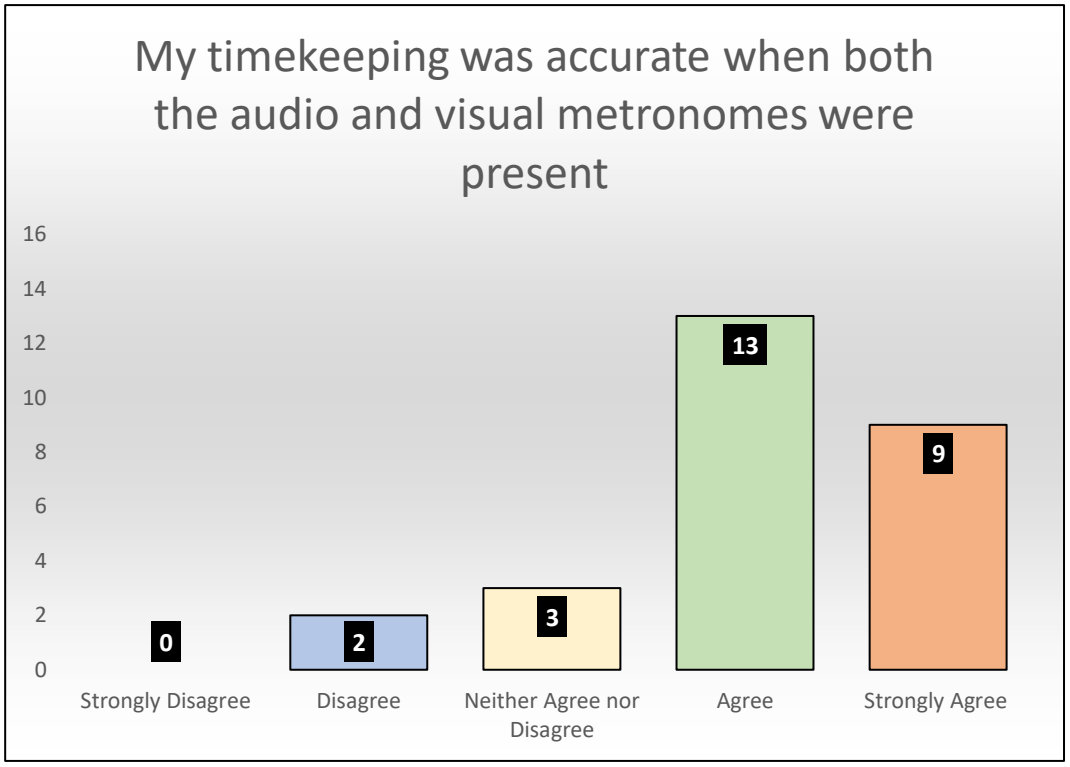

Fig. 7.16 The overall responses to Statement 5: "*My timekeeping was accurate when both the visual and audio metronomes were present*".

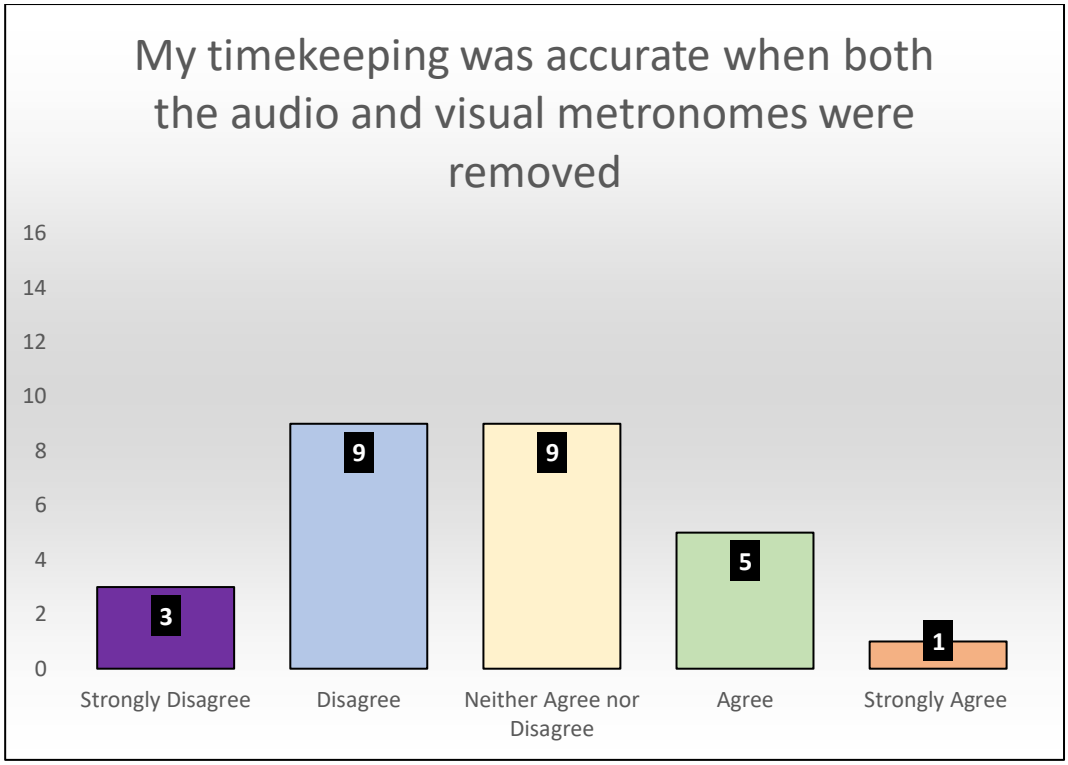

Fig. 7.17 The overall responses to Statement 6: "*My timekeeping was accurate when both the visual and audio metronomes were removed*".

7.5 Limitations

This study was focussed on ascertaining what factors might influence a participants' ability to maintain a consistent performed Inter-Tap Interval. As this represented the final study in the thesis, it was influenced by the results and observations from previous studies. The decision to use visual and auditory metronomes (plus both metronome types combined) was taken to ensure that the testing process would not be too long (and therefore fatiguing) for participants. This decision was also based on the results from the experiment described in chapter 5.

The inclusion of a cross-rhythmic auditory metronome would have increased the number of tests to 15 (i.e., cross-rhythmic metronome on its own at all three tempos, and cross-rhythmic metronome in combination with the visual metronome). The inclusion of these cross-rhythmic variations would have increased the number of tests that required completion from each participant to 27; potentially resulting in a test duration of 1 hour for each participant. However, the results of the experiments described in Chapter 4 and Chapter 6 indicated that

the auditory metronome type (cross-rhythmic or isochronous) did not play a significant role in the ITI of participants.

The design of the visual metronome was influenced by the findings of Iversen et al., (2015), Hove et al., (2013) and Hove et al., (2010). Rather than the "bouncing ball" type visual stimuli described in those studies, the testing described in this chapter used a solid fill that rose and fell to the halfway point on the screen with acceleration and deceleration. The increase in tempo was reflected in the speed at which the visual metronome hit its target and fell away. This worked well at the two slower tempos, but some participants reported difficulty in identifying the target pattern at the higher tempo. These difficulties were specifically noted in the 'Visual Only' metronome condition. It is possible that the visual metronome design could be altered to accommodate higher tempos (perhaps with some modification of the acceleration and deceleration at these tempos) to make the identification of the target pattern easier. However, the speed of the metronome movement was kept proportionately identical across the three tempi to ensure consistency in the measurements taken during this particular test.

7.6 Conclusions

The purpose of this experiment was to explore and assess the impact that differing metronome types would have on a participant's ability to keep a consistent Inter-Tap Interval, during different conditions. Specifically, the test was designed to study the effect of a visual variation of a digital metronome, compared to an audio variation, over differing tempi and with the metronome removed and reintroduced at points.

As with the previous experimental phases, the state of the metronome had a statistically significant impact on the ITI of participants. Again, following the trend of previous tests, the main effects metronome type (in this case isochronous audio, isochronous visual or isochronous audio and visual metronome) do not demonstrate any statistical significance.

The statistical test applied to the complete set of responses to the post-test questionnaire indicates that there is a consistency to the answers given by participants. This provides a

measure of confidence that the responses to the questionnaire were not random. The subjective data of the questionnaire suggests that participants believed their performances in a way that didn't necessarily match the quantitative data collected from the cowbell strikes. The perception of participants suggests that the majority felt their timekeeping was better with the audio only metronome and with the audio/visual metronome. The perception of their timekeeping with the visual metronome doesn't appear to be as consistent between participants. Based on the responses to the questionnaire, the participants perceived their timekeeping to be more accurate when the metronome (of any variation) was present, and less accurate when the metronome was removed. Statistical analysis of the cowbell strikes contradicts this perception; participants produced consistent ITIs when the metronome was present in the first instance and managed to produce comparatively consistent ITIs when it was removed. The performance of the participants dropped by a significant amount when the metronome was reintroduced, regardless of metronome type or tempo.

In terms of **RQ1:** "*What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?",* these results suggest that the reintroduction of a metronome after a period of absence has a significant effect on a participant's ITI. It could be that participants delayed strikes or struck the cowbell in quick succession to reintegrate or re-entrain with the metronome, but the sample of strikes was large enough to minimise the impact this would have on the average ITI of a participant. It is possible to extrapolate that to 'real world' scenario; perhaps a period of a performance where a musician isn't required to play and then is required to join back in with an ensemble or playing partner.

In answer to **RQ3: "***What influence does differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?",* the type of metronome does not appear to have any noticeable influence on ITI, which suggests for that for individual practice, the preference for a metronome type need be the only consideration. There is no conclusive evidence in this scenario that an individual would benefit from one type of metronome (audio, visual or combined) over another.

8. Conclusions

8.1 Introduction

This thesis is aimed to investigate the effects that varying metronome types, metronome states and tempi have on a person's ability to produce a consistent ITI. The three experimental chapters of primary research describe test conditions that included combinations of isochronous, cross-rhythmic, and visual metronomes, across three tempo variations (80bpm, 120bpm and 160bpm), and three metronome states (*present*, *removed* and *reintroduced*).

These test conditions were designed to expand upon previous published research (Hove M. J., Iversen, Zhang, & Repp, 2013; Madison, Holm, & Karampela, 2013; Repp B. , 2006; Jäncke, Loose, Lutz, Specht, & Shah, 2000). Sensorimotor synchronisation and entrainment are areas of study that have a wealth of research dedicated to them. However, the main thrust of enquiry has been the synchronisation with a target pattern or, the measure of *asynchrony*. Whilst continuation tasks exist, these typically evaluate ITIs for a relatively short period following the removal of a metronome. This thesis has presented the reintroduction of a metronome as a test variable that should be considered when assessing timekeeping accuracy.

The research findings from each experimental chapter can be considered individually and as a group to determine and synthesise the answers to the four Research Questions that were established in Chapter 1. These answers can provide a platform to make recommendations and observations to practitioners, students, and educators for programmes of study and assessment of musical timekeeping.

8.2 Research Findings

What follows is a summary of the significant findings from each experimental chapter. Alongside these findings, the observations from the subjective responses from each corresponding post-experiment questionnaire are considered.

8.2.1 Experiment 1:

Research Findings (Experiment 1)
Average ITI varied with significance over the three tempo conditions. Distance from target IOI was greatest at the slowest tempo of 80bpm, and the smallest distance of average ITI from the target IOI was at the tempo of 120bpm. The greatest variance of average ITI was at the fastest tempo of 160bpm, and the smallest variance of average ITI was at 120bpm.
Average ITI varied with significance between the three metronome states. Distance from target IOI was greatest during the *removed* state, and this state also had the greatest variance of average ITI. Average ITI changed during the *reintroduced* state but did not meet the levels of accuracy observed in the initial, *present* state.
Participants perceived their timekeeping to be more accurate when the metronome was present, in contrast to when the metronome was absent.
Participants perceived their timekeeping to be more accurate when they performed as an individual, rather than when they were part of a group.

8.2.2 Experiment 2:

Research Findings (Experiment 2)
Average ITI varied with significance over one of the three comparisons of tempo conditions. There was significance in the difference in average ITI between 80bpm and 160bpm, but not between 80bpm and120bpm, or between 120bpm and 160bpm. Distance from target IOI was greatest at the slowest tempo of 80bpm, and the smallest distance of average ITI from the target IOI was at the tempo of 120bpm. The smallest variance of average ITI was at the fastest tempo of 160bpm.
Average ITI varied with significance between the *present* metronome state and the *reintroduced* metronome state, but not between the *present* metronome state and the *removed* metronome state, or between the *removed* metronome state and the *reintroduced* metronome state.

Participants perceived their timekeeping to be more accurate when the metronome was present, in contrast to when the metronome was absent.
Participants perceived their timekeeping accuracy to be influenced by other group members, but the overall response to the statement "*My timekeeping was accurate when I played as part of a group"*, yielded a much more uniform distribution set of responses that do not give a clear indication of overall perception of group timekeeping accuracy.

8.2.3 Experiment 3:

Research Findings (Experiment 3)
Average ITI varied with significance between the *present* and *removed* metronome states, but not between the *removed* and *reintroduced* metronome states, or between the *present* and *reintroduced* metronome states.
Participants perceived their timekeeping to be more accurate when the audio metronome was present, in contrast to when the audio metronome was absent.
Participants' responses to the statement "My timekeeping was accurate when the visual metronome was present" yielded a relatively evenly distributed set of responses that do not give a clear indication of overall perception of timekeeping accuracy when the visual metronome was present.
The overall responses to the statement "My timekeeping was accurate when the visual metronome was removed" provided a clearer indication that generally, participants perceived their timekeeping accuracy decrease when the visual metronome was removed.
Most participants perceived their timekeeping to be accurate when the combined audio and visual metronome was present, but most felt that the removal of the combined audio and visual metronome had either no effect or a negative effect on their timekeeping accuracy.

8.3 Research Questions

What follows is a discussion of each Research Question and how the findings of the experimental chapters can provide answers to those questions.

8.3.1 Research Question 1

RQ1: *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping?*

The presence of an intermittent metronome has an influence on average ITI in all three experimental phases. In an individual setting, average ITI never regains the initial level of consistency once the metronome is reintroduced after its removal. Repp (2001) and Thaut *et al*. (1998) suggest that a change in tempo results in a rapid adaptation of interval duration, whilst the metronome is present. In the experimental work of this thesis, there is no change in tempo during a test sequence. The reintroduction of the metronome maintains the same tempo as when it was first *present*. However, the adaptation reported by Repp and Thaut *et al.* would appear only to occur if the metronome is not removed.

This deterioration in average ITI consistency when the metronome is *removed* and *reintroduced* is also evident when individuals perform as part of a group. In this group environment, average ITI moves further from the target IOI as the metronome is *removed* when compared to the initial *present* state but continues to move even further away when the metronome is *reintroduced*.

Tempo has an influence on average ITI in all three experimental phases, most significantly at the slower tempo of 80bpm. This result confirms the findings of Elliott, Chua, & Wing (2016), and Repp (2001), where ITI correction occurs more quickly at higher tempi. These findings suggest that there may be less margin for error if the intervals between beats or target pattern note onset are shorter.

When considering the results of the three experiments of this thesis, there is a clear indication that the reintroduction of the metronome is a disruptive influence on the consistency of participants' average ITI.

8.3.2 Research Question 2

RQ2: *What effect does playing in a group, versus individually, have on musical timekeeping?*

The results from the experimental work in Chapter 6 indicates that groups of participants would entrain with each other when the metronome was *removed* but struggled to re-entrain as a group with the rigid, fixed metronome pattern when it was *reintroduced*. This supports the findings of previous studies (Elliott, Chua, & Wing, 2016; Konvalinka, Vuust, Roepstorff, & Firth, 2010; Goebl & Palmer, 2009), wherein groups of participants use one another's taps or strikes to correct or maintain ITI duration. Himberg (2014) found that pairs of participants synchronised more accurately than a single participant with a digital metronome, although the human-to-human pairing would drift together. The experimental results of this thesis confirm this, when comparing the average ITIs in the *removed* and *reintroduced* metronome states.

When considering the results from Chapter 6 of this thesis, there is a clear indication that ITI consistency is much the same when individuals perform as part of a group, as when they perform individually, except when the metronome is *reintroduced*.

8.3.3 Research Question 3

RQ3: *What influence does differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping?*

The results of the pilot study described in Chapter 4 indicated that there was no significant difference in the influence two different types of auditory metronome had on participants' average ITI i.e. isochronous and cross-rhythmic metronomes. In the group experiment described in Chapter 6, there was also no statistical significance observed in the influence that the same differing audio metronome types had on each individual's average ITI. In the

experimental work from Chapter 7, no significant influence was observed between the audio, visual and audio/visual combined metronome states. This result shares similar features with Hove *et al*. (2013), where the inclusion of movement in a visual metronome would appear to yield from participants a consistency in timekeeping that approaches the levels of accuracy produced when playing along with an auditory metronome.

When considering the results of the three experiments of this thesis, alongside the results from the pilot study described in Chapter 4, there is a clear indication that metronome type is not a significant influence on the consistency of an individual's average ITI.

8.3.4 Research Question 4

RQ4: *What implications do the findings of the previous research questions have on musical timekeeping education and assessment?*

The presence of a metronome, whether auditory or visual, has an influence on a participant's ability to produce a consistent average ITI. Specifically, the reintroduction of a metronome after its removal results in an average ITI that is not as close to the target IOI of a metronome as when the metronome was first present. This is true in an individual setting and when an individual performs as part of a group. The implications of these findings could be used to influence contemporary methods of timekeeping assessment.

The current strategies in place to assess timekeeping accuracy primarily rely on subjective observation of synchronisation with a target tempo. In keeping with the concepts of 'feel' and 'groove', it may be advantageous to conceive a method that assesses ITI alongside synchronisation, specifically the assessment of ITI once a metronome, backing track or click track has been removed and then reintroduced. This can be seen as a more musical approach to timekeeping assessment. If we can simultaneously assess asynchrony and ITI, we will approach a methodology that combines subjective interpretation of timekeeping skills, alongside objective measurements of accuracy. This could take the form of simple timekeeping exercises that measure objective data in terms of both asynchrony and average ITI, together with the subjective assessment of musical appropriateness. This, in turn, should direct instructors and tutors to use the removal and reintroduction of a metronome to hone

the timekeeping skills of musicians under their tuition. These exercises emulate real-world musical scenarios: a solo section of a piece of music, or a section where the majority of instrumentalists in an ensemble do not play for an extended period of time. Contemporary grade syllabuses include tests or pieces that approach this concept, but the findings of this thesis indicate that there is an objective, measurable parameter that could positively develop a programme of learning. This concept can be applied to group environments and to individual practice, as both these scenarios impact upon each other.

The results of the experimental work in this thesis indicate that metronome type (isochronous, cross-rhythmic, or audio/visual) plays no significant role in influencing average ITI. However, the questionnaire responses from the study participants would suggest that their perception of their own timekeeping does not always match the objective data. This indicates that the use of different metronome types in an educational, rehearsal or studio setting should be subject to the personal preference of each individual musician. There is no conclusive evidence from the experimental work in each of the chapters in this thesis that would suggest there is a significant impact on ITI from one metronome type to another. This has implications when considering the accessibility needs individual musicians may have. If metronome type has no observable influence on average ITI, then there is no detrimental impact on musicians with hearing impairments choosing a visual metronome to rehearse, perform, or record with, or on musicians with visual impairments selecting an auditory metronome.

8.4 Recommendations for Timekeeping Education and Assessment

1. Instrumental tutors should consider the reintroduction of a metronome following its removal as a training tool, specifically in terms of improving consistency of ITI.

2. Tempo should be a consideration when instructing or assessing instrumentalists. Slower tempi produce a less consistent ITI, and this should inform the training or instruction of instrumentalists, and the assessment of their timekeeping abilities.

3. Group timekeeping study should include the removal and reintroduction of a metronome to improve group timekeeping consistency, as ITI consistency of an individual when playing as part of a group differs from that of an individual who is entrained with a metronome only.

4. Metronome type does not influence an individual's ITI consistency. Therefore, the selection of metronome type should be subject to personal preference or accessibility needs.

5. Assessment of timekeeping abilities in a more formal examination setting would benefit from the inclusion of a combination of objective asynchrony and ITI data, alongside subjective interpretation of timekeeping, to produce a more musically accurate determination of timekeeping accuracy.

8.5 Contribution to Knowledge

This thesis makes a significant contribution to knowledge by conducting a comprehensive evaluation of differing metronome configurations. This evaluation comprises different metronome types, tempi and metronome conditions, allowing for the synthesis of research strands that have existed in isolation until now. The culmination of this research is the recommendations for musical timekeeping and assessment, based on this unified, systematic investigation.

Each Research Question serves a branch of the overall Research Aim: "*to explore the technical configurations of metronomes and their effects on musical timekeeping to provide preliminary recommendations for music education and assessment*".

Research Question 1: *What influence does the presence of an intermittent metronome, and at differing tempi, have on musical timekeeping*? Prior research has concentrated largely on continuous metronomic information in experimental work. This leaves the effects of intermittent metronomes largely unexplored. The experimental work in this thesis augments knowledge by testing differing metronome conditions over varying tempi, offering insight into

the effect that differing metronome conditions have on performers, in both individual and ensemble settings.

Research Question 2: *What effect does playing in a group, versus individually, have on musical timekeeping*? The unique research in this thesis contributes an insight into how interpersonal dynamics can affect timekeeping. Mutual entrainment affects the ITI consistency of an individual when performing as part of a group – this can inform group training practices and influence approaches to developing more effective ensemble timekeeping.

Research Question 3: *What influence do differing metronome types (i.e. isochronous, cross-rhythmic, or auditory/visual) have on musical timekeeping*? The different metronome modalities explored in this thesis address the impact of new metronome types and combinations on performers' ITI. The comparative analysis of these metronome types allows for the evidence-based recommendations for individuals and groups of instrumentalists, which should in turn, inform sensory or accessibility integration strategies.

Research Question 4: *What implications do the findings of the previous research questions have for musical timekeeping education and assessment*? Through a synthesis of the results from the first three Research Questions, the thesis proposes a series of recommendations that inform preliminary strategies for teaching and assessment of musical timekeeping. The practical nature of the research, and the empirical data collected, ensures that the research has real-world implications that may have impactful value on teaching and assessment practices.

9. Future Work

The experimental work in this thesis is concentrated upon simple, sensorimotor timekeeping tasks to ascertain which factors influence a person's ability to produce a consistent average ITI. There is scope to develop this enquiry and to expand the exploration of objective and subjective methods of tuition, assessment, and measurement.

9.1 Additional Qualitative Approach

The conclusions of this thesis could be developed and further shaped by current thinking and approaches used by musicians, tutors, assessors, producers, or engineers. This qualitative enquiry should evaluate the way in which contemporary practitioners use metronomes or click tracks as timekeeping aids, how they value metronomes as teaching or performance tools, and how these practitioners believe tools of this nature can be enhanced or improved.

9.2 Accessibility

The thesis results indicate that metronome type does not have a significant impact on ITI, other than personal preference. This should be investigated further and with a specific focus on accessible metronome design for users who may have physical and cognitive impairments. Where the thesis investigates audio and visual stimuli, future work could expand modalities to include tactile metronomes and differing combinations of metronome type, to assess their efficacy in producing consistent average ITIs from users.

9.3 Case Studies

The recommendations provided in Chapter 8 of this thesis could form the basis of a bespoke programme of study for a small number of learner musicians. These case studies could provide insight into the effectiveness of varying tuition techniques, based on the thesis recommendations.

Another strand of case studies could investigate methods for implementing recommendations provided in this thesis into exam or assessment environments, possibly via a platform for objective measurement.

9.4 Instrumental Families

The experimental design of this thesis focussed on a percussive method of input from participants. This provided an accessible method of producing an isochronous pattern for musicians and non-musicians alike. This test methodology could be broadened to include other instrumental families. Brass, string, woodwind and voice all require different physical and cognitive skills to produce a note (Clayton, *et al*., 2020), and it would be of benefit to understand the impact these differences have when performing along with different metronome types and states across varying tempi.

9.5 Mass Ensembles

The group experiment described in Chapter 6 involved participants performing sensorimotor tasks as part of a small group. The size of these groups could be expanded to investigate the effect of metronome type and state upon average ITI of individuals participating in a larger ensemble. There are practical considerations, particularly in terms of data collection and, potentially, analysis. The relationship between group size and outcome would be an area worthy of further study.

9.6 Increased Rhythmic Complexity and Stimuli

The studies in this thesis have indicated that metronome type has no significant impact upon average ITI of participants. However, the studies have been focussed on exploring the isochronous sensorimotor pattern paradigm. Expansion of investigation to include patterns of more rhythmic complexity or even development of test methodologies to include simple drum kit set ups, similar to Fuji, *et al*., (2011), may provide further insight.

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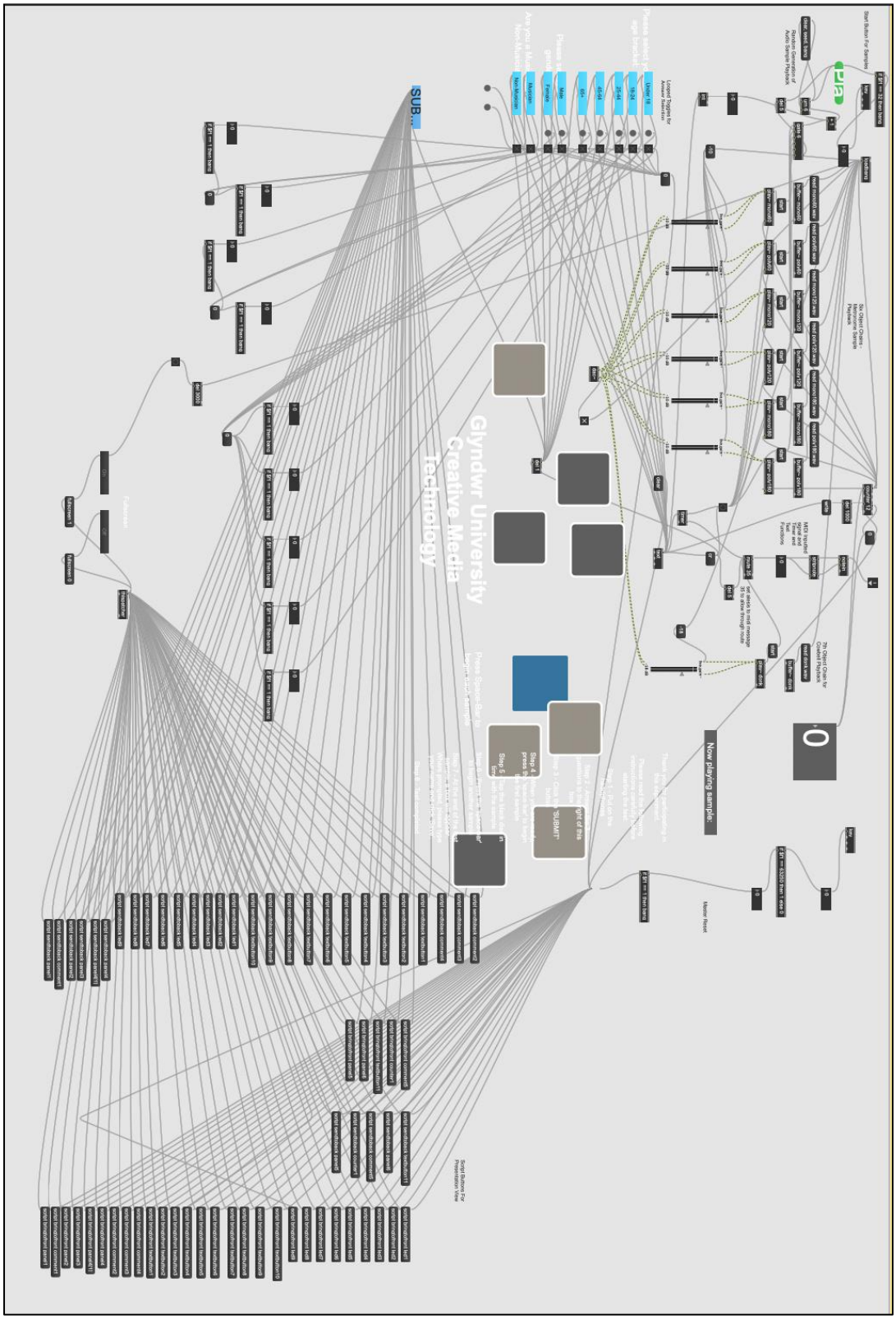
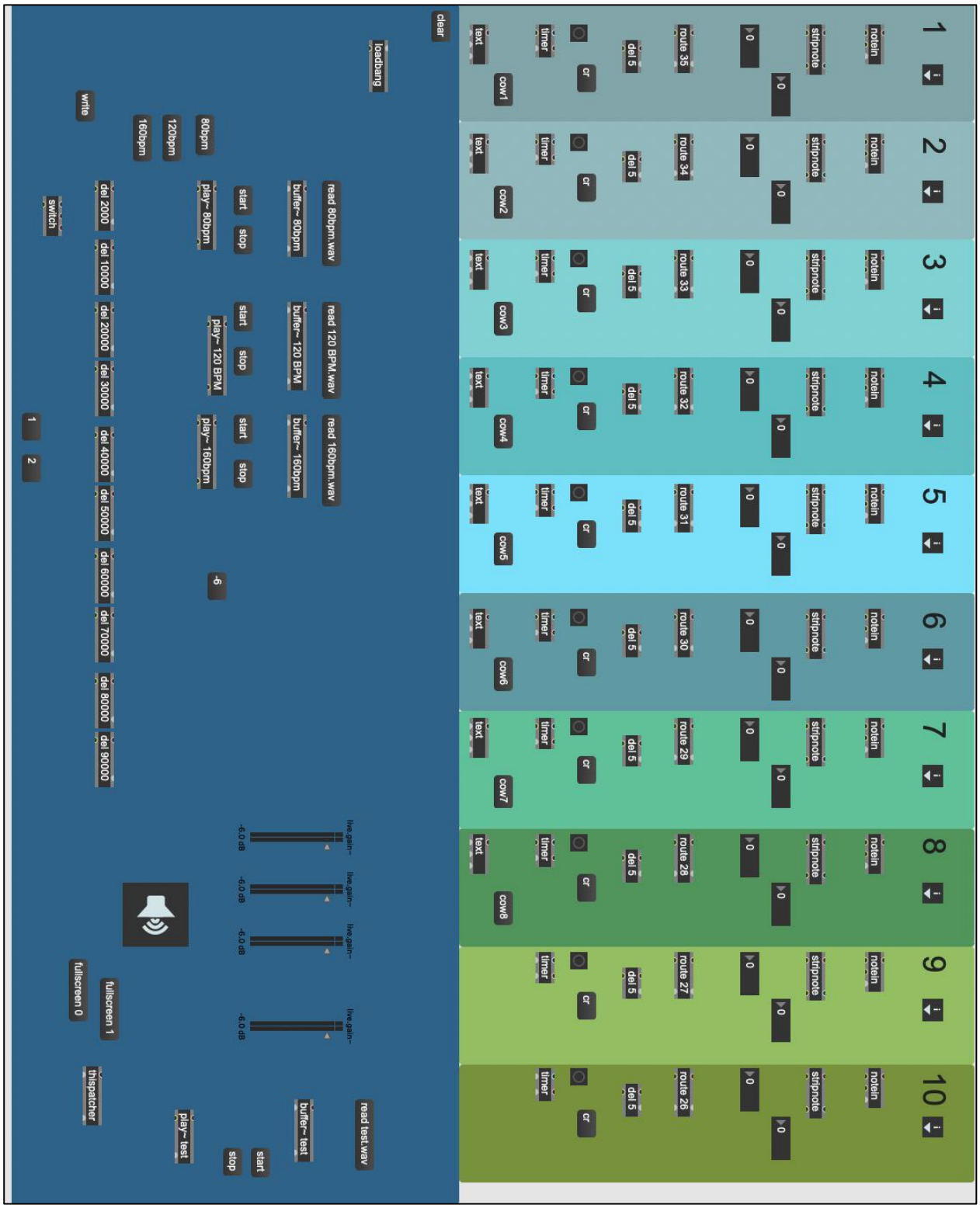
11. Appendix

11.1 Appendix A - MAX MSP Patch for Pilot Study (Chapter 4).



11.2 Appendix B – MAX MSP Patch for Experiment 1 (Chapter 5).



11.3 Appendix C – Participant Consent and Instruction Form.

Participant Information Sheet

Date:

Research Study Title:

Designing a programme of study to improve timekeeping in music.

Introduction

My name is Steffan Owens and this research forms part of my PhD study at Wrexham Glyndŵr University. You are being invited to take part in this study. Before you agree to do so, it is important that you understand the purpose and nature of the research and what your participation will involve, if you agree. Please read the following information carefully, and please do ask if anything is not clear, or if you want more information. Contact details are given at the end of this information sheet.

What is the purpose of the study and how will it be carried out?

The research objectives are:

1. To study how people keep time when playing along with music or a metronome;
2. To develop a program of study that helps musicians improve their timekeeping in music;
3. To study the differences between participants' timekeeping on their and as part of a group;
4. To study the differences between participants' timekeeping when provided with visual cues.
5.

The research methodology is (in outline);

1. An observational study of timekeeping with and without a metronome, and with and without visual cues;
2. The capture of audio and video data;
3. The analysis of participants' timing deviation from target audio markers.

Why have I been invited to take part?

We aim to recruit participants of any age, demographic or musical experience – this allows the results of the test to represent an accurate and varied cross-section of the local population.

Do I have to take part?

Participation is entirely voluntary. It is up to you to decide whether or not to take part. If you do agree to take part, you will be asked to sign a consent form. If you agree to take part, you

may still withdraw at any time, without giving a reason. If that happens, any information or data you have given will not be used in the study. The pool of potential participants will be larger than the number of participants required for the study. Should you decide to decline the invitation to take part, it will not affect the project or its outcomes.

What will taking part involve?

During the test, you will be required to wear headphones and be asked to play along to an audio sample by tapping a cowbell with a drumstick. The audio sample will stop, and you are asked to continue playing at the same speed. The audio sample will then start again after a relatively short space of time. You will be asked to repeat this process two further times at differing tempi as an individual. One group test will take place after all the individual tests are complete.
The volume of the headphones will be regulated so that it will not damage your hearing.
The studio floor may have long cable runs on the floor. These will be as tidy as reasonably practicable, but please ensure that you are mindful of them,
If you wish to leave the studio at any point, you are free to do so.
The testing will take place in rehearsal studies on the LIPA campus.

Will my participation be confidential?

All information about you collected during the study will be kept strictly confidential and stored in accordance with the Data Protection Act. The only people who will know about you are the researcher, and the study collaborators (Dr Jason Woolley, Dr Stuart Cunningham, Dr Steven Davies and Tim Pike). All data, whether electronic or paper or in any other form will be destroyed upon the completion of the PhD studies.

What will you do with the results of the research?

The results of this study will inform future experiments and may be used as part of a PhD thesis. Visual data may be used (in part) to form future presentations and reports. No participant will be named in these documents or publications.

What happens next?

Thank you for reading this information sheet. If you agree to take part, please fill in a consent form) and return in to one of the project researchers. You will then be given an approximate time for your test. Once in the rehearsal studio, the process will be explained again and any questions you may have answered. You will have an opportunity to familiarise yourself with the equipment and given an opportunity to practice.
Once your test is complete, you will be asked to return after all other participants are tested to take part in a brief group exercise, almost identical in nature to the solo test process.

You will be given a copy of the consent form to keep.

If you wish to complain about any aspect of how you have been approached or treated in respect of this research study, please contact:

Dr Jason Woolley, Glyndwr University
jason.woolley@glyndwr.ac.uk

Contact for further information

If anything is not clear, or if you want more information, please do contact me:

Steffan Owens
s.owens@lipa.ac.uk

Participant Consent Form

Research Study Title:

Name of Researcher: Steffan Owens

Please tick the box(es) to confirm each statement

I confirm that I have read and understood the Information Sheet dated _____for the above study. If I have asked for clarification or for more information, I have had satisfactory responses.	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.	☐
I understand that the researcher and the researcher's Director of Studies may look at relevant sections of the data collected from me during the study.	☐
I consent to being included in photographs / audio and video recordings	☐

I agree to take part in the above study

_____	_____	_____
Name of Participant	Signature	Date
_____	_____	_____
Name of Researcher	Signature	Date

11.4 Appendix D – Example of Post-experiment Questionnaire (Chapter 7).

Steffan Owens

LIPA

Post-study Questionnaire.

Please circle the number that represents how you feel about the following statements:

1. My timekeeping accuracy was influenced by other participants;

1----------2----------3----------4----------5

Decreased a lot | Decreased a little | Not at all | Increased a little | Increased a lot

2. My timekeeping was accurate when I played as part of a group;

1----------2----------3----------4----------5

Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree

3. My timekeeping was accurate when the metronome was present;

1----------2----------3----------4----------5

Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree

4. My timekeeping was accurate when the metronome was absent;

1----------2----------3----------4----------5

Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree

5. My timekeeping was accurate when the visual metronome was present;

1----------2----------3----------4----------5

Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree

6. My timekeeping was accurate when the visual metronome was absent;

1----------2----------3----------4----------5

Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree