Mikko Paappanen

MULTISENSORY INTEGRATION IN QUARTER NOTE BEAT PRECISION

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Moniaistinen integraatio tarkoittaa eri aistisignaalien yhdistämistä uudeksi kokonaisuudeksi. Viime vuosien teknologisen kehityksen ansiosta moniaistitutkimuksen ala on laajentunut monilla eri teollisuudenaloilla. Tässä pro gradu –tutkielmassa tutkitaan moniaistista integraatiota musiikillisessa kontekstissa, tarkemmin sanottuna musiikillisessa tahtipohjaisessa soittotarkkuudessa. Aiemmat tutkimukset ovat osoittaneet muusikoiden kyvyn hyödyntää moniaistista integraatiota reaktioaikatesteissä. Tämän tutkimuksen tavoitteena on tutkia auditiivista, haptista ja auditiivis-haptista soittotarkkuutta käyttäen kaupallisesti saatavilla olevaa metronomiratkaisua. Tutkimusmenetelmäksi valittiin kokeellinen kvantitatiivinen tutkimus. Tutkimusaineisto koostuu kymmenestä musiikillisesti aktiivisesta henkilöstä. Osallistujille annettiin kaksi rytmistä soittotehtävää, joiden avulla määritettiin soittotarkkuusarvot, jotka analysoitiin nykyaikaisella äänianalyysikehyksellä. Ensimmäisen pitkäkestoisen soittotehtävän tulokset osoittavat, että aistimodaliteettien välillä ei ole merkitseviä eroja. Toisessa kokeessa soitetun temmonmuutostehtävän tulokset osoittavat, että haptinen aistimodaliteetti on tarkin soittotarkkuuden suhteen. Tuloksissa ei havaittu moniaistisen integraation positiivisia hyötyjä. Tämä tutkielma esittää jatkotutkimusaiheita ja parannusehdotuksia siihen miten moniaistista soittotarkkuutta voidaan mitata.

Asiasanat: moniaistinen integrointi, aistit, rytmi, soittotarkkuus, metronomi

ABSTRACT

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Multisensory integration concerns the integration of different sensory signals combined into a new product. Due to the technological advancements of recent years, the field of multisensory research has expanded in many different industries. This thesis investigates multisensory integration in a musical context, more specifically, in musical beat-based timekeeping. Previous research has demonstrated musicians' ability to utilize multisensory integration in reaction time tests. The goal of this study is to investigate auditory, haptic, and auditive-haptic beat precision using a commercially available metronome solution. Experimental quantitative research design was selected as the method of research. The research data consists of 10 musically active individuals. Two rhythmic playing tasks were given to the participants for establishing beat precision values which were analyzed using a modern audio analysis framework. The results for the first long duration playing task indicate no significant differences between the sensory modalities. The results for the second experiment with tempo changes indicate the haptic sensory modality is the most precise in terms of beat precision. Positive benefits of multisensory integration were not perceived in the results. This thesis provides future research agendas regarding improvements on how to measure multisensory beat precision.

Keywords: multisensory integration, senses, rhythm, beat precision, metronome

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1 INTRODUCTION

Musical activities are based mainly on our ability to hear. The sense of hearing is the primary sense which translates soundwaves to music and gives us an understanding of given auditory signals. Guitar chords, piano, bass, drums, orchestras, and musical pieces all produce sound captured by the sense of hearing. Hearing can also shift our approach to musical activities. When we play a musical instrument, we can alter our playing according to the sound that we want to produce. For instance, if an orchestral musical piece requires a more subtle, finesse type of sound, we can play an instrument with less physical momentum applied. Where on the opposite, if a musical piece requires more volume, more force can be applied behind instruments to produce volume.

Sounds are the primary source of information for us to experience music. However, there are other sensory pathways through which to understand music. For instance, we can use vision to gain understanding of the words of singers (Thompson & Russo, 2007). Vision tells us perceivable information from musical performances, such as a dance choreography by a group of performers. The process to experience music requires sensory input from a single sense, in most cases, hearing. With hearing being the predominant sense for experiencing music, through recent technological advancements we can bring in other senses to either assist or work together with the sense of hearing. When we are working and combining multiple sensory signals, this is referred to as multisensory processing. The field of multisensory processing seeks to gain knowledge on perception through the co-operation of multiple sensory modalities.

Recent years have brought technological advancements to the music industry through which commercially available sensory substitution solutions have been developed. For instance, a haptic wearable vest from the company SubPac allows deaf dancers to perform and experience music through vibrations (Platoni, 2016). For drummers, a vibrating low-frequency transducer named Throne Thumper was created with the purpose to assist in feeling and hearing the kick drum better (D'Virgilio, 2014). These musical gadgets are involved in the process of assisting or enhancing performance during rhythmic activities.

This thesis selects rhythmic timekeeping as the area of interest and investigates timekeeping through a commercially available modern metronome solution. The purpose of this study is to, due to lack of research, investigate a modern widely available multisensory metronome device and examine its effects on timekeeping. Although research on enhancing effects of multisensory integration for musicians has been brought to light (Landry & Champoux, 2017), current commercial solutions have not been explored in-depth, and we can ask whether current commercially available multisensory solutions are able to assist in rhythmic playing. This study examines one multisensory metronome solution and investigates the metronome's effects on rhythmic timekeeping in simple playing experiments.

1.1 Research questions

RQ_1: Will multisensory integration assist rhythmic timekeeping?
RQ_2: Are haptic metronome devices equal to auditive metronome devices in terms of rhythmic timekeeping?

1.2 Scope of the research

This thesis examines the effects of multisensory integration in rhythmic timekeeping assignments. The thesis starts with an introduction to the subject area followed by a research proposal and research questions. The second chapter consists of a literature review to find principles for multisensory integration and rhythm. Metronome devices are discussed and applied in the study. A general overview of multisensory integration is discussed and applied in the thesis. Multisensory integration serves as a theoretical framework upon which the study experiment of this thesis is based on. Different areas and use cases of multisensory integration are examined and discussed. Past and current studies of multisensory integration are investigated. Definition of rhythm is performed to understand the main underlying principle of the research.

The third chapter consists of research methods and design. The chapter examines how beat precision is measured in this thesis. Data collection and analysis methods are examined in the chapter. The purpose of the empirical experiment is to understand possible effects multisensory integration and the sense of touch have on rhythmic timekeeping. This study seeks to give light on previously unknown areas of rhythmic training combined with multiple sensory modalities, by conducting experiments with tasks on long-duration timekeeping and tempo changes. The study is conducted at the University of Jyväskylä in Finland. The sample of this study consists of musically active people such as students of music, musicians, and hobbyists with at least six months of musical background on any instrument.

The fourth chapter presents the results and the statistical analysis of the experiments. During the final chapter the results and the analysis methods are evaluated. Future research agendas are provided within the final chapter.

2 MULTISENSORY INTEGRATION & RHYTHM

This chapter concerns multisensory integration and rhythm. First, a definition of multisensory integration is provided along with its use-cases. In the next subchapter, the presence of multisensory integration in music is discussed, followed by a subchapter of definition of rhythm. Within the chapter of rhythm, rhythmic precision, metronomes, and beat perception are discussed.

2.1 Co-operation of different modalities

A common topic of interest for scientists is to understand underlying mechanisms on how we perceive the external world (Calvert et al., 2004, p. 11). Human senses have been under study from an unisensory, “sense-by-sense", perspective in the past (Calvert et al., 2004, p. 11), where the focus of research is on a single sensory modality. The necessity of multisensory perspective to understand perception was recognized, which eventually led to the emergence of the field of multisensory processing, or multisensory integration (Calvert et al., 2004, p. 12). Key points of multisensory integration can be viewed as:

- Enhanced perception and cognition by utilizing multiple sensory inputs (Stein et al., 2014; Laurienti et al., 2006; Buchholz et al., 2012)
- Improves perceptual accuracy and speed in reaction times (Molhom et al, 2002)
- A crucial brain structure involved in processing of multisensory information is the superior colliculus (Stein et al., 2004)
- Sensory signals affect each other’s processing, which can lead to perceptual illusions (King & Calvert, 2001)
- Development begins early and young children are not as capable multisensory integrators as adults (Gori et al., 2008)
- Multisensory processing has practical applications in fields like virtual reality and rehabilitation (Marucci et al., 2021; Purpura et al., 2017)

Each human sense is dependent on a unique peripheral organ that operates independently from other peripheral organs (Stein & Meredith, 1990). Vision operates on eyes, smell through nose, taste through tongue, touch through skin, and hearing through the ears. Since each sense holds a distinctive perspective of the external world, incorporating information across senses gives computational advantage otherwise not available (Stein et al., 2014). Unique experiences can be created when signals from different sensory channels are put together (Stein et al., 2014), to influence overt behavior, decisions, and perception (Stein et al., 2009). A simple example of the enhancing effect of multisensory integration can be seen in co-operation of hearing and vision. Sumby & Pollack (1954) demonstrated how vision cues from lip movements enhance speech recognition in noisy environments.

Although multisensory integration is often seen to have beneficial effects on cognition, sometimes there is a mismatch with data from different senses. The McGurk effect, illustrated in Figure 1, where visual processing influences the perception of speech sounds, is an example where cross-modal interactions between different senses shape our perception reality (King & Calvert, 2001). When the syllable /ga/ is spoken and seen visually, the auditory signal is perceived as /ba/, and subjects hear /da/.

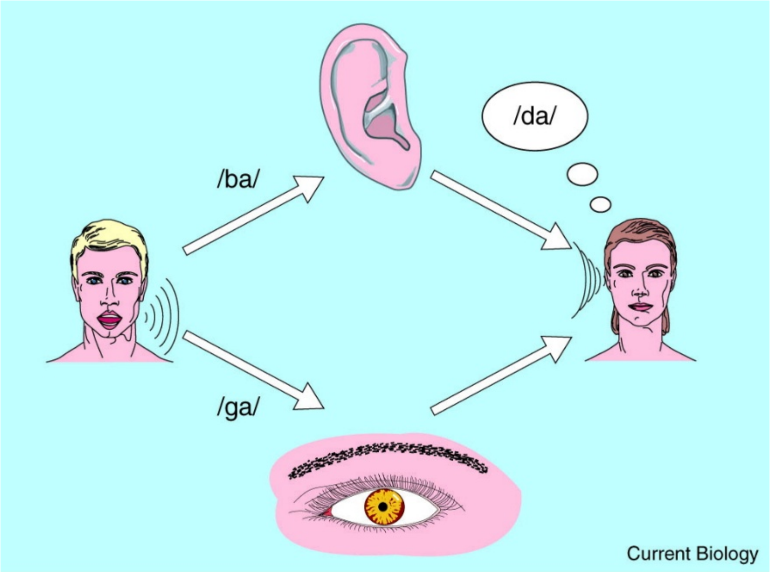

FIGURE 1 McGurk effect (King & Calvert, 2001)

The concept of sensory compensation and sensory substitution is closely related to multisensory integration. Sensory compensation refers to improvement in the remaining senses after the loss of one sensory system to counteract the lost capabilities (Röder & Rössler, 2004). Sensory substitution is a procedure of converting stimuli from one sensory modality to another, which seeks to replace or assist one or several deficient sensory modalities with another sensory modality (Deroy & Auvray, 2012). An example of sensory substitution solution is the tactile Braille alphabet which conveys verbal information through haptic stimulation (Kristjánsson et al., 2016).

The field of multisensory integration is impeded by clarity of communication, which is due to the use of different terms to mean the same thing, and the use of similar terms to mean different things (Stein et. al, 2010). To establish a common ground for terms of multisensory integration, Stein et. al (2010) provide a practical solution. This thesis utilizes the framework provided by Stein et. al (2010) in Table 1. Cross-modal matching and multisensory integration are employed in this study to assess beat precision. In this study, the static stimulation of regularly occurring metronome beats from different sensory modalities is investigated using cross-modal matching from an unisensory perspective where auditory and tactile inputs are compared.

TABLE 1 Clarification for the terms of multisensory integration

Term	**Definition**
Properties of stimuli	
Modality-specific	Describes a stimulus (or stimulus property) confined to a single sensory modality
Cross-modal	Describes a complex of two or more modality-specific stimuli from different sensory modalities
Neural or behavioral properties	
Unisensory	Describes any neural or behavioral process associated with a single sensory modality
Multisensory	Describes any neural or behavioral process associated with multiple sensory modalities
Multisensory integration	The neural process by which unisensory signals are combined to form a new product. It is operationally defined as a multisensory response (neural or behavioral) that is significantly different from the responses evoked by the modality-specific component stimuli
MSI, Multisensory index	The proportionate difference between a multisensory response to a cross-modal stimulus and the unisensory response to the most effective modality-specific component stimulus
Cross-modal matching	A process by which stimuli from different modalities are compared to estimate their equivalence
Multisensory process	A general descriptor of any multisensory phenomenon (e.g. multisensory integration and cross-modal matching)

2.2 Multisensory Integration in Music

The multilayered nature of musical performance requires a unique and multi-system contribution from the human brain (Münte et al., 2002; Herholz & Zatorre, 2012; Schlaug, 2015). Olszewska et al. (2021) note that playing a musical instrument requires sensorimotor adaptations, and a mapping of specific movements to the auditorily perceived outcomes, in addition to higher-order cognitive processes and multiple sensory modalities. Cognitive processes such as memory (Finney & Palmer, 2003), visual attention (Rodrigues, Loureiro, & Caramelli, 2010), in addition to multisensory input from auditory-motor integration (Brown, Zatorre, & Penhune, 2015), and proprioceptive (Smitt & Bird, 2013) sensory modalities, are present in playing a musical instrument.

Zimmerman & Lahav (2012) conducted a review on multisensory brain and music and noted that use of multisensory feedback while engaging in musical training should be beneficial because of the interconnectivity within and between brain's multisensory areas, which results in more brain plasticity. Brain plasticity is defined as the nervous system's ability to change its activity in response to stimuli (Mateos-Aparicio & Rodríguez-Moreno, 2019). Brain, or neural, plasticity is often associated with positive benefits such as enhanced cognition (Ryder, 2021) and recovery from brain injuries (Zotey et al., 2023), and for neurologically impaired patients brain plasticity can be extremely useful (Zimmerman & Lahav, 2012). Brain plasticity in a musical context can be said to raise the brain's general level of conscious operation (Reybrouck, Vuust, & Brattico, 2018). Brain plasticity is measured with transcranial magnetic stimulation (TMS) in addition to other neurophysiologic modalities (Freitas, Farzan, & Pascual-Leone, 2013). While it is not possible to measure brain plasticity in this thesis, understanding the underlying mechanisms behind the positive effects of multisensory feedback in musical training remains a valuable area of investigation.

Soto-Faraco & Kingstone (2004) have reviewed research in the integration of motion information across sensory modalities, noting that static stimulation in one sensory modality can modulate the perception of dynamic information in another sensory modality. When applying this to playing an instrument, for instance, a metronome pulse (a static stimulation) can alter musician's rate of motion (dynamic information). A musician performing a musical piece and utilizing a metronome simultaneously not only requires awareness to the on-going audible metronome clicks, but attention to the executed motion, like pressing the keys of a piano, or hitting a snare drum with drumsticks, and for other musicians performing simultaneously.

New and emerging multisensory technologies have allowed researchers to expand the study of multisensory integration through conventional practices (Cornelio et. al, 2021), and recently rhythm experiments have been conducted through the view of tactile, auditory-tactile and auditory inputs (Giordano & Wanderley, 2015; Landry & Champoux, 2017; Bouwer et al., 2013). However, in the case of vibrotactile musical cues more research is needed (Fontana et. al, 2018), and current commercial solutions concerning haptic bracelets have not been researched fully. This thesis expands on previous rhythmic studies (Giordano & Wanderley, 2015; Landry & Champoux, 2017; Bouwer et al., 2013), by using a commercially available multisensory timekeeping solution.

2.3 Rhythm

2.3.1 Defining rhythm

In music, rhythm is referred to as musical time or temporal organization of music, or as the shorthand term for musical time (Hartenberger & McClelland, 2020, p. 1). Rhythm in art is seen to deal with the discernible structure of temporal organization of an artwork's so called building blocks (Thaut, 2005, p. 4). Rhythm in music is said to consist of components such as pattern, meter, and tempo (Thaut et al., 2014), and assumes a role in coordinating musical events into understandable shapes and forms (Thaut, 2005, p. 6). Rhythm organizes time and leads the ear and the brain to clarify acoustical patterns and shapes by directing attention towards key moments in the unfolding of the music (Thaut 2005, p. 6).

In a musical composition, patterns can exist in surface phenomena and deep structural organization (Taube, 1995). A single sound attribute such as frequency, or multiple sound attributes, such as frequency, rhythm, and amplitude, can define pattern (Taube, 1995). A pinpoint definition of pattern can be hard to define, as in different musical contexts musical experts use different terms such as "lick", "riff", "leitmotif", or "sequence" to refer to musical patterns in music (Melkonian et al., 2019).

Meter is closely tied to time and passage (Hasty, 1997). Hasty (1997) sees meter as a mechanical, schematic, and abstract counterpart to rhythm which on the opposite side is seen as music's rich and full embodiment of music's temporal progress. The main beat that listeners instinctively follow by tapping their feet or clapping their hands can be divided into smaller sections of micro-beats, a phenomenon known metre (Ockelford, 2017, p. 91). In standard Western music common types of musical meter are duple and triplet meters (MasterClass staff, 2020). Figure 2 illustrates three different types of metre.

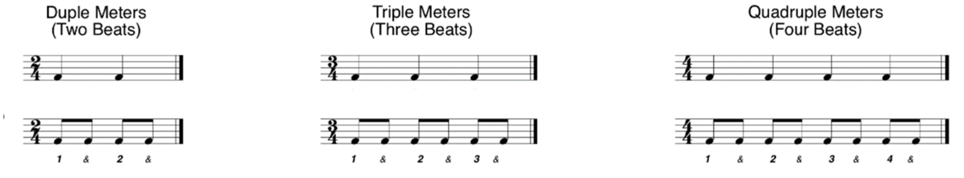

FIGURE 2 Simple meters subdivided (Young, 2020)

Related to meter are time signatures, which are usually divided into simple meters (Hamm et al., 2023), and compound meters (Hamm & Gotham, 2023). In simple meters time signatures markings such as 4/4 tell that the top value is the number of beats in each measure, and the bottom value is the note value that is the beat. A 4/4 time signature would have four beats in a measure played as quarter notes (Hamm et al., 2023). Compound meters can be viewed more complex since the beat divides into three, and then to six (Hamm & Gotham, 2023).

Thaut (2005, p. 9) describes tempo as the repetition rate of regularly occurring beats or pulses in a given amount of time. Tempo can be understood as the speed or pace of a musical piece and is measured by beats per minute (BPM). For instance, a tempo of 60 BPM means that a beat sounds once per second, and at 120 BPM there would be two beats per second (MasterClass staff, 2021b). Common tempo ranges vary from 60 to 150 BPM, and while tempos outside this range are used, they are harder to hear for the listener (Thaut, 2005, p. 9).

Accents are used on given musical events to make them stand out by changing features such as loudness, timbre, duration, or pitch contour (Thaut, 2005, p. 10). There are five basic types of accents, staccato, staccatissimo, normal, strong, and legato (OnMusic Dictionary, 2015), which all differ in note duration and strength. The fundamental purpose of accents is to give more character to a musical structure.

Displacing a musical accent from a strong beat to a weak one, is referred to as syncopation. Syncopation can also be seen as the intentional misalignment of emphasised notes in a musical part with the underlying pulse of the music (Abel, 2014, p. 32).

In this study, the main principles taken from the concept of rhythm are tempo and meter. The thesis measures the ability to stay synchronized with quarter notes on a beat level in a quadruple meter which is four beats, as it is illustrated in Figure 2. A rhythmic sequence of quarter notes is utilized, which is provided by the metronomes in the thesis. Adding attributes such as syncopation, polyrhythms, and accents are out of scope for this research since each rhythmic attribute would increase complexity to the study's experiments that are meant to be for investigating beat synchronization primarily.

2.3.2 Event-based timing solutions

To follow a specific tempo, many musicians employ a metronome to assist their timing during a musical performance. Metronome can be described as a device designed to mark time by a regularly repeated tick (Merriam-Webster, n.d.). It is often the case for musicians to follow a musical piece set to a given tempo. By utilizing an event-based timing solution, like a metronome, musicians can follow a given tempo and align their playing to the auditory cues produced by the metronome.

The common musical metronome was originally developed by Dietrich Nikolaus Winkel and patented in 1815 by Johann Nepomuk Maelzel. Widespread use of metronomes in rhythmic timekeeping happened in the late 19th century (Bonus, 2010, p. 365). Over time analog metronomes developed from a traditional design, such as the Wittner metronome illustrated in Figure 3, to an electronic digital variant, like the Boss DB-90 illustrated in Figure 4. A digital metronome, such as DB-90 by Boss, offers many features like different click samples, LCD displays, and tuners (Boss DB-90, 2022).

FIGURE 3 Wittner model No. 801 metronome (Wittner Model No. 801, n.d.)

FIGURE 4 Boss DB-90 Digital metronome (Boss DB-90, 2022)

One commercially available modern metronome solution is titled Pulse, illustrated in Figure 5, produced by Soundbrenner. The battery-operated wearable haptic metronome device aims to provide vibrations 7 times stronger than the average smartphone (Soundbrenner, n.d.-b). The metronome device seeks to assist rhythmic timekeeping by producing vibrations from the device’s motor. This way the user can utilize a tactile sensory pathway to synchronize with the metronome. It is possible to use both auditory and tactile inputs simultaneously while operating the device, making the device a candidate for studying multisensory timekeeping. The metronome’s tempo is adjustable between 20 BPM and 400 BPM, and the device can be worn on ankles, wrists, arms, thighs, and chest or shoulders with a body strap (Soundbrenner, n.d.-a).

FIGURE 5 Soundbrenner Pulse (Soundbrenner Pulse, n.d.)

The usefulness of metronomes is not restricted to musical activities only, since metronomes have been found helpful in alleviating speech stuttering (Murray, 1973; Howell & El-Yaniv, 1987), symptoms of Parkinson's disease (Thaut et al., 1996), and hypertensive blood pressure (Brady et al., 1974). A study about synchronized metronome training for soccer players shows benefits in guided attention and working memory, which may result in better motor planning and performance in the sport of soccer (Rönnqvist et al., 2018). Waterproof metronomes have been developed to assist swimmers in pace-keeping (Finis Tempo Trainer Pro, n.d.).

2.3.3 Beat precision

When it comes to beat precision, or the ability to execute playing in given time, humans rarely achieve a full machine-like synchronization. The human offset, or beat deviation, for a single beat is small (10-20 ms), but it exists (Hennig et al., 2012). This deviation from a perfect computed beat synchronization can give music listeners the feeling of human players behind a musical piece, and it can be seen as a positive for experiencing music (Hennig et al., 2012).

Human brain excitability across sensory networks and movement planning networks can be spontaneously modulated by musical rhythms (Iversen et. al, 2009; Janata, Tomic, & Haberman, 2012) The perception of rhythm and formation of rhythm may be biologically based more on the entrainment of oscillatory circuits in the brain than on actual acts of measurement in terms of timekeepers that are often conceptualized and modeled as clocks, pulse counters, or stopwatches in the brain (Thaut, 2005, p. 6). A distinction between rhythmic beat interval perception in longer durations (> 1s) and sub-second intervals can be made (Ross & Balasubramaniam, 2022). Perception of longer durations may be explained more by memory and be more uniform with internal clock models (Staddon, 2005), however timing intervals below one second may be more open to mediation by sensory expectation and attention (Large & Jones, 1999; Eagleman et al., 2005; Hurley et. al, 2018).

The ability to perceive temporal regularity in music is known as beat perception. When a beat is perceived, future events can be generated with predictions, which can influence processing of subsequent rhythmic events (Bouwer et al, 2016). Periodic events are predictable since they establish a regular time interval which acts as a predictive template, e.g., the ticking of a clock (Huron, 2006). The same works for a metronome, a steady auditory cue at regular intervals forces us to engage in predictive behavior. Beat-based perception is a distinct operation from absolute temporal perception, incorporating striato-thalamo-cortical network, whereas absolute temporal interval perception that works as a precision clock to mediate duration-based timing, originates from the inferior olive and the cerebellum (Teki et al., 2011).

In this thesis, beat precision of three different metronome variants are compared: a conventional auditive metronome, a wearable haptic metronome, and an integration of auditive and haptic metronomes. The experiments conducted during this research utilize Soundbrenner’s metronome smartphone application and the wearable Pulse metronome. The haptic metronome device was selected since it works as a real-world representation of commercially available touch-based metronome solution. It is shown that for learning fundamental rhythm skills (Holland et. al, 2018) and tempo synchronization (Giordano & Wanderley, 2015), use of haptic devices is a valid method. Previously (Giordano & Wanderley, 2015; Landry & Champoux, 2017) haptic event-based timing solutions have been researched with a do-it-yourself approach by constructing metronomes, or by using a vibrotactile device not intended primarily for musical use. Bouwer et. al (2013) reported their device caused feelings of irritation under the skin, and that the vibrations produced by the metronome felt weak and the sensing of vibrations required more concentration. In addition, the lack of portability was seen as an issue (Bouwer et. al, 2013). Using a commercially available metronome solution in this thesis gives an understanding of the status in which the technology operates for consumers.

To further add to the research of multisensory integration in rhythm, this study brings in real-world phenomena to investigate touch, hearing, and both senses combined during timekeeping tasks. In this study we bring in external attributes in the form of drumsticks for the experiments. Drummers utilize drumsticks to play the instrument. Giordano & Wanderley (2015) measured guitar players who utilized a tactile metronome, and Holland et. al (2018) investigated complex rhythmic patterns. However, no simple experiments have been conducted where drumsticks are used with commercial multisensory metronome solutions in a timekeeping emphasis.

A question arises when predictable periodic events with a regular pulse interval are adjusted so that instead of a one constant tempo, we have multiple tempo values. Since it is established that regularly timed events of a metronome are predictable by sensory attention and expectation, what happens when the pulse increases in speed? This would require a swift internal recalibration from the player. Landry & Champoux (2017) concluded musicians have faster auditory, tactile, and audio-tactile reaction times, with audio-tactile reaction time being the smallest out of the three groups. However, multisensory metronome applications have not been researched with tempo changes in mind and to further add to the research of multisensory integration in rhythm, this study incorporates an experiment where tempo is increased incrementally.

3 RESEARCH METHODS

This chapter explores the thesis's research methods. The chapter provides hypotheses for the research and describes how beat precision is within the study measured. Finally, the data analyze phase is explored.

3.1 Research design

This study is conducted as an experimental quantitative study since the purpose is to measure timekeeping in musicians. Quantitative studies gather and analyze numerical data (Bhandari, 2023a). This thesis measures three metronome variants in three different tempos and examines the produced BPM values to the target tempo.

Hypotheses:

H_1: Multisensory integration of a haptic vibrotactile metronome with an auditory metronome results in the most accurate beat precision

H_2: Use of an auditory metronome results in the most accurate beat precision

H_3: Use of a haptic vibrotactile metronome results in the most accurate beat precision

H_0: Wearable haptic metronomes have no significant impact on beat precision

This thesis uses a within-subjects design to establish whether the independent variable, a metronome modality, has any cause-and-effect relationship on beat precision.

3.2 Measuring beat precision with quarter notes

3.2.1 Playing along to a click track

Most rhythmic studies are conducted using simple assignments, such as finger tapping along to metronome sequences (Thaut, 2005, p. 41; Repp & Su, 2013). Although these studies are a valid method of extracting information about rhythm processing, they don't meet the real-word settings of rhythmic practice since they lack a musical instrument. In the context of a drummer improving rhythmic skills, practice is mostly executed using drumsticks and a practice pad. This method is slightly more advanced than a finger tapping experiment, and fits this research design, since measuring rhythmic precision won't require a full-sized drum kit, and the research can be conducted with volume levels which do not disturb other people in the environment. The metronomes utilized in the playing tasks are from Soundbrenner, and the metronome application which controls the metronomes is titled "The Metronome by Soundbrenner" and is run on an Apple iPhone X smartphone. Three different metronome variants are measured:

1. Auditive – Stimulus from an auditive input
2. Haptic – Stimulus from a haptic input
3. Auditive-Haptic – Simultaneous stimuli from auditive and haptic inputs

Beat precision is investigated in two different rhythmic playing tasks. The tasks are kept simple in order that the sample size of the study can be grown, and the general musician can take part in the tasks. In the first task, subjects are given three different tempos to follow. The click tracks are played as quarter notes in a simple 4/4 time signature. By using quarter notes, subjects' playing precision is captured with more clarity: Quarter notes can be analyzed more effortlessly, as subdivisions such as 8th notes would fall between the quarter note clicks. Since the study measures beat synchronization with a metronome, subjects' playing as quarter notes can be compared with the click track directly.

The tempo categories, which are illustrated in Table 2, are divided into three segments. These tempo categories introduce a varied selection of temporal changes for the experiments. To categorize tempos in general, Italian music terminology has been used in classical music for centuries (MasterClass staff, 2021a). Common tempo indicators vary from slow and solemn (20-40 BPM) Grave, all the way to very fast (178 BPM and over) Prestissimo (Symphony Nova Scotia, n.d.). The tempo indicators change usually with 10-20 BPM increments, e.g., from Allegretto to Allegro the tempo increases by 11 BPM (Symphony Nova Scotia, n.d.). The Slow tempo category, 60 BPM, in Table 2 seeks to capture a common BPM area for what is considered slow. According to GetSongBPM, an open-source database of beats per minute, the most common BPM for a modern pop song is around 120 BPM (GetSongbpm, n.d.), which serves as a BPM for the Medium category. Finally, to investigate extreme use cases of musical speed, a third tempo category titled Very Fast is included to investigate extreme tempos. Although modern pop music or jazz is not played at such a tempo, this tempo is included to examine the effects in extreme cases.

During the first long duration playing task, each tempo category is measured for three minutes using each sensory modality. By measuring with long time periods, this study seeks to understand whether the different sensory modalities have variance in playing precision. Subjects are given two measures of time to prepare for each tempo before playing.

TABLE 2 Tempo categories

Tempo category	**Tempo in beats per minute (BPM)**
Slow	60
Medium	120
Very Fast	256

The average duration for a modern musical piece is approximately three minutes (UCLA DataRes, 2020). The first experiment seeks to examine quarter beat precision in long-duration playing tasks by integrating three-minute tasks. Problems with hearing may result in performance errors, since musicians have an elevated risk of noise induced deafness (BMJ-British Medical Journal, 2014), and extended playing time could bring these issues to the front. Thomson et al. (2014) demonstrated how mind wandering increases over time in laboratory tasks, and how mind wandering, and task performance are tightly coupled. Mind wandering in this study is not possible to measure, but it should be noted that as the time of a given task increases, more performance errors arise (Thomson et al., 2014).

There are many different rhythmic patterns in the drumming world, such as single stroke roll, double stroke roll, and paradiddles, which could be used as patterns to measure rhythmic precision. However, since the goal is to study strictly timekeeping in musicians, a simple single stroke roll as quarter notes is utilized during the experiments. By leaving out more complex rhythmic patterns, compound time signatures, and more advanced musical concepts such as polyrhythms, subjects from different instrumental backgrounds can take part in the experiments. The experiments' pattern is illustrated in Figures 6 and 7 at a tempo of 120 BPM, for both right-handed and left-handed players.

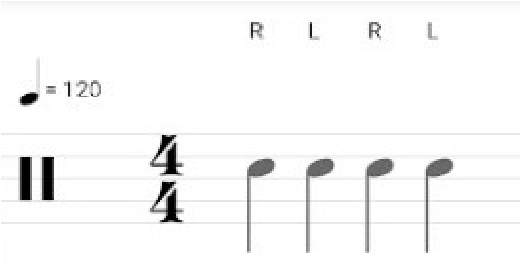

FIGURE 6 Quarter note pattern for right-handed players

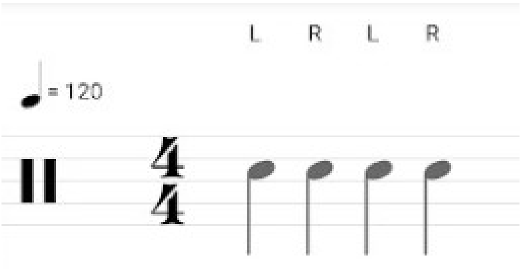

FIGURE 7 Quarter note pattern for left-handed players

The second task concerns tempo changes. The static stimulation of a regular metronome pulse is turned dynamic as tempo changes are added to investigate the dynamic nature of rhythmic precision. During this task participants are asked to play a single stroke roll as quarter notes synchronously along a click track, which at some point in time increases in speed. This task seeks to capture any variance with beat precision that an exponentially growing tempo change brings. The starting tempo for the task is set to 60 BPM and incremented by 40 BPM every 16 bars all the way up to 300 BPM. Participants' goal is to shift from one tempo to another and maintain as precise synchronization with the click track as possible. Again, subjects are given two bars of time at the starting tempo to prepare for playing. The 40 BPM increment was selected since it produces a bigger temporal change. For instance, a tempo increment of 5 BPM would show a smaller change in quarter note intervals, whereas a 40 BPM increment is a more noticeable tempo difference. This effect can be demonstrated in milliseconds:

Formula to convert BPM's (quarter notes) to milliseconds:

$$\frac{The\ number\ of\ milliseconds\ per\ minute\ (60\,000\ ms)}{Beats\ per\ minute}$$

At 60 BPM, a quarter note lasts for a second:

$$\frac{60\,000\text{ ms}}{60\ BPM} = 1000\ ms$$

At 65 BPM, a quarter note lasts for a 923 ms:

$$\frac{60\,000\text{ ms}}{65\ BPM} = 923\ ms$$

Demonstrating the quarter note difference between 60 BPM & 65 BPM, and 60 BPM & 100 BPM:

$$1000\ ms - 923\ ms = 77\ ms$$

$$1000\,ms - 600\,ms = 400\,ms$$

Table 3 illustrates the chosen incremental tempos for experiment 2. As the tempo increases the quarter notes shorten in time. The largest difference in milliseconds is between the first two tempos, 60 BPM & 100 BPM. 40 BPM increments were selected since it offers a drastic change from the starting tempo.

TABLE 3 The second experiment tempos in milliseconds

Tempo (BPM) in quarter notes	**Milliseconds** (ms) per quarter note
60 BPM	1000 ms
100 BPM	600 ms
140 BPM	429 ms
180 BPM	333 ms
220 BPM	273 ms
260 BPM	231 ms
300 BPM	200 ms

The metronome device in both experiments is fitted using a body strap and strapped around the waist. This way subjects' hands are free to operate since a wrist-strapped device would cause a feeling of imbalance between the hands. The device is strapped firmly around the subject's waist according to the subject's preference. It must be noted that the pressing force of the metronome device can be altered by tightness of the body strap. A loose coupling with the metronome and the skin results in less stimulation, and an overly tight connection produces feelings of discomfort. Subjects are asked to adjust the strap firmly so that the strap does not produce uneasiness. The audio is recorded using a Shure SM57 microphone which is connected to a Zoom H4N audio recorder. The auditive metronome signal plays through in-ear headphones. The research environment is displayed in Figure 8.

FIGURE 8 The research environment

3.2.2 Subject grouping

The study follows a within-subjects setting, where each starting sensory modality and tempo category are randomized for every participant. The effects of earlier sensory modalities and tempo categories are prevented from spilling over onto later conditions by randomizing the order of each condition. Randomizing conditions prevents types of research bias like sampling bias and selection bias (Bhandari, 2023b). Each participant plays the two tasks with all three metronome variants. All musicians with a minimum of six months of musical instrumental background can take part in the study. Although in this study beat precision is measured from a percussive perspective by playing with drumsticks, participants are not required to have background in playing drums. Beat precision is not solely a phenomenon in drumming, but in playing of all musical instruments. However, the importance of beat precision is emphasized in playing percussive instruments as they often guide other players to stay in time.

3.2.3 Data analysis

To assist the data analysis phase, a Python package titled librosa (McFee et al., 2023) is utilized. Librosa is a Python package intended for music and audio analysis (McFee et al., 2023). Audio file formats such as .mp3 and .wav can be analyzed using librosa's tools like tempo estimation and onset detection. The package allows an extraction of a computational tempo value from the recorded audio material. If we have a constant metronome tempo set at 60 BPM and subjects are asked to play synchronously to the click track, by analyzing the recorded audio file with librosa, we can calculate a close computational approximate of what is the produced tempo that the subject is performing at.

The statistical analysis of the data is conducted with a multilevel regression model analysis. The model assumes a presence of a hierachical data structure, with one single result or response variable that is calculated at the lowest level, and explanatory variables at all existing levels (Hox et. al, 2010, pp. 11). In a multilevel model analysis, multiple observation levels are put together into a single statistical analysis, which allows the measurement of individual and group attribute effects, and their possible interactions (Bringé & Golaz, 2022). The use of multilevel modelling gives a comprehensive framework to correctly account for complex data structures, whereas a single level regression analysis can result in underestimated standard errors (National Centre for Research Methods (NCRM), 2019). The general idea with multilevel modelling is to simultaneously analyze data at a lower level (participants) and at a higher level (clusters of participants), which allows one to separate the effects of individual effects from contextual effects and inspect how individual effects and contextual effects relate to one another (Sommet & Morselli, 2021). In this thesis, the multilevel model examines groups (2nd level data), which consist of observations (1st level data). By placing the participant as a random effect which groups the observations, the variations between the 2nd level groups are controlled in the multilevel model.

The multilevel model examines musical beat precision in musically active individuals. By using a multilevel model, we can figure out how does utilizing a specific metronome modality influence beat precision produced by participants, and whether participants' individual musical playing experience in years has any effect on beat precision.

The multilevel model in this thesis consists of musically active individuals with different years of musical experience, inside different sensory modality (Auditive, Haptic, & Auditive-Haptic) groups. When the basic structure for the model has been established and the data has been gathered from the participants, tests for whether the construction of a multilevel model is warranted are performed. These include building a simplest possible multilevel model (Hox, Moerbeek, & D. S. R., 2010, p. 56), and calculating the intraclass correlation value (ICC) (Hox, Moerbeek, & D. S. R., 2010, pp. 14-15). In addition, Sommet & Morselli (2021) recommend calculating the design effect (DEFF) (Kish, 1965; Muthén & Satorra, 1995) value to quantify the degree to which a multilevel sample differs from a random sample. Basic assumptions for constructing a multilevel model are:

1. The model assumes normality and linearity (Hox, Moerbeek, & D. S. R., 2010, p. 23).
2. The model assumes homoscedasticity, which signifies that the residual errors' variance is independent of the values of the explanatory variables (Hox, Moerbeek, & D. S. R., 2010, p. 14).
3. By inspecting residuals, we can simultaneously investigate linearity and homoscedasticity (Hox, Moerbeek, & D. S. R., 2010, p. 23).

4. For multilevel modeling a sample size of 30x30 is preferred, meaning at least 30 groups with minimum of 30 individuals in a group (Hox, Moerbeek, & D. S. R., 2010, p. 235).
5. The model also assumes an intraclass correlation (ICC) value of higher than zero, and a design effect value (DEFF) below 2 (Sommet & Morselli, 2021).

4 RESULTS & ANALYSIS

This chapter examines the quantitively gathered results of the research. The first two subchapters present descriptive statistics and multilevel mixed models for playing tasks 1 & 2. The data is analyzed with an average mean (M) BPM value. Finally, the results are discussed and evaluated. 10 participants with various musical backgrounds took part in the playing tasks. The subjects' musical instrument experienced ranged from 2 years to 35 years of experience.

4.1 Task 1 — Long duration measurements

Table 4 presents descriptive statistics for the Task 1. For all measurements except "Haptic 256 BPM", ten participants' result BPM values were calculated into an average BPM value. Difference to target BPM column explains the difference between the task's target BPM value and the resulted average BPM value from the participants. The descriptive statistics for Task 1 reveal that at 60 BPM, the Auditive sensory modality is the most accurate (-.04), at 120 BPM it is Auditive-Haptic (.52), and at 256 BPM Haptic again proves most accurate (.05). On the opposite side at 60 BPM the least accurate sensory modality is Auditive-Haptive (.29), at 120 BPM it is Haptic (-.56), and at 256 BPM the least accurate modality is Auditive-Haptic (1.47).

TABLE 4 Descriptive statistics for Task 1

Sensory modality & BPM	***N***	**Mean BPM (Standard deviation)**	**Difference to target BPM (Standard deviation)**
Auditive 60 BPM	10	59.96 (.62)	-.04 (.62)
Auditive 120 BPM	10	120.52 (.96)	.52 (.96)
Auditive 256 BPM	10	256.87 (2.48)	.87 (2.48)
Haptic 60 BPM	10	59.92 (.52)	-.08 (.52)
Haptic 120 BPM	10	119.44 (1.16)	-.56 (1.16)

Haptic 256 BPM	9	256.05 (3.48)	.05 (3.48)
Auditive-Haptic 60 BPM	10	60.29 (.34)	.29 (.34)
Auditive-Haptic 120 BPM	10	120.52 (.44)	.52 (.44)
Auditive-Haptic 256 BPM	10	257.47 (2.85)	1.47 (2.85)

First, calculations to check the necessity of building multilevel models were performed. Intraclass correlation (ICC) was calculated from an intercept-only multilevel model, which has no predictor, where the dependent variable (DV) was set as the difference to the target mean tempo. ICC was 1.99% which points out what proportion of the DV is explained by group level phenomena, in this case, the participants. The participant's individual difference explains 2% of the difference to the target BPM value. With an ICC value of higher than zero, one requirement to build a multilevel model is met. Next, the design effect (DEFF) was calculated from the mean cluster size ($n = 10$) and the ICC, to investigate the degree to which a multilevel sample differs from a random sample. The resulted DEFF value of 1.18 points out that the data for Task 1 is better analyzed with a traditional regression analysis, as it is recommended to use with DEFF values below 2 (Peugh, 2010). However, since the ICC requirement was met, and the multilevel model has a fixed effect with three layers, the multilevel model is constructed.

Table 5 shows the multilevel model for Task 1. The estimate column explains the relative difference to the zero-level factor variable, which in this model is the haptic metronome. The dependent variable (DV) of the model is beat precision, which is the mean difference BPM value to the target tempo. The factor variable is sensory modality, and the covariate variable is musical playing experience in years. The intercept is the model’s beat precision using a haptic metronome. 95 % confidence interval illustrates the range for lower and upper BPM values calculated from the estimate.

First, the model fit of the new multilevel model in Table 5 was compared to the previous intercept-only model. This done to investigate whether the new multilevel model is better fit to explain DV’s variance. The previous model fit (-2RLL) from the unconditional mean model without any fixed or covariate variables was more suitable (356.71 < 357.64) than the model in Table 5. This finding indicates that the new multilevel model explains less of the DV’s variance. However, since the model fits (-2RLL) have a difference of only .93, the new multilevel model is investigated.

Tests of fixed main effects were performed to find statistically significant fixed variables. Sensory modality (auditive, haptic, auditive-haptic) received a value of $p > .105$, and participants’ playing experience in years received a value of $p > .987$. These findings display that in Task 1, neither variable has any statistically significant effect on beat precision.

In Table 5, since the ICC value is larger than zero (ICC > .038), the model signals that there exists a difference in beat precision between the groups. ICC displays 3.8 % of the multilevel model’s unexplained variance could be explained by differences between participants’ beat precision.

The multilevel model shows that the use of haptic metronome made subjects play a little earlier off the target tempo. On average, the subjects’ beat precision is -.21 BPM off the target tempo, however this is not statistically significant with $p > .704$. Statistically significant results appear only in the use of multisensory auditive-haptic metronome, with a value of $p < .038$. Beat precisions for auditive and auditive-tactile modalities are calculated from adding the intercept estimate together with estimates from the sensory modalities. The auditive sensory modality produces a beat precision value of .44, and the multisensory variant produces a beat precision value of .75. The multilevel model analysis illustrates the haptic metronome is the most precise, with the auditive metronome being second precise and multisensory metronome being third, however, the only statistically significant result is the multisensory metronome having the least accurate beat precision. The participants’ playing experience in years does not have any statistically significant impact on beat precision in Task 1.

A multilevel model where the auditive sensory modality was set as the baseline fixed effect showed $p < .498$ for significance between the auditive and the multisensory modality. This supports the findings that there are no substantial differences in beat precisions between the sensory modalities in Task 1.

These results indicate no support for any of the thesis's H_1, H_2, or H_3 hypotheses. Based on the statistical significance ($p < .038$) of the auditive-haptic metronome, for Task 1 the null hypothesis is not supported since the wearable haptic metronome does have a significant impact on beat precision by increasing BPM compared to the target tempo, although here the effect is seen during a combination of both auditive and haptic signals.

TABLE 5 Multilevel model for Task 1

Fixed effects	Estimate	Standard error	*p*	95 % confidence interval
Intercept	-.21	.54	.704	-1.38 - .96
Auditive	.65	.46	.155	-.25 - 1.56
Auditive Haptic	.96	.46	.038	.06 - 1.87
Haptic	0*	0		
Experience in years	0	.02	.987	-.05 - .05
Random effects	$\sigma 2$			
Intercept (participant)	.12	.24	.607	.003 - 5.51
Residual	3.05	.49	< .001	2.23 – 4.19
Intraclass correlation (ICC)				
Participant	.038			
Model fit (-2RLL)	357.64			

* The factor above is compared to factor that gets the value of zero

Figures 9, 10, and 11 illustrate the residual distribution in a histogram, a Q-Q plot, and a scatterplot for the Task 1 multilevel model. The histogram shows a slight normal distribution with some outliers present in the graph. The Q-Q plot shows that the normal distribution for residuals is not normally distributed since the points are off the diagonal line. The scatterplot shows clusters that are located far off each other, which signals moderate homoscedasticity. These graphs illustrate that the multilevel model explains beat precision moderately.

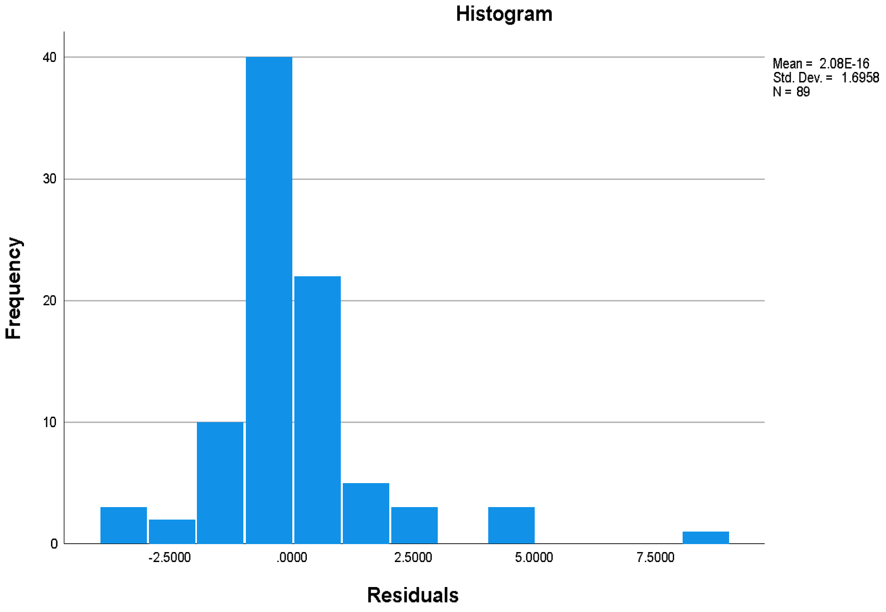

FIGURE 9 Histogram of residual distribution for Task 1 multilevel model

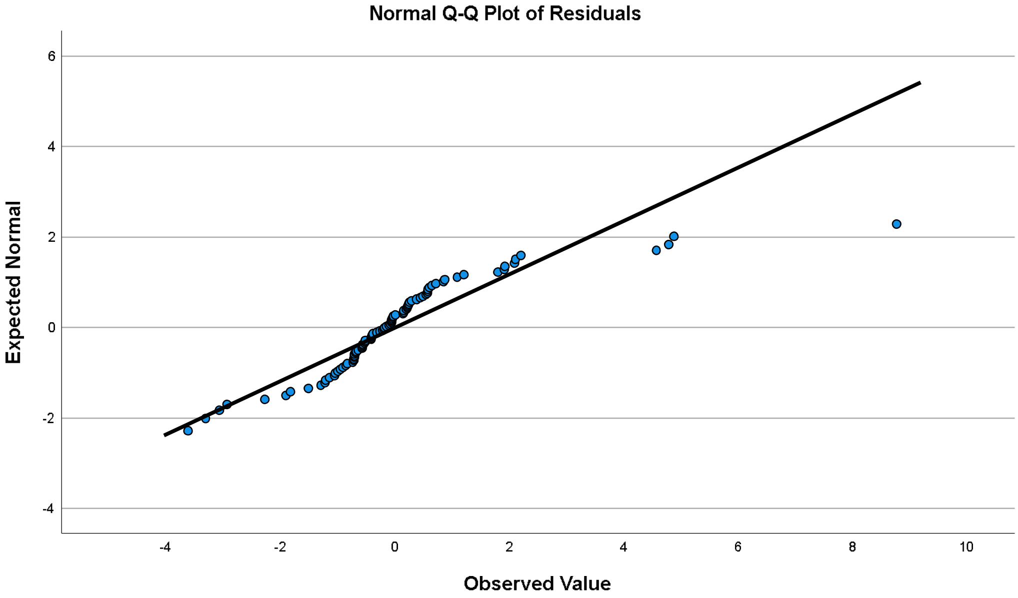

FIGURE 10 Q-Q probability plot of residuals for Task 1 multilevel model

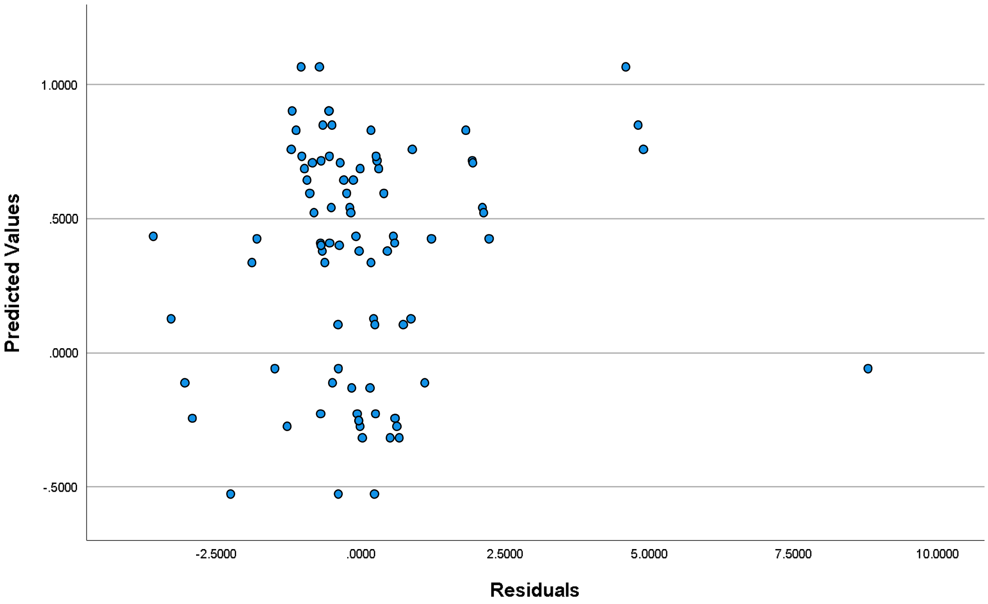

FIGURE 11 Scatterplot of residuals for Task 1 multilevel model

4.2 Task 2 — Incremental tempo change

Task 2 is analyzed by first calculating an average beats per minute value from the total number of beats produced by the experiment's metronome click track with the formula:

$$Average\ BPM = \frac{\text{Total amount of beats}}{\text{Length of the click track in minutes}}$$

Total number of beats is calculated from all 7 tempos, as each tempo has 16 bars, or measures of time, and each bar has 4 beats:

$$16 * 4 * 7 = 448$$

Which produces an average BPM for the incremental tempo change click track:

$$Average\ BPM = \frac{448}{3{,}1618}$$

The participants' mean BPM value is compared against the target BPM value of 137.017.

Table 6 presents descriptive statistics for the Task 2. As in Task 1, ten participants' result BPM values were calculated into an average value. Difference to target BPM column explains the difference between the task's target BPM value and the resulted average BPM value from the participants. The descriptive statistics for Task 2 illustrate the Haptic modality having the most accurate beat precision (21.55), and the Auditive modality being the least accurate (29.21).

TABLE 6 Descriptive statistics for Task 2

Sensory modality	***N***	**Mean BPM (Standard deviation)**	**Difference to target BPM (Standard deviation)**
Auditive	10	107.80 (9.94)	29.21 (9.94)
Haptic	10	115.47 (7.67)	21.55 (7.67)
Auditive-Haptic	10	111.67 (8.06)	25.34 (8.06)

The ICC was calculated from an intercept-only model where the dependent variable (DV) was set as the difference to the target mean tempo. The result value (ICC = 47.3 %) points out what proportion of the *DV* is explained by group level phenomena, the participants. The participant's individual difference explains 47.3 % of the difference to the target BPM value. The ICC value of 47.3 % tells that in Task 2, the participant’s individual capabilities to stay synchronized with the metronome has a high role. Next, DEFF was calculated from the mean cluster size which resulted in a value of 5.26, signalling that a multilevel model fits Task 2 better than Task 1. With the ICC value of higher than zero and the DEFF higher than 2, requirements to build a multilevel model is met, and the model can be constructed.

The multilevel model for Task 2 is shown in Table 7. Similarly to the results of the multilevel model in Task 1, the haptic metronome is set as the zero-level factor variable. The dependent variable (*DV*) of the model is beat precision, which is the mean difference BPM value to the target tempo. The factor variable is sensory modality, and the covariate variable is experience in years. The intercept is the model’s beat precision using a haptic metronome.

The model fit of the new multilevel model was compared to the previous intercept-only multilevel model. The new model fit *(-2RLL*) with fixed and covariate variables was more suitable (192.21 < 206.64) than the intercept-only model’s fit. This finding indicates that the new multilevel model in Table 7 has a better fit to explain more of the DV’s variance. The ICC value of 60.8 % signals that majority of the variance in DV is due to the participant’s variance in beat precision.

Tests of fixed main effects showed that sensory modality (auditive, haptic, auditive-haptic) received a value of $p < .024$, and participants’ playing experience in years received a value of $p > .876$. In Task 2, sensory modality has a statistically significant effect on beat precision, and similarly as in Task 1, participants’ playing experience in years has no statistically significant effect on beat precision.

The multilevel model illustrates that with a haptic metronome, on average, the subjects’ beat precision is 20.77 BPM off the target tempo, with a statistically significant result of $p < .005$. By calculating beat precision values from the intercept and the estimates, the auditive sensory modality produces a beat precision value of 28.44 and the multisensory modality produces a beat precision value of 24.57. The multilevel model analysis displays the haptic metronome is the most precise, with the multisensory metronome being second precise and auditive metronome being third. The statistically significant results are the haptic metronome being most precise and the auditive metronome being the least precise. As in the multilevel model of Task 1, the subjects' playing experience in years does not have any statistically significant impact on beat precision.

Inspecting a multilevel model where the auditive sensory modality was set as the baseline fixed effect showed $p < .141$ for significance between the auditive and the multisensory modality. This shows that in Task 2 there are no significant differences in beat precisions between the auditive and multisensory modalities.

Based on the multilevel model results from Task 2, there is support for H_3, as the use of haptic vibrotactile metronome produced the most accurate beat precision with statistical significance ($p < .005$). The null hypothesis, H_1, and H_2 are not supported by these findings.

TABLE 7 Multilevel model for Task 2

Fixed effects	Estimate	Standard error	*p*	95 % confidence interval
Intercept	20.77	5.58	.005	8.18 – 33.36
Auditive	7.67	2.51	.007	2.38 – 12.95
Auditive Haptic	3.80	2.51	.148	-1.48 – 9.08
Haptic	0 *	0 *		
Experience in years	.04	.26	.876	-.56 - .65
Random effects	$\sigma 2$			
Intercept (participant)	49.05	29.99	.102	14.78 – 162.59
Residual	31.61	10.53	.003	16.45 – 60.74
Intraclass correlation (ICC)				
Participant	.608			
Model fit (-2RLL)	192.21			

* The factor above is compared to factor that gets the value of zero

Figures 12, 13, and 14 illustrate the residual distribution in a histogram, a Q-Q plot, and a scatterplot for the Task 2 multilevel model. Compared to the Task 1 residual inspection, the histogram in Figure 12 has a better normal distribution, and the Q-Q plot in Figure 13 has more points on the diagonal line. The scatterplot in Figure 14 has no clusters, which supports that the multilevel model is homoscedastic. These findings suggest that the multilevel model in Task 2 fits to describe the model relatively well.

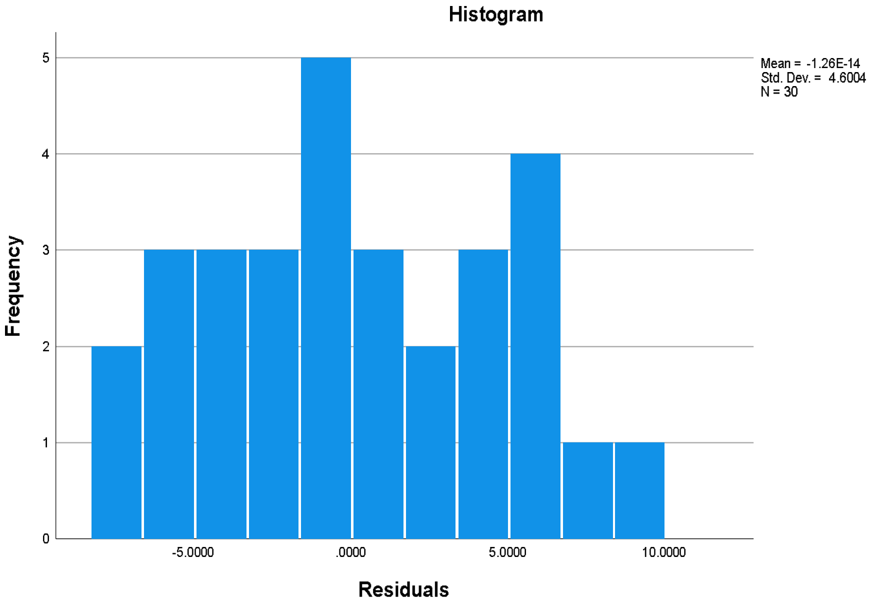

FIGURE 12 Histogram of residual distribution for Task 2 multilevel model

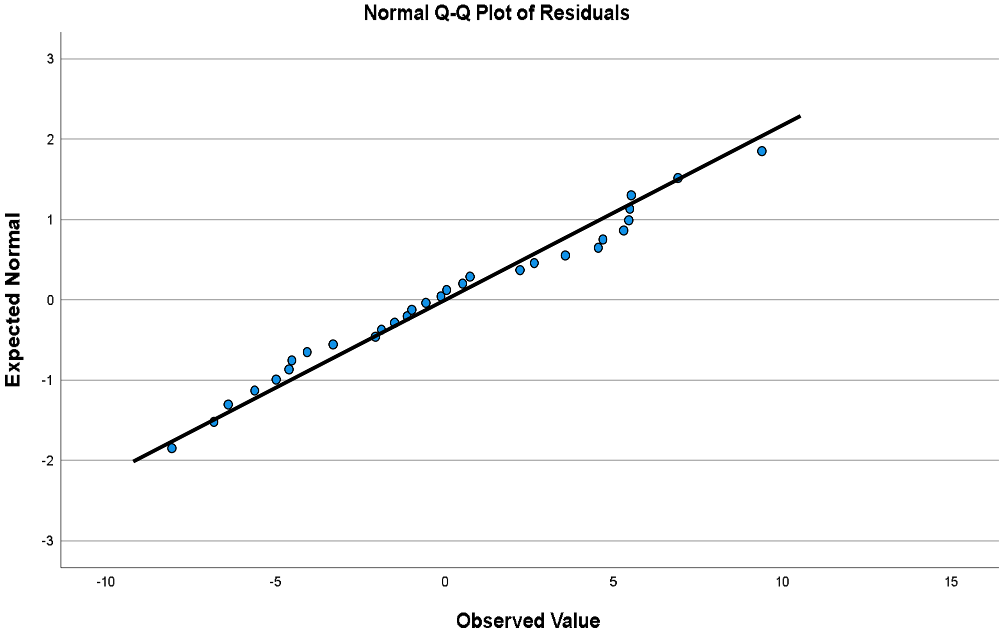

FIGURE 13 Q-Q probability plot of residuals for Task 2 multilevel model

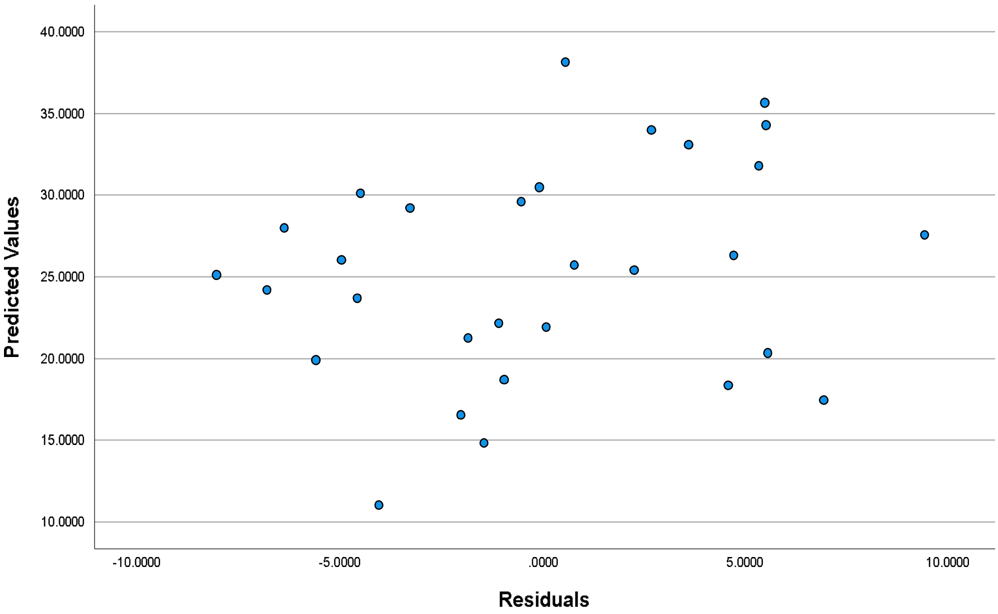

FIGURE 14 – Scatterplot of residuals for Task 2 multilevel model

4.3 Reliability, validity, and results

Some statistical significance can be found in the multilevel models and both models in Tasks 1 & 2 are supported by the ICC values of the initial intercept-only models. The results in Task 1 do not show any significant variance between the sensory modalities, whereas results of Task 2 have more statistical significance.

Bhattacherjee (2019) mentions that the key strength of experimental research lies in its internal validity, which allows for establishing causality. This is achieved through the manipulation of treatments while controlling for the effects of extraneous variables. Laboratory experiments conducted in laboratory environments tend to have high internal validity, but low external validity. This thesis has some internal validity since it was conducted as a laboratory experiment, however the low sample size of this study does not produce high external validity which tells the results cannot be generalized to apply beyond the laboratory environment.

The small sample size of the study reduces the results' reliability. Hox & McNeish (2020) point out that the sample size for a multilevel model fluctuates based on, for instance, the model's complexity, the number of random effects, and the intraclass correlation. With a small sample size in a multilevel model, the use of Restricted Maximum Likelihood (REML) can bring out more accurate results, since REML separates the estimation of the fixed effects and the variance components by removing the fixed effects when the variance components are estimated (Hox & McNeish, 2020), however, REML was utilized in this study and the results in Task 1 have no statistical power. If each starting sensory modality and tempo for the participants were randomized, the sample size would turn out to be 36. This would produce more reliable results and possible statistical effects for the multilevel models.

Both multilevel models in tasks 1 & 2 displayed the haptic metronome having the most accurate beat precision by producing mean values closest to the target tempos, which tells the null hypothesis H_0 is not supported, and hypothesis H_3 is supported by these findings. Beat precision of auditive and auditive-haptic metronomes switch places between tasks, with auditive being the least accurate in Task 2, and 2nd accurate in Task 1. The Task 2 residual inspection supports that beat precision between different sensory modalities is better fit to be examined through incremental tempo changes.

5 DISCUSSION

5.1 Summary

New multisensory technologies have emerged recent years which has allowed the research of multisensory integration to expand its area. The attractive concept of enhancing cognitive capabilities through the combination of different sensory modalities gains the attention of multisensory researchers in many different industries. This thesis investigated multisensory integration in quarter note timekeeping. The fast audio-tactile reaction times musicians possess (Landry & Champoux, 2017) inspired this study to research whether current modern metronome solutions could have a similar enhancing effect. The objective of this study was to understand whether a commercially available multisensory solution enhances musicians' beat precision during simple timekeeping experiments that were conducted as part of the research. The study had participants play timekeeping tasks with drumsticks for measuring beat precision in two different playing tasks.

5.2 Evaluating the sensory modalities

The haptic metronome turned out to have the most accurate beat precision by producing average BPM values closest to the target tempos in both playing tasks. In Task 1 the auditive and haptic modalities produced beat perception results like each other. The major deviation from the target tempo between the three sensory modalities (Auditive, Haptic, Auditive-Haptic) in beat precision was produced by the Auditive-Haptic modality at a very high tempo. This suggests that the multisensory solution in this thesis may not be optimal for extreme cases of speed if timekeeping is the primary objective of a musician. The results of Task 1 indicate that there is little difference in beat precision between the sensory modalities during long duration quarter note synchronization. It could be due to neural mechanisms behind beat precision establishing a template for regularly occurring beats. If a regular metronome cue is played for a long duration, there is less significance through which sensory modality the metronome cues are played. On the opposite, the playing Task 2 shows that when a static metronome signal is turned dynamic with tempo changes, sensory modalities play a more significant role in beat precision.

In terms of beat precision, the Auditive-Haptic stimulus did not produce the most accurate beat precision in this study. The exact reason why the multisensory modality was the least accurate is unknown. There could be a misalignment of auditory and haptic signals, which could explain the beat precision difference to the other sensory modalities. However, the concept of multisensory integration has some additional benefits compared to unisensory approaches. Since two sensory modalities are working with the same synchronized tempo signal, in case one metronome has a technical malfunction, the other metronome can keep producing metronome cues and secure the tempo, if the metronome device is able to produce an unisensory cue. For musicians who find it crucial to hear or feel the beats of a metronome, using a multisensory integrated approach may bring more security on staying synchronized with the tempo.

The Modality Appropriateness hypothesis by Welch and Warren (1986) is cited when investigating which sensory modality dominates under what circumstances. Ernst & Bülthoff (2004) mention that these hypotheses state that discrepancies are always resolved in favor of the more precise or more appropriate modality. In spatial tasks, for instance, the visual modality generally dominates, because it is the most precise at determining spatial information. For temporal judgements, the audition is seen more appropriate and to have better estimates over vision (Shams, Kamitani & Shimojo, 2000; Spence & Squire, 2003). The results of this thesis indicate that in the context of beat precision the haptic pathway dominates over other sensory pathways, although the auditive and haptic modalities produced similar beat precision results. This could be due to the auditory and haptic pathways sharing common neural processes for rhythm perception (Bernard et al., 2022).

Both playing task results support the use of haptic stimulus as a sensory substitution method for musical timekeeping. If a musician is suffering from hearing loss, it may be suitable to replace the auditory stimulus with a haptic stimulus instead. In terms of beat precision, the study results showed the haptic metronome having better or equal beat precision to the auditory metronome. In addition, the haptic metronome device is an accessible easy-to-use solution free from time-consuming configuration, which supports the comfort and ease of use guidelines (Kristjánsson et al., 2016) for constructing a successful sensory substitution device.

5.3 Limitations of the study

The initial method for measuring the participants' beat precision was to synchronize the haptic metronome device and metronome application to a Digital Audio Workstation (DAW) environment. This would have allowed more options for tempo automation, for instance, tempo increments of higher than +40 BPM can be assigned from a DAW directly. Unfortunately, at the time of the experiments DAW synchronization with the haptic metronome provided to be unreliable due to MIDI Clock limitations and latency issues. Future improvements can be seen here to investigate multisensory metronome devices that allow DAW synchronization or construct a metronome device with a do-it-yourself approach that can be used from multisensory perspective and with tempo changes.

The crucial weakness of the study lies in the low sample size (*N*) of 10. By having more participants take part in the experiments, the analysis would have more reliability, internal and external validity, and statistical power. A simple reaction time test shows its power here since the test format is more accessible to participants. The sample size could also be grown by expanding the experiments in this thesis to a wider group of participants that are not musically active. However, even with the small sample size of the study, Task 2 showed some statistically significant results. The format of the experiment produced statistically significant variance between auditive and haptic sensory modalities. However, the task compared mean values, which do not tell the true beat precision during the individual tempos of the incremental tempo change experiment. Future improvements can be seen here to calculate beat precision individually for each tempo segment.

At high tempos participants reported paying more attention to the sound of the haptic device, instead of the vibrations the haptic device produced. Further investigation about sensory overload could be beneficial in understanding the thresholds where multisensory metronome stimulus is perceivable. Other audio analysis methods could be explored in calculating tempo values from participants, such as Essentia (Bogdanov et al., 2013). One way of conducting the playing experiments would be to restrict sensory input to auditory and haptic pathways entirely by covering the participants eyes, since the visual channel is the primary source of information which we rely on to navigate in the external environment (Marucci et al., 2021).

Further investigation about real world usage of multisensory metronome usage is needed since this study was produced in a laboratory environment. Inside a musical playing environment there are multiple stimulus a musician needs to pay attention to, such as the composition of the musical piece and other musicians performing simultaneously. From a drummer's perspective, a song often consists of other patterns than quarter notes, so other rhythmic patterns could be explored. Measuring beat precision could be explored by measuring musical precision, where the emphasis is on keeping musical time and participants are asked to perform songs instead of synchronizing with a metronome click track.

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