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INSTITUTE OF PSYCHOLOGY

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**Rhythmic movement:
the role of expectancy and skill in event and emergent timing.**

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Rhythmic movement: the role of expectancy and skill in event and emergent timing.

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AUTORIZO A REPRODUÇÃO E DIVULGAÇÃO TOTAL OU PARCIAL DESTE TRABALHO, POR QUALQUER MEIO CONVENCIONAL OU ELETRÔNICO, PARA FINS DE ESTUDO E PESQUISA, DESDE QUE CITADA A FONTE.

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{Dedico este trabalho à minha mais dedicada educadora, minha mãe.

*Obrigada por me ensinar a ler e escrever,
a sonhar e buscar, perseverar e conquistar.}*

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Abstract

Braun Janzen, T. (2014). *Rhythmic movement: the role of expectancy and skill in event and emergent timing*. (PhD Thesis). Institute of Psychology, University of São Paulo, São Paulo.

Recent investigations suggest that rhythmic movements rely on two distinct timing systems: event and emergent timing. Event timing is based on an explicit internal representation of the temporal interval marked by clear perceptual detectible events whereas emergent timing is derived from the dynamics of smooth and continuous movements. However, crucial aspects of the distinction between these mechanisms remain unclear. This thesis investigates the role of expectancy and skill in the internal representation of time in event timing and emergent timing. Chapter 1 introduces the theoretical framework that supports the differentiation between event and emergent timing mechanisms and presents the hypotheses that were tested. Chapter 2 describes a series of five experiments that investigated the role of expectancy through examining the effect of a single unexpected perturbation of feedback content (e.g. pitch, timbre, intensity) on timing of finger tapping. Chapter 3 expands this question by investigating the effect of unexpected auditory perturbations on two types of timed movements: event and emergent timing. The role of expertise and training on motor timing is the subject of discussion of Chapters 4 to 6 where a total of 4 experiments tested the effect of expertise and music training on accuracy of finger tapping and circle drawing tasks. More specifically, Chapter 4 compares accuracy levels of experts in movement-based activities (music and sports) with non experts, whereas Chapters 5 and 6 focus on the effect of music training on event and emergent timing in students of 10 to 14 years of age. Finally, Chapter 7 reviews and discusses the main findings of this body of work with respect to current theories of timing and movement. Foremost, these data challenge current models of human movements controlled by event and emergent timing mechanisms demonstrating that expectancy and training are crucial in determining the timing strategy and the type of expectancy mechanisms adopted to perform distinct rhythmic movements.

Keywords: Motor Timing – Expectancy - Auditory Feedback – Training – Accuracy – Event Timing – Emergent Timing.

Resumo

Braun Janzen, T. (2014). *Movimentos rítmicos: o papel de expectativas e treino no controle temporal de movimentos contínuos e discretos*. Tese de Doutorado. Instituto de Psicologia, Universidade de São Paulo, São Paulo.

Estudos recentes sugerem que movimentos rítmicos dependem de dois sistemas distintos para controle do tempo, chamados tempo emergente e discreto. Sugere-se que tempo discreto baseia-se em uma representação interna do tempo intervalar que é marcada por eventos perceptuais evidentes, enquanto tempo emergente origina-se da própria dinâmica dos movimentos contínuos. No entanto, aspectos cruciais da diferença entre esses mecanismos ainda necessitam ser examinados. Esta tese investiga o papel de expectativas e treino no controle temporal de movimentos rítmicos contínuos e discretos. Capítulo 1 introduz as bases teóricas que subsidiam as hipóteses testadas no presente trabalho. Capítulo 2 descreve uma série de cinco experimentos que investigam a importância da retroalimentação auditiva e dos mecanismos de expectativa, e assim examina o efeito de uma perturbação inesperada e transitória no conteúdo do feedback (e.x. altura, timbre, intensidade) na precisão temporal de movimentos rítmicos discretos (i.e. finger tapping). Capítulo 3 expande essa investigação e analisa o efeito de perturbações inesperadas da retroalimentação auditivo em tarefas de movimentos contínuos, como desenhar círculos repetidamente. O papel do treinamento para o controle temporal é foco de discussão nos Capítulos 4 a 6, onde se descrevem um total de quatro experimentos que testam o efeito de expertise e treino na precisão de movimentos em tarefas de finger tapping e desenho de círculos. Mais especificamente, Capítulo 4 compara a performance de músicos e atletas com participantes sem nenhum treinamento nestas áreas a fim de examinar o papel do treinamento no controle motor, enquanto os Capítulos 5 e 6 focam no efeito do treino em música no controle temporal de movimentos rítmicos discretos e contínuos em estudantes de 10 a 14 anos de idade. Capítulo 7 revisa e conclui as discussões propostas com base nos principais resultados descritos neste trabalho. Em suma, os resultados apresentam novas e relevantes informações a respeito da importância de expectativas e do treinamento no controle temporal de movimentos rítmicos, cujas implicações podem contribuir significativamente para áreas relacionadas à pedagogia e reabilitação motora. Além disso, esta tese apresenta novas informações que ampliam modelos atuais sobre os mecanismos envolvidos no controle temporal de movimentos rítmicos demonstrando a

importância do papel de expectativas, retroalimentação auditiva e do treinamento para determinar os diferentes mecanismos de expectativa adotados pelo sistema nervoso na execução de movimentos rítmicos.

Palavras-chave: Controle Motor – Expectativas - Retroalimentação auditiva – Treinamento – Precisão – Tempo discreto – Tempo emergente.

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Chapter 1

Introduction to timing of rhythmic movements: examining the role of expectancy and skill in event and emergent timing

ABSTRACT

Skilled performance, such as dance, music and athletic sports, relies on precise timing of bodily movements and the capacity to predict and respond to the timing of events. Recent studies suggest that discrete and continuous movements rely on different timing mechanisms, named *event* and *emergent timing*. In this thesis, I argue that to better understand the distinction between these timing mechanisms in sensorimotor synchronization, it is important to examine the role of expectancy and skill. This introductory chapter describes the theoretical framework that supports this proposal and presents the fundamental questions explored in this work.

Introduction of Timing of Rhythmic Movements: Examining the Role of Expectancy and Skill in Event and Emergent Timing

Time is an intrinsic and defining dimension of life. It determines the duration and order of events, establishes patterns and interval between events, and can represent the past, present and future. Determining the timing of events, understanding the temporal relation between different stimuli, and anticipating when the next event will occur, are crucial cognitive processes that are deeply involved in a variety of everyday activities. For instance, walking down a crowded street involves timing one's own movements so as to navigate successfully while avoiding any collisions with others. To hit a ball with a tennis racquet, to tackle a player in rugby, to dance, to participate in an exercise class, to play the piano, and to sing 'Happy Birthday', are all examples of activities in which precise timing of bodily movements and the capacity to predict and respond to the timing of events are essential.

Humans have an additional capacity: to synchronise their movements with an external pacing signal. This ability is exemplified whenever we clap along with music. Although some non-human animals (particularly species characterized as *vocal imitators*) can move in synchrony with external rhythmic stimuli (Patel, Iversen, Chen & Repp, 2005; Patel, Iversen, Bregman & Schulz, 2009; Hattori, Tomonaga & Matsuzawa, 2013), humans are especially skilled at accurately and flexibly synchronising their actions to music (Jackendoff & Lerdahl, 2006; Grahn & Rowe, 2013; Bispham, 2006).

For most people, clapping to music is a trivial skill. However, despite the seemingly effortless nature of this task, it relies on a complex and sophisticated set of cognitive-motor processes that interpret dynamic tonal information, infer an underlying beat or pulse, and then generate movements that are optimally synchronised with the external signal but flexible enough to adapt to changes in the signal. The goal of this thesis is to elucidate the

mechanisms that generate and maintain such timed movements. In particular, I sought to further understand how elements such as expectancy and skill interact with timing mechanisms involved in discrete and continuous body movements.

The representation of temporal information remains one of the most puzzling concepts in neuroscience and psychology, in part because of the variety of mechanisms responsible for processing information in different time scales and sensory modalities. In a dynamic environment, where scenarios, people, and objects are continually changing, the amount of information available at different time scales imposes a challenge for the brain to solve. Organisms process temporal information and generate timed behaviors in time scales ranging from milliseconds to seconds, minutes, and daily circadian rhythms. It has been shown that there are areas of the brain, such as the posterior temporal sulcus, that are responsible for the processing of visual motion, whereas, at the other end of the spectrum, the control of daily sleep-wake cycles and the regulation of hormone levels are processed by biological clocks located in different specialized neural networks, such as the suprachiasmatic nuclei (Grossman & Blake, 2002; Czeisler et al., 1999; Duffy et al., 2011; Wager-Smith & Kay, 2000; Pittendrigh & Daan, 1976; Reppert & Weaver, 2002; Buhusi & Meck, 2005; Buonomano & Karmarkar, 2002). Time estimation and interval comparison on scales of seconds and minutes are the focus of a growing body of research in the area of time perception. This research suggests that time judgments require conscious and cognitive control based on attention and memory processes (Gibbon, 1990; Meck, 2005; Kacelnik, A., 2002; Buhusi & Meck, 2005; Grondin, 2010; Lewis & Miall, 2003). Given the variety of timing mechanisms involved in the processing of temporal information in such a great range of time scales, the terms ‘time’ and ‘temporal processing’ encompass a broad range of phenomena and theories in the literature, which often results in ambiguity and disagreement (Ivry & Schelff, 2008; Buonomano & Karmarkar, 2002). This thesis focuses on the

mechanisms involved in the control of timed motor actions that operate in a range of milliseconds.

Timing mechanisms required for the control of fine coordinated movements in music, sports, and dance, operate in the range of milliseconds (Buhusi & Meck, 2005; Grondin, 2010; Buonomano & Karmarkar, 2002; Macar, 2002). For instance, in skills such as hitting a ball with a tennis racquet or maintaining synchrony in a music ensemble or rowing crew, it is essential to know with millisecond accuracy when to perform an action and for how long, and to have the capacity to adapt to changes in planning even during the trajectory of the movement. These tasks require the ability to anticipate when the event will occur and to orchestrate movements so as to coincide with external stimuli (e.g. the ball, the beat of the music). The coordination of movements that coincide with predictable external events is referred as *sensorimotor synchronization* (Repp, 2005).

One important aspect of sensorimotor synchronization in music is that the actions and the external stimuli are periodic. Thus, in contrast to single timed action¹ (e.g., reaching, grasping, kicking), synchronization to music requires rhythmic movements that adhere to regular cycles of timed events (meter). Rhythmic movements can be classified in two distinct classes based on their kinematic features: discrete and continuous. Discrete rhythmic movements are periodic actions preceded and followed by a period of no or little motion, as in finger tapping. Continuous rhythmic movements are characterized by uninterrupted, smooth, actions occurring at regular intervals, such as circle drawing (Hogan & Sternad, 2007; Huys et al., 2008). To date, there is limited understanding of exactly how these two types of actions are controlled, and whether there are overlapping processes underlying the

¹ Also defined as ‘discrete’ movements (Hogan & Sternad, 2007; Degallier & Ijspeert, 2010; Huys et al., 2008, 2010).

temporal precision in such distinct rhythmic movements (Ivry & Scherlf, 2008; Torre & Balasubramaniam, 2009; Repp & Steinman, 2010; Huys et al., 2008; Zelaznik et al., 2005).

Neural models of temporal representation

Two types of mechanisms have been proposed to account for the representation of time, as illustrated in Figure 1.

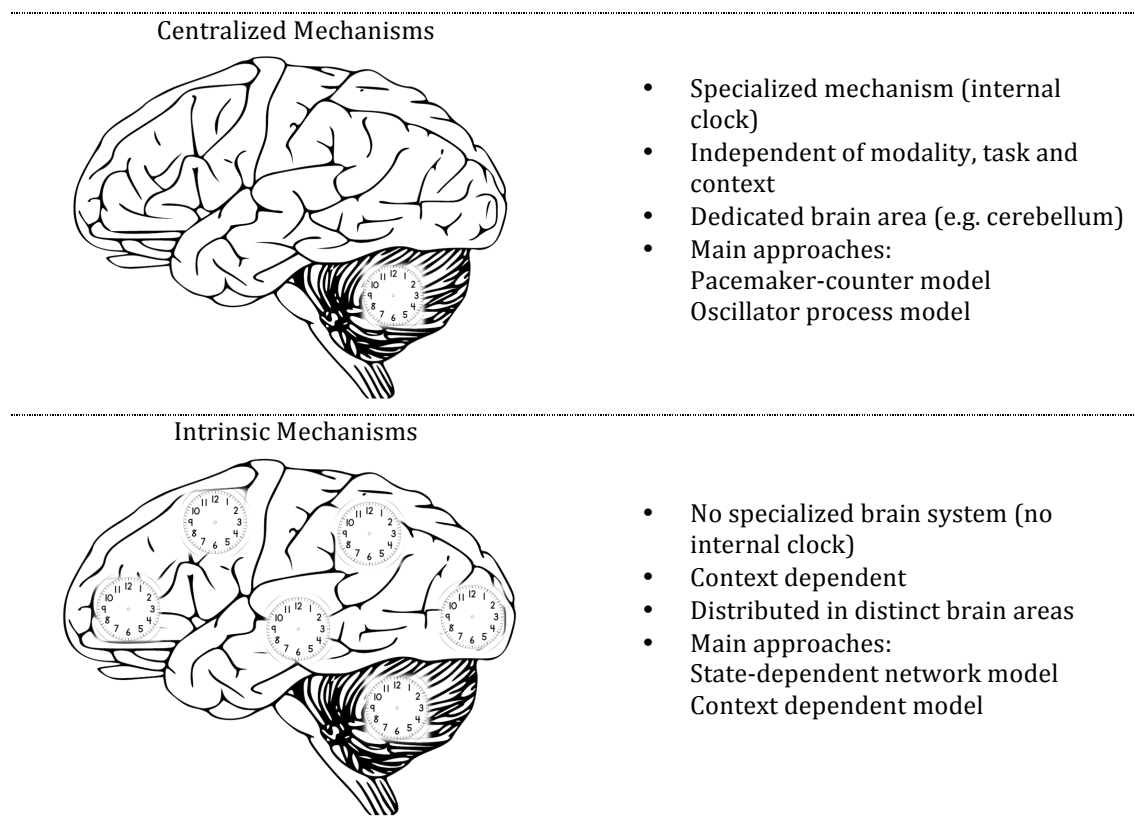


Figure 1. Neural models for temporal representation. Modified from Ivry & Spencer (2004).

Internal clock models are based on the idea that timing relies on a central and specialized mechanism that represents temporal relations across tasks and modalities (Ivry et al., 2002; Ivry & Schlerf, 2008; Grondin, 2010). Supporting evidence has been provided by studies demonstrating that people are able to compare the duration of stimuli across

modalities (e.g., tone, light), and that accuracy in perceptual and motor timing tasks are correlated, suggesting a common mechanism (Guttman, Gilroy & Blake, 2005; Spence, 2011; Keele, Pokorny, Corcos & Ivry, 1985; Schubotz, Friederici & von Cramon, 2000; Ivry & Schlerf, 2008; Buonomano & Karmakar, 2002). Neuroimaging and neurological research have supported the hypothesis that the cerebellum is a central mechanism in tasks where an explicit representation of time is necessary, and is especially important for predicting the time of events (O'Reilly, Mesulam & Nobre, 2008; Ivry, Spencer, Zelaznik & Diedrichsen, 2002; Grondin, 2010; Buhusi & Meck, 2005). However, the prefrontal and parietal cortices, as well as the basal ganglia, are also involved in timing (Grahn, 2012; Merchant, Zarco & Prado, 2007).

One influential model suggests that the internal-clock is composed of three elements: a clock, a memory component, and a decision/comparison (Matell & Meck, 2000). The presence of a central mechanism is assumed in two main theoretical models: the pacemaker-counter model, and the entrainment model. The *pacemaker-counter model* suggests that the stimulus that marks the beginning of a temporal interval triggers the closing of a gate that allows pulses to enter and be temporarily stored in an accumulator. Upon reinforcement or feedback, the number of pulses received/counted by the accumulator is stored in reference memory, and this temporal information can then be used to predict future events. In tasks that involve judging or comparing a standard interval with the duration of a second temporal interval, the decision making process requires the comparison between the current number of pulses counted with that in reference memory (Figure 2) (Wearden, 1999; Ivry & Schlerf, 2008; Grondin, 2010; Buonomano & Karmakar, 2002).

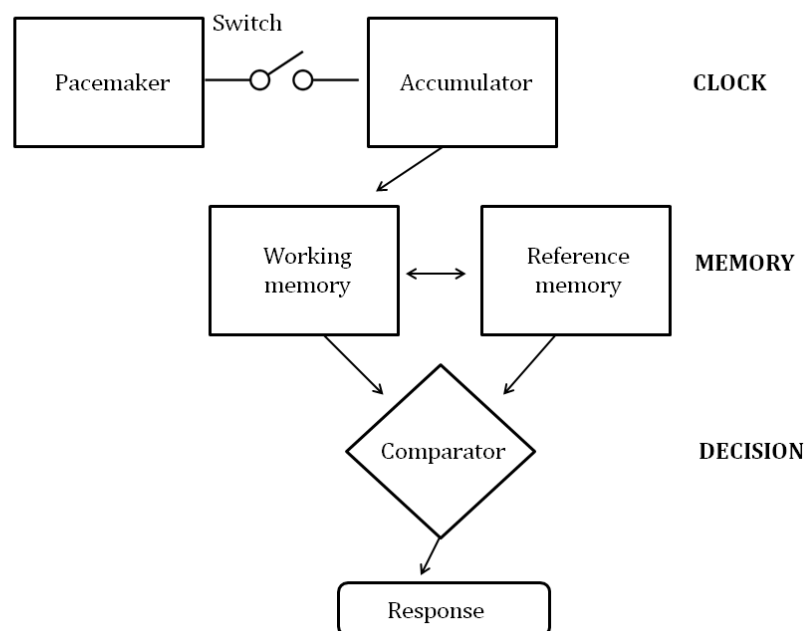


Figure 2. Schematic of the information-processing version of the scalar expectancy theory.

Modified from Buhsu & Meck (2005).

The *Entrainment model* assumes that the timekeeper is composed of self-sustained oscillators that entrain, or adapt, their internal rhythm to synchronise with the expected onset of temporally-coherent events (Large, 2000; Barnes & Jones, 2000). According to *Dynamic Attending Theory* (Jones & Boltz, 1989), the regularity of temporal events in the environment generates predictions about subsequent events. Based on the regularity of external rhythms, oscillators synchronise their internal rhythmicity to the timing of external stimuli.

Intrinsic timing models, on the other hand, postulate that time is inherent in neural dynamics; thus, a central and dedicated brain system is not needed to process timing information (Ivry & Schlerf, 2008). Within this theoretical framework, one line of research assumes that time processing is modality-specific, such that the modality of the temporal stimuli defines the neural network that is activated (Jantzen, Steinberg & Kelso, 2005). In other words, the processing of the duration of a visual stimulus should depend on the

dynamics of neurons in visual regions of the brain. Studies demonstrating modality-specific illusions, and significant differences in interval discrimination between sensory modalities, have supported this perspective (Morrone, Ross & Burr, 2005; Jantzen, Steinberg & Kelso, 2005; Grondin, 2003).

The *state-dependent network* model suggests that time durations are represented through patterns of activation of excitatory and inhibitory neurons distributed across a set of neural structures, and the state of the network at the onset of the stimulus influences information processing (Buonomano & Karmakar, 2002). Physiological studies have located single-unit activity in response to the duration of visual stimuli, supporting this model (Leon & Shadlen, 2003).

It has been noted that most research on the timing of rhythmic movements have focused on discrete movements, such as finger tapping (Repp, 2005; Repp & Steinman, 2010; Degallier & Ijspeert, 2010). More recent studies, therefore, have started to investigate the mechanisms involved in the control of continuous movements. Comparisons of these two types of movements suggest that the timing mechanisms underlying discrete movements (*event timing*) are different than the mechanisms that control the timing of continuous movements (*emergent timing*) (Robertson et al., 1999; Zelaznik et al., 2002; Huys et al., 2008; Zelaznik & Rosenbaum, 2010; Studenka et al., 2012; Degallier & Ijspeert, 2010).

Event and emergent timing as distinct mechanisms

The first study to support a distinction between the mechanisms underlying discrete and continuous rhythmic movements was reported by Robertson et al. (1999). They compared participants' performance in tapping and circle drawing, and observed no significant correlation between measures of accuracy in these two tasks, suggesting that continuous and discrete movements involve distinct timing mechanisms. If timing relies on a central and general mechanism, then a correlation between different timing tasks would be

expected (Buonomano & Karmarkar, 2002). Therefore, the results reported by Robertson and colleagues challenged models that assume that temporal processing relies on a single centralized mechanism (Treisman, 1963; Keele, Pokorny, Corcos & Ivry, 1985; Ivry & Schlerf, 2008; Wearden, 1999, 2003).

Subsequently, Zelaznik, Spencer and Ivry (2002) compared the accuracy in performances of finger tapping, circle drawing, intermittent circle drawing (i.e., with pauses inserted between each circle) and an auditory duration discrimination task. Results showed that the timing variability of the tapping, intermittent drawing, and the discrimination tasks were significantly correlated, whereas timing of continuous circle drawing was not correlated with the other tasks. Taken together, these findings led to the suggestion that event timing requires an explicit representation of a temporal interval to be produced based on an internal clock-like mechanism, whereas emergent timing arises from the dynamic control of nontemporal parameters of the produced movement, such as velocity, thus not requiring an explicitly defined mental representation of time (Zelaznik, Spencer & Ivry, 2000; Ivry, Spencer, Zelaznik & Diedrichsen, 2002; Repp & Steinman, 2010).

A growing body of evidence from mathematical studies (Huys et al., 2008, 2010) and behavioral research (Elliot, Welchman & Wing, 2009; Studenka & Zelaznik, 2011; Zelaznik et al., 2005; Repp & Steinman, 2010; Torre & Balasubramaniam, 2009) has corroborated the hypothesis that different timing mechanisms are involved in the temporal control of discrete and continuous rhythmic movements. Neurological and imaging studies have also supported the hypothesis that event timing processes are based on a centralized clock-like mechanism, and that the cerebellum is essential for tasks that require an explicit temporal representation (Spencer, Zelaznik, Diedrichsen & Ivry, 2003; Spencer, Ivry & Zelaznik, 2005; Ivry et al., 2002; Schaal, Sternad, Osu & Kawato, 2004; Spencer, Verstynen, Brett & Ivry, 2007). In particular, patients with cerebellar damage are significantly impaired in finger tapping and

intermittent drawing, but not in continuous circle drawing (Ivry et al., 2002; Spencer, Zelaznik, Diedrichsen & Ivry, 2003).

The discovery that event and emergent timing are dissociable neurologically and functionally is an important step towards understanding the mechanisms underlying rhythmic movements. However, the idea that emergent timing does not require an explicit temporal representation imposes a challenge regarding the control of timing in continuous rhythmic movements. Without a temporal representation of the duration of interval to be produced or when it will occur, can continuous rhythmic movements be synchronised to rhythmic stimuli, such as music?

Central to this question is the concept of expectancy. Expectancy is intrinsically related to rhythmic actions. Tasks such as clapping along with the beat of the music, or hitting a ball in a baseball game, are only possible given that movement planning integrates into the motor command predictions of where and when the stimuli will occur, and the expected outcome of that action. For instance, musicians need to anticipate when the next beat will occur in order to synchronise their movements with the music. Thus, anticipation allows musicians to respond to the timing of events rather than reacting once the beat of the music has been presented and processed. This thesis examines the possibility that the dissociation between event and emergent timing is also manifested in the way expectancy mechanisms interact with discrete and continuous movements.

The role of expectancy in rhythmic movements

Skilled motor behavior relies on accurate representations of both our own actions and the environmental stimuli with which we are interacting. Expectation can be defined as a mental representation of what is predicted to occur and when it will happen (Wolpert & Flanagan, 2001; Bubic, Cramon & Schubotz, 2010). A prerequisite of prediction is the presence of regularity in event-relationships. In music, for instance, there are regular

temporal intervals between successive musical beats, which allow the brain to extract structural regularity and use this information to predict what and when subsequent events will occur (Bubic et al., 2010; Pecenka & Keller, 2011). Expectancy mechanisms allow musicians to synchronise with the timing of events rather than reacting to those events once they have taken place. Such a mechanism can explain why, in a finger-tapping synchronization task, taps tend to *precede* the onset of tones by a few milliseconds – an anticipatory tendency that gives rise to a negative mean asynchrony (Aschersleben & Prinz, 1995; Aschersleben, 2002; Repp, 2005).

The *forward model* was proposed to explain how the motor system anticipates a motor command in response to predictable stimuli, and how the outcome of the action interacts with the executed movement (Miall & Wolpert, 1996; Schubotz, 2007; Davidson & Wolpert, 2005; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010). According to the forward model, movement is controlled by sending a copy of the motor command (efference copy), and then outputting a prediction of the expected consequences of the motor command. The difference between the predicted and actual body positions is registered and used to refine the set of motor commands. Studies have suggested that premotor regions, but especially the cerebellum, play a crucial role in comparing the course of the motor action and its expected outcome, and making any necessary trajectory corrections as the movement is being produced (Kawato et al., 2003; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010; Nobre & O'Reilly, 2004; O'Reilly, Mesulam & Nobre, 2008). Once the movement is produced, sensory feedback (e.g. tactile, visual, auditory) informs the motor system of whether the prediction “matches” the outcome, or whether there was an error (“mismatch”) that requires an adjustment to the motor plan (Figure 3).

The forward model is an example of an *internal model of motor control*, designed to represent sensorimotor relations between the input and output of actions. They also include

inverse models that account for the relation between a *desired* body position (as opposed to a *predicted* body position) and the motor command required to achieve that position.

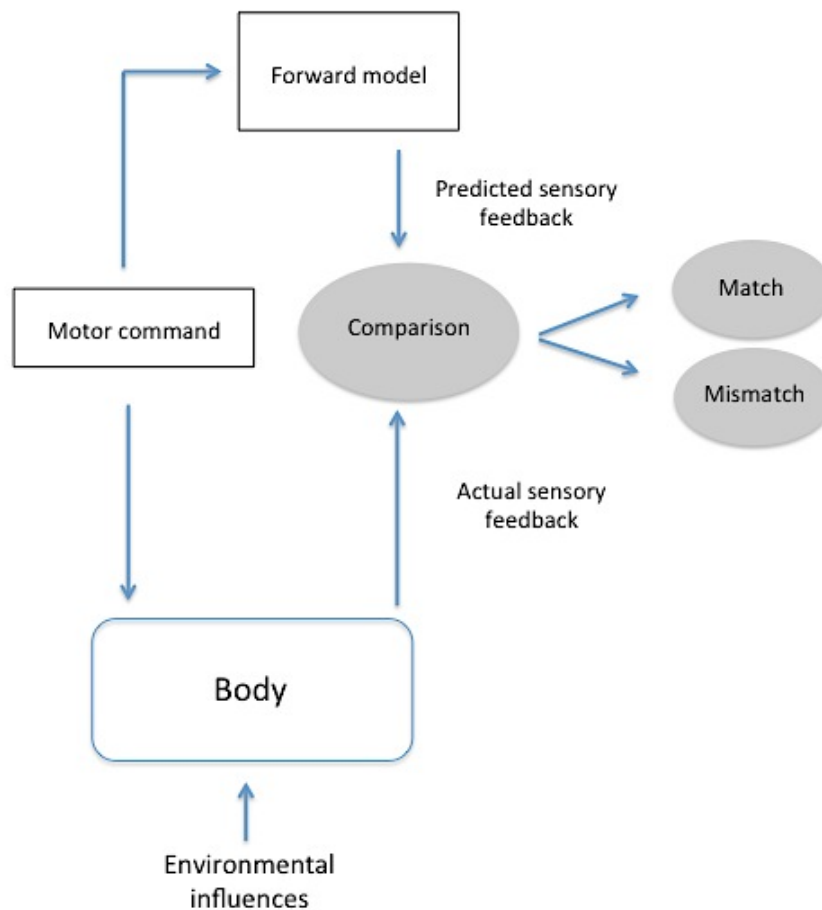


Figure 3. Prediction in motor control based on the forward model. Modified from Bubic et al. (2010)

Evidence suggests that predictions may be engaged not only for one's own actions, but also during the observation of actions by others, action simulation, or actions that we cannot physically reproduce (Rizzolatti & Craighero, 2004; Schubotz, 2007; Keller, 2012). Despite the success of internal models in explaining motor control, they have not been adapted to explain the distinction between event and emergent timing.

The role of expectancy in event and emergent timing

Synchronization between rhythmic movements and external rhythmic stimuli requires the capacity to anticipate the onset of the external event. According to forward models, motor prediction involves a central representation that integrates expectations for both motor and perceptual outcomes, and then evaluates whether the predictions correspond to the outcome (Bubic et al., 2010). The discrepancy between actual and predicted sensory feedback is essential for the production of accurate movements (Wolpert & Flanagan, 2001).

Consider a rhythmic action in which there is a stable association between the motor predictions and action outcomes. In this circumstance, the correlation between environmental events and motor response gives rise to “strong anticipations”, such that the sensory feedback provided by the environment reinforces a largely internal process of maintaining an established rhythm. The goal of the system in such a stable scenario is to maintain smooth and uninterrupted rhythmic movements based on global and often long term expectations. However, if an unexpected event causes a sudden change in the environment, the sensory feedback of that perturbation will arrive when the system has already implemented the motor plan. In this case, the feedback provided by the unpredictable event can only effect the *following* action.

Repp (2008) suggested that continuous movements have a greater “maintenance tendency” compared with discrete movements, due to the *inertia* associated with the movement (Repp, 2008; Repp & Steinman, 2010). The continuous movements of circle drawing, for example, have greater inertia than the discrete movements of tapping. Therefore, a decoupling between a sequence of motor actions and the external environment may not lead to an instantaneous correction to address this perturbation. This prediction is supported by studies showing that, in comparison with discrete movements, continuous movements are

slower to adjust following changes in sensory input (Repp & Steinman, 2010; Elliott, Welchman & Wing, 2009).

In contexts where the environment is dynamically changing and adjustments are needed between the planned action and its expected outcome, the system must rely on detailed timing information provided by environment. Dynamic environments tend to evoke a “weak anticipation”, as unpredicted events require rapid and efficient corrections to maintain an accurate response. In this case, it can be suggested that the system may be unable to generate long-term or global expectancies, and will tend to generate local short-term expectancies.

It has been suggested that event timing is linked to weak (local) anticipations, whereas emergent timing is associated with strong (global) anticipations (Dubois, 2003; Stephen et al., 2008; Marmelat & Delignieres, 2012). However, the amount of sensory feedback may also be a factor, as it is strongly correlated with timing error (Aschersleben, Gehrke & Prinz, 2000; Aschersleben, 2002; Stenneken et al., 2006; Merchant, Zarco & Prado, 2008; Repp, 2005). Moreover, local and global processes are not mutually exclusive, so event timing may employ global expectancies in contexts where, for instance, the tempo of the stimuli interval is too fast to be processed locally (Repp, 2008). Conversely, emergent timing may engage local expectancies to perform rhythmic movements in contexts where sensory feedback is emphasized (Zelaznik & Rosenbaum, 2010; Studenka et al., 2012). In short, both local and global expectancies may be associated with continuous and discrete rhythmic movements.

The role of skill and training in event and emergent timing

Training in a movement-based skill may be defined as the process of aligning internal predictions of motor and perceptual outcomes with the dynamic conditions of the environment and the body, and the capacity to adjust rapidly to any misalignment. Therefore, training in a movement-based skill such as music or an athletic sport should lead to improved timing. Such an improvement should be evident in measures of both event timing and

emergent timing, because skill should enhance the ability to generate local and global expectancies.

It is well documented that musically trained participants show smaller asynchronies in synchronization tasks, lower tapping variability, and faster motor timing correction following timing perturbations (Repp, 2005, 2010; Repp & Su, 2013; Aschersleben, 2000). Interestingly, Aschersleben (2003) trained nonmusicians to improve their ability to synchronise tapping actions with a pacing signal, indicating that training can enhance people's ability to synchronise discrete movements.

However, we do not know whether musical training can enhance accuracy in emergent timing or whether expertise in non-musical domains, such as sports or dance, can improve timing. If event timing and emergent timing are dissociated, then training in a domain that emphasizes event timing may not benefit emergent timing (Baer et al., 2013; Spencer, Zelaznik, Diedrichsen & Ivry, 2003; Spencer, Ivry & Zelaznik, 2005; Ivry et al., 2002). On the other hand, it is possible that both global and local expectancy processes benefit from training in any movement-based skill.

Experimental hypotheses

To examine the role of expectancy in the timing of motor actions, experiments described in this thesis focused on evaluating the effect of unexpected feedback perturbations on the accuracy of discrete and continuous rhythmic movements. Based on assumptions defined by the forward model that expectancies are intrinsically related to actions and that expected motor and perceptual outcomes are integrated in the motor command, the thesis examined three main hypotheses:

- 1) **Hypothesis 1:** Expectancy processes are engaged in the temporal coordination of continuous and discrete rhythmic movements. However, emergent timing relies

predominantly on global expectancies, whereas event timing predominantly engages local expectancies.

- 2) **Hypothesis 2:** All expected environmental information should be integrated in motor representations of timing. This not only includes temporal information but also relevant non-temporal information such as pitch, timbre and loudness, defined as *content* information. Therefore, unexpected transient perturbations of feedback *content* triggered by the performed action should significantly interact with timed movements;
- 3) **Hypothesis 3:** Expertise in a movement-based activity (sports, music) will impact the development of timing skills and will be reflected in enhanced timing accuracy.

Experimental approach

One assumption of the forward model is that predictions generated by the motor system include both motor and perceptual outcomes (Schubotz & von Cramon, 2003; Schubo, Prinz & Aschersleben, 2004). This argument has been revisited by theories suggesting the existence of a shared representation between perception and action (James, 1980; Prinz, 1990; Hommel et al., 2001). In relation to sensorimotor synchronization, Aschersleben (2002) suggested that “synchrony is not only controlled by but also established at a central representation level on which both stimuli and actions are represented in terms of their sensory consequences” (p. 68, see also Aschersleben & Prinz, 1995; Mates & Aschersleben, 2000; Aschersleben, Gehrke & Prinz, 2001). Although research has examined the effect of unexpected time perturbations in accuracy of discrete rhythmic movements, studies of the relation between the *content* of feedback and motor timing are limited methodologically. Feedback content refers to nontemporal characteristics of the auditory feedback, such as pitch height, intensity and timbre, while preserving the temporal relation between movement and feedback.

One strategy for investigating how sensory information affects motor timing is to alter pacing signals or auditory feedback and observe the effect on timing. Pacing signals are acoustic events to which participants synchronise their actions (such as a metronome), whereas auditory feedback refers to sounds evoked by motor actions. The effects of timing perturbations can be examined by introducing a local shift in the timing of a pacing signal at a certain position of the synchronization sequence, shifting the signal forward or back in time (Mates & Aschersleben, 2000; Pfordresher & Benitez, 2007; Repp, 2005; Repp & Su, 2013).

This paradigm has been adopted to study how unexpected timing perturbations of pacing signals elicit error corrections mechanisms. Two distinct error correction mechanisms have been identified. In phase correction, the pace or tempo of the synchronization response (e.g., tapping) is held constant but the participant shifts the onset of their response. In period correction, the participant adjusts the tempo of the synchronization response (Mates, 1994; Repp, 2005; Repp & Su, 2013; Repp & Keller, 2008; Repp & Keller, 2004).

Relatively few studies have examined how the *content* of feedback or pacing signals influence timing. As an exception, Repp conducted a series of experiments examining timing in the presence of manipulations to both time and pitch of a pacing signal, and concluded that correction mechanisms are ‘insensitive’ to pitch perturbations (Repp, 2003; Repp & Penel, 2004; Repp, 2005). However, these experiments did not distinguish the unique effect of pitch changes on timing, and subtle effects of pitch on motor timing might have been masked by the much stronger effect of shifts in the timing of the pacing signal.

The serial shift paradigm has also been suggested to investigate the effect of altering the pitch of feedback on timing (Pfordresher, 2003; Pfordresher, 2006 for review). Serially shifted perturbations cause the feedback triggered by each tap to match a tone intended for a different sequence position, thereby introducing a constant mismatch between planned action and expected outcome. Participants memorize a short melody and practice several times on

the piano to guarantee accurate performance. On the experimental trial, participants perform the standard melody while receiving an auditory feedback that does not match the keystrokes. Specifically, at a given position in the melody the pitch presented is the following note of the sequence (“hearing the future”) or a previous note of the sequence (“hearing the past”) (Pfordresher & Palmer, 2006). Findings suggest that alterations of feedback significantly disrupt performance by increasing error rates (i.e. striking a wrong key), but there is surprisingly little effect on timing variability. One critical aspect of this paradigm is that it focuses on a global internal representation of motor sequence structure (Pfordresher & Kulpa, 2011) rather than motor timing and correction mechanisms. Moreover, serial shifts of auditory feedback do not correspond to real music performance situations.

In this thesis, I argue that feedback content (e.g., pitch, timbre, intensity) is integrated in the representation of timed action. Therefore, unexpected feedback content should significantly interact with the timing of rhythmic movements. This hypothesis is supported by anticipatory models that assume that all feedback derived from movements (tactile, kinesthetic, auditory) are integrated in a central representation of time (Mates & Aschersleben, 2000). Recent behavioral studies have also suggested that the pitch contour and pitch distance of sequential feedback tones influence tapping velocity and accuracy (Ammirante, Thompson & Russo, 2011; Ammirante & Thompson, 2012).

To test this hypothesis, the protocol adopted in this thesis aimed to isolate the effect of feedback content on motor timing by investigating the effect of a single unexpected perturbation on accuracy of timing. The protocol is closely related to real situations of music performance, in that players often need to adapt rapidly to an unexpected change in the music while attempting to maintain precision in timing.

Chapter 2 describes five experiments that tested the hypothesis that unexpected transient perturbations of feedback content interact with the timing of event timing. The

experiments examined the effect of an unexpected perturbation of pitch (Experiments 1-2), intensity (Experiment 3) and timbre (Experiment 4). Finally, Experiment 5 examined whether unexpected perturbations of feedback content require conscious detection and identification, or whether unexpected changes are automatically processed by the motor system.

The role of sensory feedback in *emergent timing* is examined in **Chapter 3**. Based on the hypothesis that temporal and (relevant) nontemporal information are integrated in the representation of timing, I suggest that unexpected changes in the feedback content (e.g. pitch) significantly interact with the timing of continuous rhythmic movements, just as they did for the discrete movements examined in Chapter 2. However, I predicted that the effect of perturbations can be explained by a “maintenance tendency” described by Repp (2008). Therefore, the effect of content perturbations on timing should not be evident immediately but in subsequent actions.

Chapter 4 evaluates the effect of movement-based expertise (sports and music) on emergent and event timing mechanisms. Based on the hypothesis that musicianship predominantly engages event timing and that athletic sports tend to engage emergent timing, I predicted that music training might affect performance on a tapping (event timing) task, whereas athletic training might benefit performance on a continuous timing task (circle drawing). I also examine whether experts in music and sport are differentially impacted by auditory feedback. This study represents the first to examine whether intensive training in sports can enhance accuracy on emergent timing and/or event timing.

Chapter 5 further examines the effect of training on timing by investigating whether formal musical lessons interact with the development of motor timing skills in children and adolescents of 10 to 14 years old. This study examines whether school-age students with formal musical training for more than 2 years are significantly more accurate than students

with little or no musical training (< 2 years). I predicted that age and musical training will significantly interact with students' performance.

Chapter 6 further discusses the effect of intense training on timing skills by describing a case study of an exceptionally talented 12 year-old musician. This study compares the results of this highly trained young musician on the tapping and circle drawing tasks with age-matched students with and without music training.

Finally, **Chapter 7** summarizes the findings described throughout the thesis and discusses the implications of the work with respect to current models of timing.

Overview

In this thesis, I explore the role of expectancy and skill in sensorimotor synchronization of discrete and continuous rhythmic movements. Drawing from existing data and models of motor timing, I argue that expectancy mechanisms are intrinsic to the timing of rhythmic movements, and greatly influence sensorimotor synchronization of discrete and continuous rhythmic movements. Based on the assumptions defined by the internal forward model that expectancies are intrinsically related to actions and that the expected motor and perceptual outcomes are integrated in the motor command, I tested three hypotheses, as follows: 1) Expectancy mechanisms are engaged in the coordination of continuous and discrete rhythmic movements; 2) Feedback content (e.g. pitch, timbre, intensity) is integrated in the representation of timed motor actions; and 3) Skill and training should influence the interaction between expectancy and timing, resulting in enhanced accuracy of timed actions.

The most direct way to explore the role of expectancy for sensorimotor synchronization is to manipulate the feedback triggered by movements. In this thesis, I focused on perturbations of the content of feedback while preserving the temporal relation between action and auditory feedback. I adopted this approach to demonstrate that expectancy mechanisms in general – and not simply expectations about timing – are

integrated with timing mechanisms. The effect of the unexpected change in the intertap intervals following the perturbation was used to assess the interaction between expectations and timing. The interaction between movement-based skill and accuracy of timed actions may be understood as an indirect strategy to examine the role of expectancy in timing, in that training tightens the alignment between expectations and environmental events.

The experiments described in the thesis were designed to extend our knowledge of the mechanisms underlying the fascinating precision by which people produce timed actions and synchronise movements in a dynamic environment. By investigating the role of expectancies and skill in the production of rhythmic movements, this thesis has potential to advance current knowledge of timing and sensorimotor synchronization.

Chapter 2:

Understanding the role of feedback content in event timing

ABSTRACT

This chapter examines the role of expectancy in sensorimotor synchronization by investigating the effect of feedback perturbations on timing. Based on the assumption that expected motor and perceptual outcomes are integrated in a central representation of timing, five experiments tested the hypothesis that unexpected transient changes in feedback content (e.g. pitch, timbre, intensity) significantly interact with event timing. The experiments examined the effect of unexpected pitch (Experiment 1 and 2), intensity (Experiment 3) and timbre (Experiment 4) in accuracy of finger tapping. Finally, Experiment 5 attempted to elucidate whether the interaction between expectancy and timing requires conscious awareness or whether it relies on automatic bottom-up processes. Results are discussed in light of current models of timing.

Understanding The Role Of Auditory Feedback On Event Timing

Every movement that we make depends on precise expectations for the consequences of our actions. These expectations gradually develop through our interaction with the environment, which provides us with feedback about our actions – whether they have been successful or unsuccessful. Some of this feedback is kinesthetic: when we walk we feel the ground under us; some is visual: we can see our foot successfully coming into contact with the ground; and some is auditory: each step we take results in the sound of a footstep. All of this sensory information is rapidly and unconsciously used as feedback to our sensorimotor system, allowing us to navigate through the environment effectively. Without such feedback, we would be unable to monitor our movements or refine our movement skills. In this chapter, we focus on *auditory* feedback arising from our actions, and examine how this feedback interacts with the timing of these actions.

The *forward model* was proposed to explain how the motor system anticipates a motor command in response to predictable stimuli, and how the outcome of the action interacts with the executed movement (Miall & Wolpert, 1996; Schubotz, 2007; Davidson & Wolpert, 2005; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010). According to this model, movement is controlled by sending a copy of the motor command (efference copy), and then outputting a prediction of the expected consequences of the motor command. The difference between the predicted and actual body positions is registered and used to refine the set of motor commands. Studies have suggested that premotor regions, but especially the cerebellum, play a crucial role in comparing the expected and actual motor outcomes, and making any necessary adjustments to the trajectory of the movement as it is being produced (Kawato et al., 2003; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010; Nobre & O'Reilly, 2004; O'Reilly, Mesulam & Nobre, 2008). Once the movement is produced,

sensory feedback (e.g. tactile, visual, auditory) informs the motor system of whether the prediction “matches” the outcome, or whether there was an error (“mismatch”) that requires an adjustment to the motor plan.

Sensory information is particularly relevant for precise motor synchronization and error-correction mechanisms. It has been shown, for instance, that tactile information significantly increases precision in tapping tasks and piano performances (Aschersleben, Gehrke & Prinz, 2001; Goebel & Palmer, 2008). Visual and auditory feedback are also fundamental for learning. Participants provided with sensory information about their performances were able to perfectly synchronise taps with the metronome after a few training sessions, whereas participants that did not receive sensory feedback did not benefit from simple repetitions of the task (Aschersleben, 2003). Studies have also shown that patients with complete loss of proprioceptive information below the neck can still synchronise finger taps with a metronome when visual and auditory feedback are provided (Stenneken et al., 2006), which indicates the crucial role of sensory information for timed movements.

Studies examining the effect of altered auditory feedback have also shed light on the interaction between feedback and timing. There is a long history of investigations on the impact of timing perturbations of feedback on tapping. These studies typically introduce time shifts between actions and the expected outcomes of those actions, and then analyze the effect of such manipulations on the timing of taps (Pfordresher, 2006; Repp, 2005; Repp & Su, 2013 for reviews). A number of studies demonstrated that disruptions to the timing of feedback significantly interact with timing mechanisms. In particular, immediately after a feedback perturbation, timing compensation is observed (Repp, 2000, 2005; Repp & Su, 2013; van der Steen & Keller, 2013). This automatic and pre-attentive process of phase correction indicates that the nervous system has developed mechanisms to continuously

compensate for timing perturbations (Mates & Aschersleben, 2000; Repp, 2005; Shadmehr, Smith & Krakauer, 2010).

This body of evidence demonstrates that the sensory feedback derived from movement (tactile, kinesthetic, auditory) greatly improves accuracy in sensorimotor synchronization tasks and that perturbations of the onset of the feedback significantly interferes with the timing of taps. A question that follows is whether perturbations in the *content* of feedback also interfere with timing mechanisms.

Feedback content and timing

The vast majority of research in the effect of altered pitch content of feedback to date has been based on the serial shift paradigm (Pfordresher, 2003; Pfordresher, 2006 for review). Serially shifted perturbations cause the feedback triggered by each tap to match a tone intended for a different sequence position so that a constant mismatch between planned action and expected outcome is introduced. Typically in this paradigm participants memorize a short melody and practice several times on the piano to guarantee accurate performance. On the experimental trial participants perform the standard melody while receiving an auditory feedback that does not match the keystrokes, rather the pitch presented is referring to the following note of the sequence (“hearing the future”) or a previous note of the sequence (“hearing the past”) (Pfordresher & Palmer, 2006). Findings suggest that alterations of feedback significantly disrupt performance by increasing error rates (i.e. striking a wrong key), however having little effect on timing variability. One critical aspect about this paradigm is that it focuses on a global internal representation of motor sequence structure (Pfordresher & Kulpa, 2011) rather than motor timing and local effect of perturbations. Moreover, serial shifts of auditory feedback do not correspond to real music performance situations.

To test whether feedback content (e.g. pitch, timbre, intensity) interacts with the representation of time, we propose a new paradigm. Firstly, we sought to isolate the effect of feedback content without manipulating the timing of feedback. That is, only nontemporal characteristics of the auditory feedback were manipulated, such as pitch height, intensity and timbre, while preserving the temporal relation between movement and auditory feedback. Additionally, to avoid confounding sequence planning and serial retrieval (Pfordresher & Kulpa, 2011; Furuya & Soechting, 2010) the paradigm did not use melodies. Instead, every tap triggered a “standard” feedback presented repeatedly in the tapping sequence, except for one unexpected change, the “oddball”. This protocol is based on the *oddball paradigm* widely used in evoked potential studies and target detection studies (Näätänen et al., 2007), hence I will use the same term to refer to unexpected changes in the content of feedback. The proposed protocol is closely related to real situations of music performance, as players often need to adapt rapidly to unexpected changes in pitch or intensity while maintaining the timing of the performance.

The series of experiments described in this chapter investigated whether unexpected changes of feedback content significantly interact with the timing of motor tapping. Support for this prediction can be found in recent studies showing that pitch contour and pitch distance in a melodic context significantly interact with timing in a tapping experiment (Ammirante & Thompson, 2010; Ammirante, Thompson & Russo, 2011). Models that assume that feedback from movement (tactile, kinesthetic, auditory) is integrated in a central representation of time, such as the internal forward model, (Mates & Aschersleben, 2000; Miall & Wolpert, 1996; Schubotz, 2007; Davidson & Wolpert, 2005; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010) also support the hypothesis that feedback content and timing should interact. Neuroscientific evidence for an interaction between auditory and premotor cortices also suggests sensorimotor interaction at neural level (Chen, Penhune &

Zatorre, 2009). On the other hand, a model based on the serial shift paradigm would predict that unexpected changes in feedback content should not interact with timing as it assumes that only timing perturbations should disrupt motor timing (Pfordresher, 2006; Pfordresher & Kulpa, 2011).

Experiment 1: Unexpected Pitch Changes

Experiment 1 investigated the hypothesis that unexpected transient perturbations of feedback content would interact with motor timing in tapping tasks. More specifically, this experiment tested whether unexpected pitch changes of 6, 13 or 23 semitones in an isochronous sequence would affect motor timing. The effect of local perturbation was analyzed by comparing the average intertap intervals (ITI) from the taps preceding the change with the ITIs immediately after.

It was predicted that that unexpected pitch changes would significantly affect timing of the intervals following the unexpected change. Confirmation of this prediction would corroborate models that assume integration between expected motor and perceptual outcomes (Mates & Aschersleben, 2000; Miall & Wolpert, 1996; Schubotz, 2007; Davidson & Wolpert, 2005). However, if content manipulations of auditory feedback were not to disturb tapping, showing that not all types of perturbations interfere with timing of motor actions, then, effects observed in the timing perturbation literature would show that the interaction between timing and feedback is specific, supporting models that assume some sort of dissociation between perceptual events and action (Pfordresher, 2006; Repp, 2000).

Methods

Participants

Thirty-six undergraduate students (25 females, 11 males) were recruited from the participant pool of students enrolled in an Introductory Psychology course at Macquarie University and received partial course credit for their participation. The average age was 21

years ($SD = 4.2$ – range 18 to 38), and participants had different levels of formal music training, ranging from 0 to 14 years ($M = 2.5$; $SD = 2.8$). Six participants reported being involved with musical activities for at least 2 hours weekly. None of the participants reported any form of hearing or motor impairment, and two had participated previously in a tapping experiment. The project was approved by the Macquarie University Human Research Ethics Committee. All participants gave informed consent and were debriefed about the goals of the experiment after their testing.

Materials and Equipment

Stimulus presentation and data storage were accomplished with Max/MSP/Jitter (Cycling '74, San Francisco, CA) and Matlab *R2011a* running on an Intel iMac computer. The tones were produced by a Roland RD-250s digital piano and were presented over Sennheiser HD 515 headphones at 74 dB SPL. A percussion pad Roland Handsonic HPD-10 was used for data collection (Figure 1). This device has been widely used in timing research and measures were adopted to guarantee precision in data collection (Sternad, Dean & Newell, 2000; Pecenka & Keller, 2011; Repp, London & Keller, 2005; Hove & Keller, 2010; Repp & Steinman, 2010).

Participants tapped with the index finger of their dominant hand on the lowest left key of the drum pad. To prevent fatigue, the wrist and forearm of participants' dominant hand were supported by a platform level with the drum pad keys.



Figure 1. Data collection device (percussion pad) and simulation of the experimental setup.

Stimuli and Procedure

The synchronization-continuation paradigm was adopted (Stevens, 1886). For each trial, participants first synchronised their taps with a pacing signal for 8 taps. The signal tones were 20 ms square waves clicks of 1000 Hz of frequency and 68dB. Participants tapped on the drum pad to start every trial and were instructed to begin to synchronise with the pacing signals at their discretion. In the synchronization phase taps did not trigger any auditory feedback and sound output of the percussion pad was not used. After 8 taps the pacing signal stopped and every tap triggered a feedback tone. Auditory feedbacks were provided directly through the computer and were not influenced by tapping force on drum pad. These feedback sounds were piano tones of 200 ms in duration and 261.63 Hz (C4), presented repeatedly in the continuation sequence except for one single feedback tone, the *oddball*. The continuation phase consisted of 20 taps and only one oddball per trial (Figure 2).

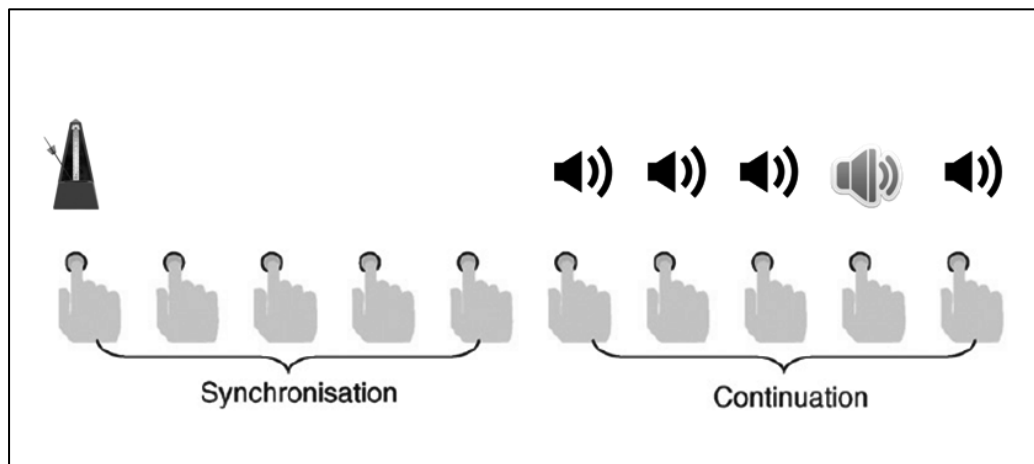


Figure 2. Diagram of the synchronization-continuation paradigm. Oddball feedback was introduced unexpectedly from positions 11th to 16th in the continuation phase of the task.

Participants were instructed to maintain the tempo set by the pacing signal to the best of their abilities until the end of the trial and to ignore any changes in the pitch of the feedback tones. To maintain task vigilance, after each trial, participants were presented with the standard deviation of the continuation phase inter-tap intervals (ITIs) and instructed to try to achieve as low a score as possible on the next trial. To make sure that participants would attend to the feedback tones, at the end of every trial participants had to inform if they heard any difference in the feedback tones by selecting 1 of 3 options (“Higher”, “Lower”, “Did not occur”).

Oddball tones were manipulated between trials regarding pitch distance, direction, target position and initial tempo. Stimuli had the same characteristics in duration, intensity, across all conditions, with the exception of frequency. There were 3 pitch distances: 6, 13 and 23 semitones and they could be presented either above or below the reference tone (Up, Down). These pitch distances correspond to dissonant tones, and they were chosen in order to guarantee that the oddballs were noticeable and evident, and also to prevent any confounding tonal reference. To avoid habituation with the location of the oddball presentation, the

incongruent feedback tone was equally likely to occur in between the 11th and 16th tones of the continuation phase. Finally, there were 3 different initial tempi: fast (380 ms), medium (600 ms) and slow (820 ms). In addition to these manipulations there were monotone (control) trials equally likely to occur (Figure 3).

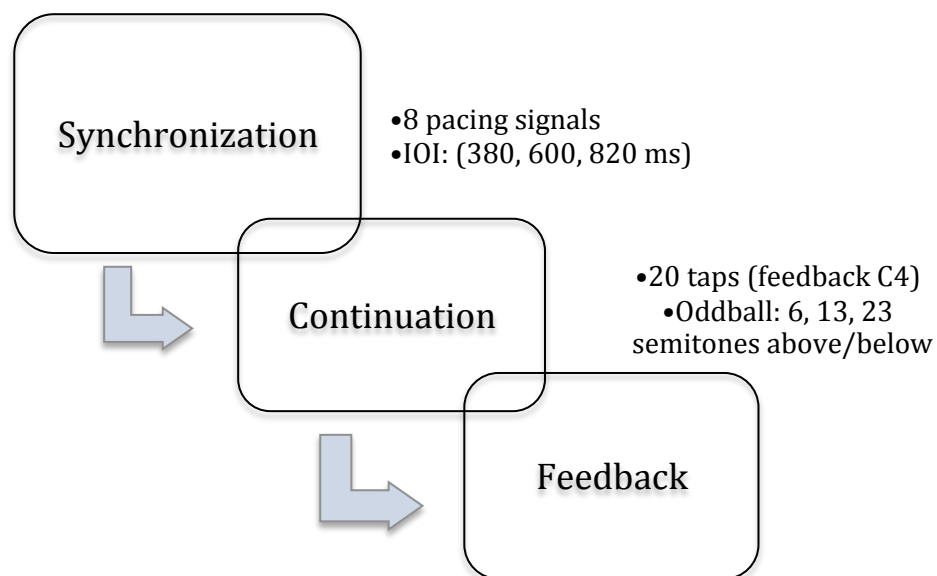


Figure 3. Scheme of trial sequence.

Participants had 6 practice trials (2 of each IOI, with standard auditory feedback) followed by 3 blocks in the testing phase. Trials were blocked by IOI where the order of presentation was counterbalanced and the oddball presentation was randomized between trials. Each condition was repeated 5 times consisting of 42 trials per block, 126 trials in total. Trials where ITIs were above or below 60% of the mean ITI for the trial were discarded and re-done immediately. With breaks offered between blocks, the task took approximately 1 hour.

Data Analysis

Taps in the synchronization phase were used for the purpose of ensuring that tempo was consistent between participants. Therefore, only taps in the continuation-phase were analyzed. It is well established that accelerations commonly occur at the transition between synchronization and continuation phases (Flach, 2005). Thus, the first 5 taps in the continuation phase were discarded and the final 15 taps were subjected to analysis.

ITIs were defined as the time difference between MIDI “note on” events in milliseconds captured by the drum pad. Tap Velocity (TV) is a measure of force applied for each tapping in MIDI units. To evaluate general interference effects of oddballs on timing we analyzed participant’s coefficient of variation (CV), which was defined as the standard deviation of ITIs within a trial divided by its mean ITI (SD/Mean). The average coefficient of variation was calculated across all trials for each condition and individual. This measure provides information about the combination of all sources of variability, such as long-term drift through the trial. No further treatment was applied in the time series responses.

To allow comparisons among the conditions that presented different IOI, a normalized measure was adopted by calculating the ratio between successive ITIs according to the formula ITI_n/ITI_{n-1} . Thus, an ITI ratio of less than one would mean that the current ITI (i.e., ITI_n) is shorter than the previous one (i.e., ITI_{n-1}), a ratio of 1 would mean the current ITI is exactly the same as previous, and a ratio greater than 1 would mean the current ITI is longer than the previous one (Repp, 2000; Ammirante & Thompson, 2010). The same was done for Tap Velocity data.

The analysis focused on 3 ITIs before and 3 ITIs after the oddball presentation. Initial analysis indicated that there was not a significant difference among the three intervals before the oddball. Therefore, for each trial an average of 3 ITIs ratio preceding the oddball was calculated and labeled as $ITIp$ (where $P = pre-oddball$). The following ITIs were coded O,

O+1, O+2 (where O = oddball). For the purpose of illustration, target ITIs were aligned and average across positions. These values were average across trials for each participant and for each condition and subjected to repeated-measures ANOVA with 5 factors: pitch distance (6, 13, 23 semitones), direction (up, down), sequence position (P, O, O+1, O+2), target position (11, 12, 13, 14, 15, 16) and IOI (380, 600, 820 ms). The Greenhouse-Geisser correction was applied to p values where appropriate.

Results

Experiment 1 tested the hypothesis that pitch changes would interact with the timing of motor actions in a tapping task. For that purpose, one auditory feedback tone in the continuation phase was unexpectedly changed in pitch. The distance and direction of this pitch change, as well as the position at which the change occurred, varied.

Mean ITI ratio values according to pitch distance, direction, sequence position, target position and IOI were entered into a $3 \times 2 \times 4 \times 6 \times 3$ repeated-measures ANOVA. Given that there was no global effect of target position, $F(5, 175) = 1.00, p = .40$, data were reanalyzed now using only 4 factors: pitch distance, direction, sequence position and IOI.

Results revealed a main effect of Sequence Position, $F(3, 105) = 9.84, p < .0005$. Further analysis determined that the ITI following the oddball presentation was significantly shorter than all the other positions analyzed, which suggests that participants tended to accelerate the following tap in response to the unexpected change (Figure 4).

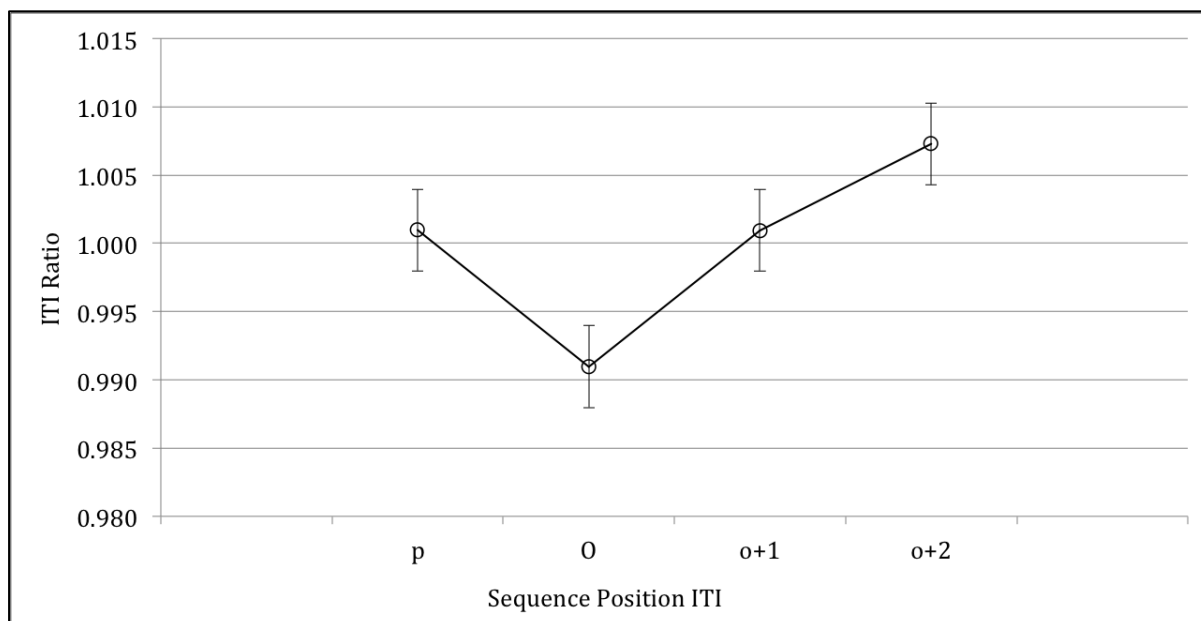


Figure 4. Main effect of Sequence Position on Experiment 1. ITI ratio of less than 1 indicates that the current ITI is shorter than previous ITI. Error bars are standard errors.

P (pre-oddball ITI), O (ITI immediately after oddball), O+1 O+2 (ITI following oddball).

Repeated-measures ANOVA comparing conditions with and without Pitch Change (2) and Sequence Position (4) indicated that the unexpected pitch change had a significant impact on timing, as indicated by a significant interaction of Pitch Change and Sequence Position, $F(1, 430) = 4.83, p = .02$. Further comparisons between Sequence Position and Pitch Change revealed that the only significant difference between control and pitch change conditions was evident at ITI₀, $F(1, 430) = 6.35, p = .01$. No reliable differences were observed at the other sequence positions analyzed. To further investigate the effect of each pitch distances manipulated, pairwise comparisons among 6, 13 and 23 semitones changes at oddball position indicated that there were no differences among the pitch distances in this experiment, which suggests that all manipulations had similar effects on timing (Figure 5).

Using a significance level set at 0.01 to correct for multiple comparisons (Zelaznik & Rosenbaum, 2010), the ITI for the control condition was compared with the ITI for all pitch

distances. This analysis revealed a significant difference at the oddball position between the control condition and the 6-semitone oddball, $t(214) = 2.37, p = .01$, and between the control condition and the 13-semitone oddball, $t(214) = 2.31, p = .02$. Surprisingly, there was no significant difference in ITO between the control condition and the 23-semitone oddball ($p = .16$).

Analysis of the effect of Pitch Direction on Sequence Position indicated that there was no significant difference between changes upwards or downwards at the oddball position ($p = .79$), and the interaction between Direction and Sequence Position was also not significant, $F(3, 105) = 1.45, p = .24$.

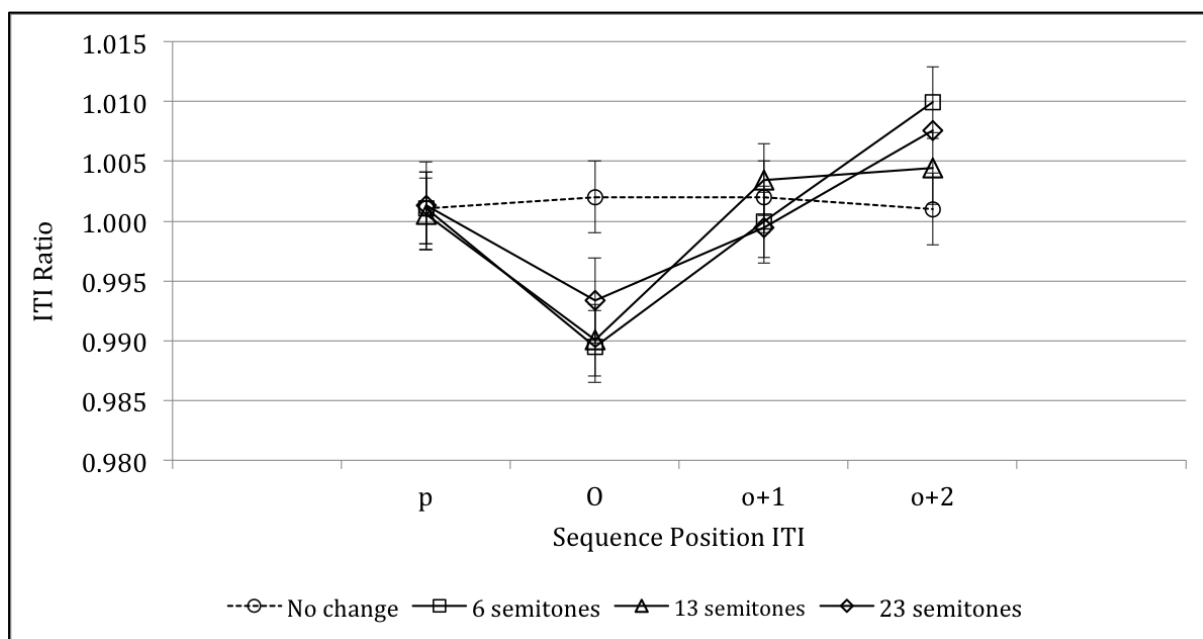


Figure 5. Main effect of Pitch Distance: 6, 13 and 23 semitones.

Analyses of the effect of the oddball for three different tempi revealed a significant main effect of tempo, $F(2, 70) = 4.22, p = .01$. Although the interaction between IOI and Sequence Position did not reach significance, $F(6, 210) = 1.95, p = .07$, pairwise tests indicated that at the oddball position (ITIo) the effect of Sequence Position at the slow tempo

was significantly different from medium tempo $t(286) = 2.18, p = .02$, but no difference was found between the medium and fast tempi $t(286) = .50, p = .61$. Furthermore, one-way ANOVA comparing all conditions with and without pitch changes (4) at slow IOI indicated that there was no statistical difference among the pitch conditions at slow tempo, $F(3,140) = 1.61, p = .19$, whereas a significant effect was observed at fast and medium tempi, $F(3, 284) = 3.72, p = .01$, suggesting that pitch changes did not elicit an effect on timing at slow tempo (Figure 6).

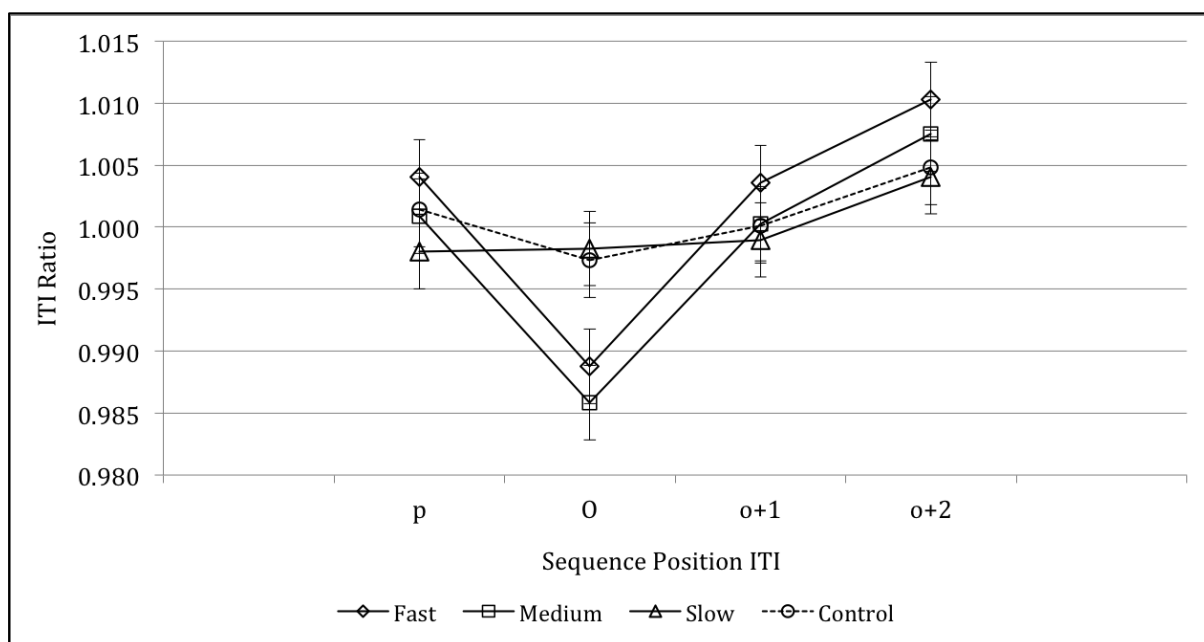


Figure 6. Main effect of the IOI. Mean ITI at Fast (380 ms), Medium (600 ms) and Slow (800 ms). Control represents conditions where there was no pitch change.

Variability

To evaluate interference effects of oddballs on timing, the participant's coefficient of variation (CV) was analysed. Each participant's CV values were averaged across trials for each condition and subjected to a repeated-measures analysis (ANOVA) with 4 factors (pitch distance, direction, sequence position, IOI) and years of training as a continuous between-

subjects covariate. There was a significant main effect of Sequence Position, $F(3, 102) = 4.19$, $p = .01$, and post hoc analysis suggested an increase in variability after the oddball presentation as the ITI following the oddball presentation (O+2) was significantly more variable than ITI at oddball position ($p = .002$). There was no evidence that this variability is dependent on musical training given that the interaction between Sequence Position x Training was not statistically significant ($F < 1$).

Tap Velocity (TV)

Mean Tap Velocity (TV) ratio values according to pitch distance, direction, sequence position, IOI, were entered into a 3 x 2 x 4 x 3 repeated-measures ANOVA. A main effect of sequence position was significant, $F(3, 105) = 8.65$, $p = .001$, and pairwise comparisons confirmed that TV was significantly faster at the oddball position compared with the sequence positions after pitch changes (O+1 $p = .02$; O+2 $p < .005$ respectively). The consistency between TV and ITI results indicate that once participants heard the unexpected tone, they tapped faster and therefore reached the key bed sooner.

Discussion

Experiment 1 tested the hypothesis that unexpected pitch changes interact with timing of motor actions in a tapping task. Results revealed a significant main effect of feedback content perturbation on the ITI immediately after the oddball presentation. Participants tended to speed up, thus shortening the ITI following the perturbation. This finding provides evidence that transient perturbation in the content of the auditory feedback interferes with timing in motor actions.

Importantly, there were no significant differences among the pitch distances investigated given that results demonstrated that all perturbations elicited similar effect trends on timing. Similarly, there was no significant difference of the direction of the change,

suggesting that regardless of the size or direction of the perturbation, ITI was similarly disrupted by the perturbation.

Interestingly, the effect of the perturbation was significantly reduced at the slower IOI (820 ms) in comparison to the medium and fast tempi. Participants were instructed to ignore any changes on the feedback tones and try to be as precise as possible, thus the reduction of interaction in this case may be a result of voluntary control. Similar results were found in studies examining the effect of timing perturbations. It was observed that phase correction was greatly reduced and even completely suppress at slow tempo when participants were instructed to ignore the perturbations and avoid reacting to them (Repp & Keller, 2004; Repp, 2009; Repp & Moseley, 2012).

It was also found that perturbations affected tap velocity, suggesting that unexpected changes also influenced tap trajectory by accelerating the velocity in which taps reached the key bed. This result is corroborated by recent findings that showed changes in tap velocity as result of pitch contour change (Ammirante & Thompson, 2010). Furuya & Soechting (2010) also found that keystrokes velocity in a piano performance was greatly affected by perturbations in timing, pitch and intensity. These authors also described that altering feedback in a melody played with the right hand also affected timing and velocity of keystrokes with the left hand, suggesting an integrated processing of sensory information and timing in bimanual tasks.

Taken together, the results support the hypothesis that unexpected changes in feedback content significantly interact with timing of motor timing. Data suggested that unexpected changes elicited a rapid compensatory mechanism as the interval immediately after the perturbation was shorter than adjacent taps, and it seems that the amount of compensation was not impacted by pitch distance or direction of the perturbation.

There are several possible interpretations of the results, and further research is needed to narrow down the possible mechanisms responsible for the observed effects. For instance, these findings raise the question of whether results would be replicated with smaller pitch perturbations. Pitch distances presented in the present experiment were intentionally dissonant and on a great pitch range to guarantee that participants would note the perturbations. On the other hand, it could be argued that these pitch changes would not reflect transient perturbations commonly observed in a real performance situation. Therefore, Experiment 2 tested whether pitch changes as small as 1 semitone and constrained to 1 octave would also affect timing of tapping. It was also tested whether pitch perturbations would similarly affect musicians and nonmusicians. If musicians and nonmusicians were similarly affected by pitch perturbations, results may suggest that the mechanism underlying the effect does not depend on extensive training, thus indicating that more fundamental processes are at play.

Experiment 2: Unexpected Small Pitch Changes

Experiment 2 aimed to expand results of the previous experiment by examining whether pitch changes ranging from 1 to 12 semitones disrupt the timing of motor actions. In addition, the effect of pitch perturbations was compared between musicians and nonmusicians to verify whether musical training interacts with the oddball effect.

Previous studies have shown that melodic contour change with great pitch distances elicited faster ITI and tap velocity, whereas pitch contour that implied negative accelerations induced slower tapping intervals, suggesting that there may be a fine tune between auditory feedback and timing (Ammirante, Thompson & Russo, 2011; Ammirante & Thompson, 2010). Perceptual studies also demonstrated similar illusions as findings suggested that a melody containing fewer contour changes is judged as faster than target, even when sequences were isochronous (Boltz, 1998). Based on these findings it would be expected that

greater pitch distances (23 semitones) would elicit faster ITI following the perturbation. However, results in Experiment 1 did not reveal differences in tapping intervals and velocity related to the amount or direction of the change, perhaps because the pitch distances applied did not induce a sense of melodic contour. Thus, this experiment applied pitch changes smaller than 1 octave to investigate whether pitch distance could be linked with timing and movement trajectory.

It is possible that musical training affects the amount of timing disruption elicited by unexpected perturbations on feedback. Research thus far has shown that the effect of unexpected perturbations on timing does not differ from musicians and nonmusicians (Ammirante, Thompson & Russo, 2011; Pfordresher, 2006), suggesting that the connection between timing and feedback does not depend on training but may be inherent to the system's operation. This hypothesis is further tested in this experiment.

It was predicted that unexpected perturbations of feedback content would significantly interact with timing of tapping. Confirmation of this prediction would provide further evidence for a link between feedback content and timing. However, if predictions were not confirmed, results may indicate that the effect observed on Experiment 1 was due to the introduction of a surprisingly discrepant auditory feedback, thus suggesting an arousal effect.

Methods

Participants

Twenty-five nonmusicians (17 females, 8 males) and 13 musicians (11 females, 2 males) were recruited from the departments of Psychology and Music at Macquarie University and local universities at Sydney/Australia. Macquarie University undergraduates received partial course credit and all other participants received financial compensation for their participation. Nonmusicians average age was 21.3 years ($SD = 6.6$ – range 18 to 43), and had no musical training ($M = 0.2$ years, $SD = 0.5$). Musicians group average age was 29.2

years ($SD = 17.9$ – range 18 to 65), and participants had a minimum of 10 years of formal musical training with many of them being professional musicians with an extended career in teaching or performance ($M = 19.3$ years, $SD = 14.2$). None of the participants reported any form of hearing or motor impairment, and one had participated previously in a tapping experiment. All participants gave informed consent.

Materials and Equipment

The materials and apparatus were identical to those described for Experiment 1.

Stimuli and Procedure

The stimuli and procedure were similar to that described for Experiment 1. Participants were instructed to synchronise their taps with a pacing signal (metronome) at 600 ms IOI for 8 taps, and then maintain the tempo in the absence of a pacing signal to the best of their abilities on the following 30 taps. In the continuation phase, every tap triggered a feedback tone, which was a piano tone of 261.63 Hz (C4) presented repeatedly, except for one single feedback tone, the *oddball*.

The pitch distance of oddball tones was manipulated¹, and included 8 distances: 1, 2, 3, 4, 5, 6, 7, 8 and 12 semitones higher than the standard tone (C4). An equal number of monotone trials were included to ensure that oddballs were unexpected.

Oddball presentation was randomized between trials and each condition was repeated 12 times, consisting of 108 trials per participant. Trials for which ITIs were above or below 60% of the mean ITI for that trial were discarded and repeated immediately. Participants had 3 practice trials with standard auditory feedback tones before the testing phase and, with breaks, the task took approximately 1 hour.

Data Analysis

¹ Target position was also manipulated between the 10th and 15th tones of the continuation phase to avoid habituation, but initial analysis indicated no effect of the position in which the oddball was presented in the sequence.

Only taps in the continuation phase were subjected to analysis and the variables of interest were Intertap Interval (ITI ms^2), Coefficient of Variation and Tap Velocity. As in the first experiment, the analysis focused on 3 ITIs before and 3 ITIs after the oddball presentation. For each trial an average of 3 ITIs preceding the oddball was calculated and labeled as ITIp and the following ITIs were coded following procedures described in Experiment 1. ITI values were average across trials for each participant and for each condition and subjected to repeated-measures ANOVA with 2 factors: pitch distance (9) and sequence position (4) and music training as a continuous between-subjects covariate. The Greenhouse-Geisser correction was applied to p values where appropriate.

Results

This experiment tested the hypothesis that small pitch changes, ranging from 1 to 12 semitones, would significantly affect timing of intertap intervals in an isochronous sequence comparing the performance of musicians and nonmusicians. To initially determine if pitch changes would generally interact with timing, a first analysis comparing mean ITI (ms) values according to pitch distance (control, small pitch intervals, large pitch intervals) and sequence position (p, O, O+1, O+2) were subject to a repeated-measures ANOVA. Small pitch changes ranged from 1 to 4 semitones, and large pitch perturbations were arbitrarily grouped from 5 to 12 semitones. Music training was included as a continuous between-subjects covariate.

Results indicated a main effect of Sequence Position, $F(3, 108) = 12.96, p < .005$. Pairwise comparisons among all four Sequence Positions indicated that the ITI immediately after the oddball was significantly shorter than the previous and following intervals ($p < .005$, $p = .001$, respectively), but was not significantly different from ITIO+2 ($p = .32$).

² Given that stimuli were presented at a fixed IOI (600 ms), data analysis focused primarily on absolute measures of intertap interval in milliseconds.

It was also shown that there was a main effect of Pitch Changes ($F(2, 72) = 4.11, p = .03$). Although the interaction between Pitch Change and Sequence Position did not reach significance ($p = .24$), pairwise comparison analysis indicated that under control conditions there were no difference among ITIs for all positions analyzed. On the other hand, small and large pitch changes did affect sequence position, with the ITI immediately after oddball presentation (ITI_o) significantly different from the ITI pre-oddball and O+1. This suggests that not only large pitch changes but also pitch perturbations smaller than 5 semitones also affected timing of tapping (Figure 7).

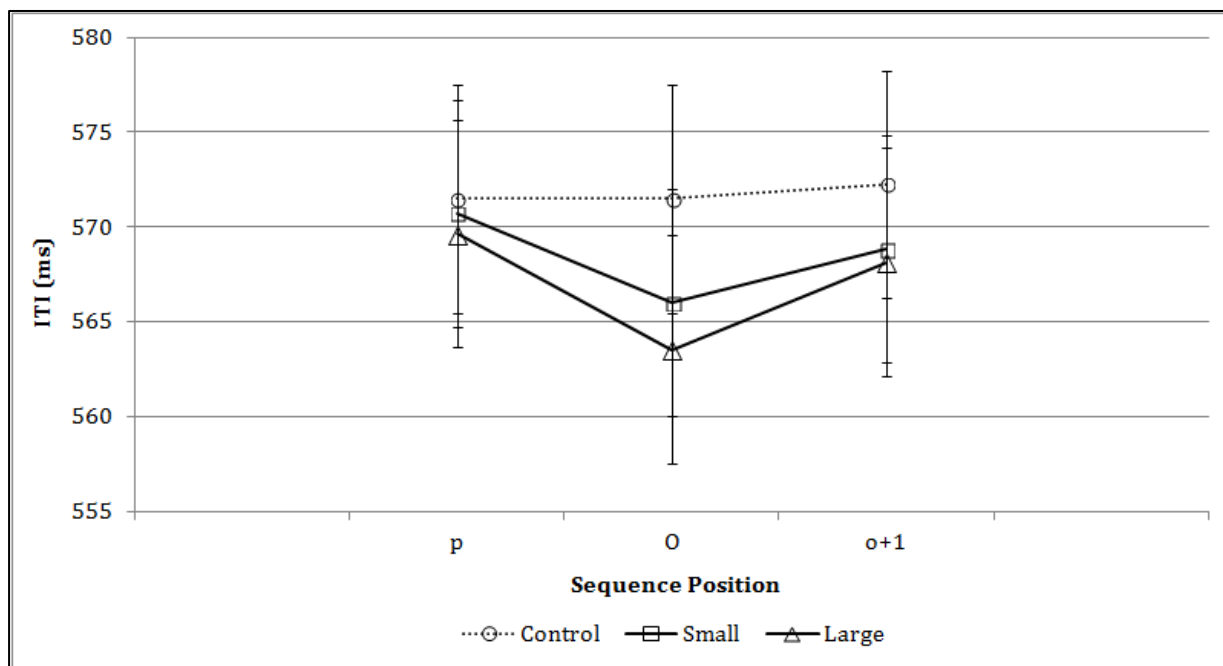


Figure 7. Main effect of Pitch Changes. Small pitch changes comprise 1 to 4 semitones, whereas large included 5 to 12 semitones.

To further examine the unique effect of each pitch perturbation, a repeated-measures ANOVA was conducted comparing all Pitch Changes, including control (9) and Sequence Position (3). Since previous results indicated that ITI at oddball position did not significantly

differ from position O+2, we focused on the previous and following intervals for this analysis. Results confirmed the main effect of Pitch Change, ($F(8, 288) = 2.68, p = .04$) and pairwise comparisons revealed that at the oddball position (ITIo), the vast majority of pitch perturbations elicited significant disruption on timing when compared to previous and/or the following tap interval. No change on the timing series was noted in the control condition, as expected, but also for the 5 semitones change ($p = .15, p = .59$, respectively).

Interestingly, no interactions with music training reached significance, suggesting that the effect of oddball was similar between the musicians and nonmusicians group. Between subject analysis showed that indeed musicians ($M = 581, SD = 9.9$) tended to keep the time established by the metronome more precisely than nonmusicians ($M = 554, SD = 7.1$), $F(1, 36) = 4.69, p = .03$, however, unexpected pitch changes disrupted timing of tapping similarly in both groups.

The observation that the ITIo was significantly different from the preceding and following intervals but not significantly different from position O+2 raised the question of whether the effect caused by the unexpected changes persisted over the course of the trial perhaps by disrupting the period established by the metronome. To investigate this issue, repeated-measures ANOVA was conducted examining the effect on 10 intervals after the oddball perturbation (Figure 8). Taking in consideration the well-documented observation that intervals tend to shorten due to the tendency to speed up along the trial, difference scores ($ITI_n - ITI_{n-1}$) were used to minimize the effects of outliers or long-term drifts variability (Pfordresher & Dalla Bella, 2011; Ammirante & Thompson, 2012). For this relative measure, ITI difference scores of less than zero would mean that the current ITI (i.e., ITI_n) is shorter than the previous one (i.e., ITI_{n-1}), a score of zero would mean the current ITI is exactly the same as the previous one, and a score above zero would mean that the current ITI is longer than the previous. As illustrated in Figure 8, the effect of the oddball did not alter the average

period of the intertap intervals over the course of the trial, suggesting that the effect of the unexpected change is local and not global. Taking as reference the position before the perturbation, pairwise comparisons indicated that the oddball significantly affected the 3 intervals after the perturbation (ITIO to ITIO+2), but positions o+3 and o+4 did not differ from the interval preceding the oddball ($p = .89$, $p = .12$, respectively), which suggests that the perturbation on timing was quickly readjusted after a few taps.

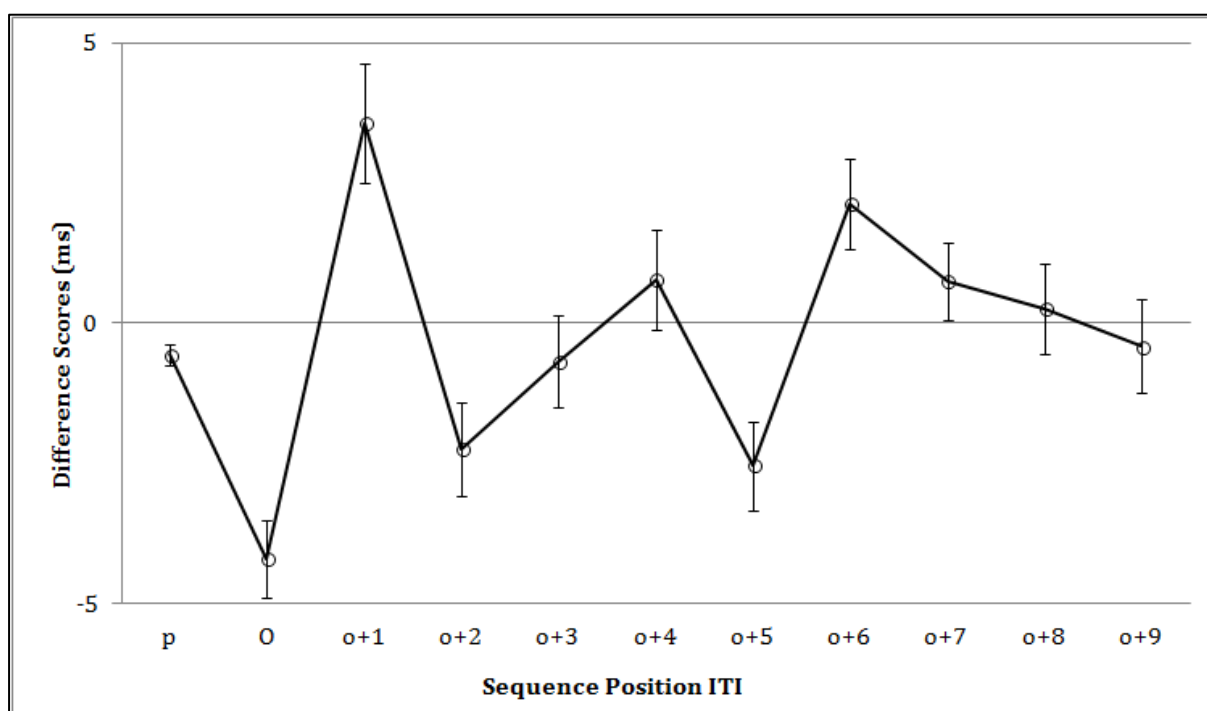


Figure 8. ITI difference scores (ms) of ten intervals after the oddball perturbation.

Variability

Each participant's CV values were averaged across trials for each condition and subjected to repeated-measures ANOVA with Pitch Change (8) and Sequence Position (4) as factors and music training as a continuous between-subjects covariate. Results indicated that variability was not significantly affected by the oddball given that none of the factors reached significance (main effect of Sequence Position, $F(3, 108) = .53$, $p = .65$). The interaction of

Sequence Position x Music Training was also not significant ($F = .09, p = .88$). This result indicates that participants were precise in their tapping despite timing disruption at the oddball position induced by the unexpected event.

Between subject analysis revealed that overall musicians tended to be significantly more accurate than nonmusicians in maintaining the tempo set by the metronome, $F(1, 36) = 17.62, p < .005$. However, since none of the interactions tested reached statistical significance, results indicate that the effect of the oddball on timing was not significantly different between groups.

Tap Velocity (TV)

Mean TV scores according to Pitch Change (1-8, 12 semitones) and Sequence Position (P, O, O+1, O+2) were entered into a repeated-measures ANOVA. Results indicated that, although a main effect of Sequence Position did not reach significance, $F(3, 22) = 1.96, p = .14$, pairwise comparisons analysis informed that TV at oddball position was significantly different from the previous and following intervals ($p = .04$), suggesting that participants tapped slightly slower at the interval immediately following oddball presentation. This finding indicates that oddball perturbation not only affected timing of tapping but also the trajectory of the movement.

Discussion

Experiment 2 tested the hypothesis that unexpected pitch changes ranging from 1 to 12 semitones interact with the timing of motor actions, and whether musical training interacts with this effect. As predicted, results demonstrated that small unexpected pitch changes significantly interacted with the timing of finger tapping, as participants tended to shorten the timing interval immediately after oddball presentation.

There was no significant effect for small pitch changes (1 to 4 semitones) when compared to larger perturbations in pitch distance (5 to 12 semitones), which favors the

hypothesis that feedback content interacts with motor timing, even for small changes in pitch. Moreover, these results indicate that the degree of perturbation did not influence the degree of timing disturbance, as observed in Experiment 1. That is, larger changes in pitch did not elicit stronger effects on timing than smaller changes in pitch, suggesting that the degree of pitch change is not related to the magnitude of the observed timing effects. This result is contrary to results obtained by Ammirante et al. (2010, 2011), who reported that ITI and TV mirrored implied tonal acceleration in melodies (Ammirante, Thompson & Russo, 2011; Ammirante & Thompson, 2010). Results described in Experiment 1 and 2 did not reveal differences in tapping intervals and velocity related to the size or direction of the pitch change. This perhaps is because the pitch sequence used in our experiments did not induce a sense of melodic contour, which could be explored in future studies.

It was also observed that the effect of the perturbation did not affect overall timing and accuracy over the course of the trial, as disruption in the timing of intervals was quickly recovered after 3-4 taps, thus being restricted to a local perturbation. Interestingly, the effect of pitch perturbation did not differ between musicians and nonmusicians. Similar results were obtained in behavioral studies (Ammirante, Thompson & Russo, 2011; Pfordresher, 2006) and neurophysiological experiments (Tervaniemi et al., 2006). Tervaniemi and colleagues found that mismatch negativity potentials (which are event-related brain potentials elicited by stimuli that do not match the predictable pattern elicited by regular event whether or not attention is engaged) did not differ between musicians and nonmusicians, suggesting that expertise may play an important role when attention and discrimination are required but not necessarily at pre-attentive levels (Tervaniemi et al., 2006). This evidence reinforces the suggestion that the connection between timing and feedback does not depend on training to be established but may be inherent to the system's operation. Taken together, the findings thus far suggest that unexpected changes in pitch elicit timing disruptions, regardless of pitch

distance and direction, and that the effect of unexpected changes did not differ between musicians and nonmusicians.

An important question is whether such timing effects are unique to pitch changes or whether other unexpected content changes might interact with motor timing. In other words, it is possible that any change in the content of feedback might interact with timing. To test this possibility, Experiment 3 repeated the basic conditions of Experiments 1 and 2 but introduced changes in timbre rather than changes in pitch. Based on the hypothesis that expectancy and timing are tightly linked, it was expected that timbre changes interact with timing, as was the case for pitch changes. Such an outcome would be consistent with the hypothesis that any unexpected changes of feedback content will interact with timing mechanisms. However, if this prediction failed to be confirmed, perhaps pitch is integrated in motor planning in specific ways (Aschersleben, 2000).

Experiment 3: Unexpected Pitch and Timbre Changes

Experiments 3 further examined the hypothesis that transient manipulations of auditory feedback content disrupt timing of motor actions by modifying a second attribute, timbre. Timbre can be defined as the attribute that allows discrimination between sounds that are equivalent in pitch, duration and intensity and that are often generated by different instruments (Thompson, 2010). Pitch and timbre, although perceptually integrated in some degree, can be defined and manipulated independently (Krumhansl & Iverson, 1992). To avoid confounding variables such as arousal, timbre manipulations were restricted to instruments with similar sound envelopes, such as harp and organ, which would guarantee that the effect observed is not related to a completely dissociated event.

It was predicted that unexpected changes of timbre would significantly interact with timing. Confirmation of this prediction would reaffirm suppositions that the effect of content

perturbations interacts with timing. However, if this prediction were not confirmed, findings would suggest a unique interaction between pitch and timing.

Methods

Participants

Thirty-two undergraduate students (25 females, 7 males) were recruited from the departments of Psychology and Music at Macquarie University and local universities at Sydney/Australia. Macquarie University undergraduates received partial course credit and all other participants received financial compensation for their participation. Their average age was 25.1 years ($SD = 10.0$, range 18 – 36), and the number of years of formal music training ranged from 0 to 15 years ($M = 5.5$; $SD = 5.2$). None of the participants reported any form of hearing or motor impairment, and one had participated previously in a tapping experiment. All participants gave informed consent.

Materials, Equipment, Stimuli and Procedures

The apparatus and procedures used in this experiment follow the same protocol as established in Experiment 1, except for the feedback tones in the continuation phase. For each trial, participants first synchronised their taps with a pacing signal for 8 taps. The signal tones were 20 ms square waves clicks of 1000 Hz of frequency presented at a fixed IOI of 380 ms. No auditory feedback was provided during synchronization phase. In the continuation phase, every tap triggered a feedback tone. To prevent habituation to the feedback tones, there were 5 initial tones presented in the continuation phase, which were B \flat 3, B3, C4, C#4 and D4. Every initial tone was equally likely to occur. Feedback tones were presented repeatedly in the continuation sequence except for one single incongruent feedback tone, the *oddball*. The continuation phase consisted of 20 additional taps and only one oddball per trial.

Oddball tones were manipulated in between trials regarding pitch distance, timbre (target position was manipulated for the sake of habituation, but not analyzed). Oddballs were 6 semitones higher than the original feedback tones and there were also monotone (control) trials. Therefore, pitch change was considered a two-level variable (pitch change vs. no pitch change). The timbre of the oddballs was also modified. In addition to piano timbre that was presented repeatedly in the sequence, there were also harp and organ tones presented only at the oddball position. The envelope onset and offset, and intensity for all stimuli were controlled (200 ms in duration, 74 dB). Oddballs were equally likely to occur in the 10th, 12th or 14th tones of the continuation sequence. All trials were presented at a fixed IOI of 380 ms.

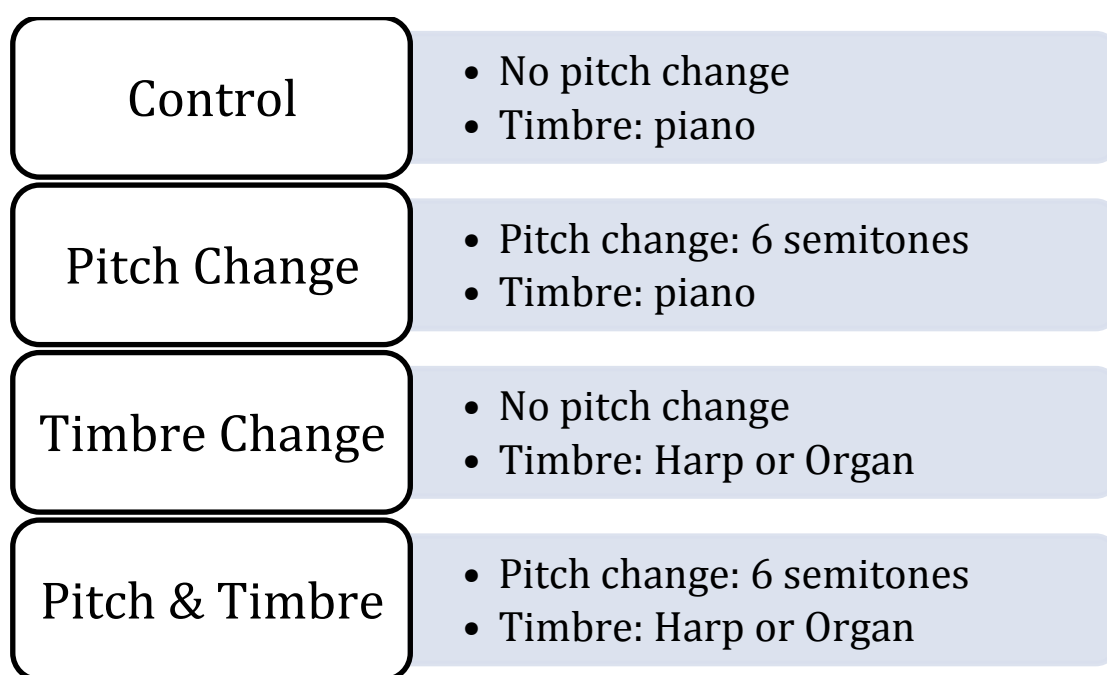


Figure 9. Conditions in Experiment 3.

Participants were instructed to maintain the tempo set by the pacing signal to the best of their abilities until the end of the trial and to ignore any changes in the feedback tones. At the end of each trial participants were given a feedback of their performance by presenting

the standard deviation of the continuation phase inter-tap intervals (ITIs) and a question where they had to indicate if they heard any difference in the feedback tones by selecting 1 of 3 options (Yes, No, Did not occur).

Participants had 3 practice trials without feedback perturbations, followed by the testing phase. Each condition was randomly presented and repeated 15 times, consisting of a total of 90 trials. Trials where ITIs were above or below 60% of the mean ITI for the trial were discarded and re-done immediately. With breaks offered regularly, the task took approximately 40 minutes.

Data Analysis

Continuation-phase taps were subjected to analysis as in Experiment 2. The variables of interest were ITI (ms), Coefficient of Variability and Tap Velocity. ITI values were average across initial pitch and target position for each participant and condition, and subjected to repeated-measures ANOVA with 3 factors: Pitch change (0, 6), Timbre (piano, harp, organ), and Sequence Position (P, O, O+1, O+2). The Greenhouse-Geisser correction was applied to p values where appropriate.

Results

Mean ITI (ms) as a function of Pitch Change (2), Timbre (3) and Sequence Position (4) were entered into a repeated-measures ANOVA. Results indicated that there was a significant main effect of Sequence Position, $F(3, 93) = 13.96, p < .0005$. Post hoc analysis comparing the effect in between sequence positions confirmed that the ITI immediately after the oddball is significantly different from the preceding and from the following one ($ITIo < ITIp$; $ITIo < ITIO+1, p < .0005$), but did not differ from position O+2 ($p = .13$).

For pitch change, there was a significant interaction between Pitch Change and Sequence Position, $F(3, 93) = 6.28, p = .002$. Pairwise comparisons analysis indicated that

the ITI at oddball position was significantly different between control condition and pitch change condition, $F(1, 31) = 11.62, p = .002$ (Figure 10).

For timbre, there was significant interaction between Timbre and Sequence Position is significant ($F(6, 186) = 2.68, p = .04$), and further pairwise comparisons analysis revealed that there was a significant difference between the control condition and timbre condition at oddball position (ITI_o/harp < ITI_o/piano, $p = .001$; ITI_o/organ < ITI_o/piano, $p = .002$). Recall that the repeated tones in the continuation phase were piano tones, therefore, the discrepant timbres were only harp and organ and the piano condition was used as control. Interesting to notice however, was that there was no difference between the effect of timbre change to harp or organ timbre at oddball position (harp = organ, $p = .14$). This result suggests that an unexpected change of timbre also affected timing significantly, regardless of the instrument.

Furthermore, there was also a significant interaction of Timbre x Pitch x Sequence Position, $F(6, 186) = 3.45, p = .01$. As shown in Figure 8, there was not a significant different in effect size among the conditions tested. Multiple comparisons analysis indicated that unexpected perturbations of timbre, pitch or both combined, affected timing intervals similarly (pitch change = timbre&pitch, $p = .65$; timbre&pitch = timbre only, $p = .47$; pitch change = timbre change, $p = .52$). This result suggests that there was not an additive effect of combined features (pitch&timbre) on timing.

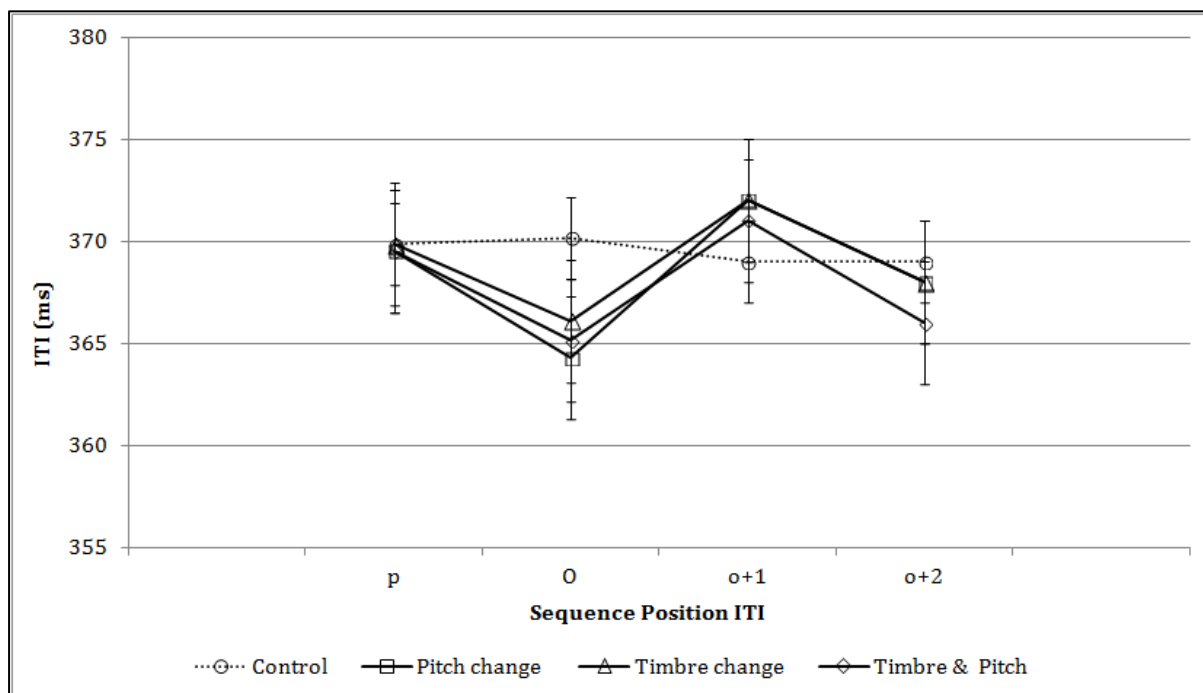


Figure 10. Main effect of Pitch, Instrument and Sequence Position.

Variability

Each participant's CV values were averaged across trials for each condition and subjected to repeated-measures ANOVA with 3 factors (pitch change, timbre, sequence position) and years of training as a continuous between-subjects covariate. Results showed that variability was not significantly affected by the oddball given that none of the factors reached significance (main effect of Sequence Position, $F(3, 57) = .86, p = .96$). The interaction of Sequence Position x Training was not significant either ($F = .78, p = .77$). This result indicates that participants were precise on their tapping despite evident timing disruption at the oddball position induced by the unexpected event.

Tap Velocity (TV)

Mean TV scores according to Pitch Change (2), Timbre (3) and Sequence Position (4) were entered into a repeated-measures ANOVA. A main effect of Sequence Position was significant, $F(3, 93) = 5.62, p = .006$, and pairwise comparisons analysis informed that TV

at oddball position was significantly different from previous interval ($p = < .005$). None of the other conditions evaluated reached significance.

Discussion

Findings confirmed the predictions and revealed a significant effect of unexpected timbre change on timing. ITI immediately after the perturbation was significantly shorter than adjacent intervals as participants tended to speed up after the oddball presentation. These results confirm and expand what was observed in Exp. 1 and 2 as pitch and timbre changes disrupted timing of tapping.

These observations favor the hypothesis that perturbations in the content of auditory feedback can interact with timing in tapping tasks, not only pitch changes. Interestingly, there were no differences between the timbres manipulated in these experiment (harp and organ), which indicated that the stimuli were well controlled and that both timbre manipulations induced similar patterns of disruption on timing. Moreover, there were no differences among the conditions (pitch, timbre, pitch/timbre), which indicated that there was no additive effect generated by the manipulations of two combined attributes. Again, evidence suggests that the effect of content perturbations is not processed based neither on the amount of change nor on the nature of the manipulation.

It was also seen that the effect was not only on timing of intervals, but the unexpected perturbation also influenced trajectory of the movement. This result corroborates studies that also reported a disruption of tap velocity following a perturbation (Ammirante & Thompson, 2012; Goebel & Palmer, 2008; Furuya & Soechting, 2010), which suggests a great correlation between ITI and movement trajectory. The intensity of the tones was experimentally controlled in these experiments, but in actual music performances, an increase in tap velocity would result in a louder tone, and vice-versa. This association raises interesting questions

regarding the spontaneity of the relation between intensity (dynamic accents) and movements in music performance (Ammirante & Thompson, 2012).

Experiment 4 tested whether intensity changes also influence the timing of movements. Because the effects of pitch change on timing were stable across all pitch changes, I predicted that both an increase and a decrease in the intensity of the feedback would lead to a comparable disruption of motor timing.

Experiment 4: Unexpected Intensity Change

Experiments 1-3 demonstrated that unexpected changes in the pitch or timbre of feedback tones interfered with the timing and velocity of finger tapping. To further investigate the hypothesis that transient manipulations of auditory feedback content interfere with the timing of motor actions, Experiment 4 evaluated the effect of intensity changes on timing. It was predicted that an intensity changes would interfere with timing of motor actions, which would corroborate the hypothesis that perturbations in the content of feedback directly interacts with timing mechanisms, regardless of the nature or amount of change. On the other hand, differential effects would imply that the interaction between feedback and timing is mediated by other mechanisms, such as expectancy, attention or arousal.

Methods

Participants

Twenty-two undergraduate students (13 females, 9 males) were recruited at Macquarie University and received partial course credits for their participation. Subjects' average age was 20.6 years ($SD = 5.6$, range 18 – 45), and the number of years of formal musical training ranged from 0 to 12 ($M = 4.5$ years; $SD = 4.5$), however only three participants reported being currently involved in musical activities for at least 2 hours per week. No participants reported any form of hearing or motor impairment, and none had participated previously in a tapping experiment. All participants gave informed consent.

Materials, Equipment, Stimuli and Procedures

The apparatus and procedures used in this experiment follow the same protocol as established in Experiment 1, except for the feedback tones in the continuation phase. For each trial, participants first synchronised their taps with a pacing signal for 8 taps presented at a fixed IOI of 600 ms. The continuation phase consisted of 20 additional taps and every tap triggered a feedback tone. To prevent habituation to the stimuli, 5 initial tones were equally likely to occur in the continuation phase, which were B \flat 3, B3, C4, C#4 and D4. Feedback tones were presented repeatedly in the continuation sequence except for one incongruent feedback tone, the *oddball*.

Intensity at oddball tones was increased or decreased by 10dB in relation to standard feedback tones. Thus, oddball tones were either louder (82 dB) or softer (62 dB) than standard feedback tones (72 dB). Each condition was equally likely to occur and presented randomly 30 times, consisting of a total of 90 trials per participants. Participants had 3 practice trials with no alterations followed by the testing phase. Trials where ITIs were above or below 60% of the mean ITI for the trial were discarded and re-done immediately. The task took approximately 40 minutes.

Data Analysis

Continuation-phase taps were subjected to analysis and main procedures for data analysis follow guidelines established in Experiment 2. The main dependent variables of interest were ITI (ms), Coefficient of Variability and Tap Velocity. ITI values were average across initial pitch and target position for each participant and condition, and subjected to repeated-measures ANOVA with 2 factors: Intensity Change (0, +10, -10) and Sequence Position (P, O, O+1, O+2). The Greenhouse-Geisser correction was applied to p values where appropriate.

Results

A first analysis comparing mean ITI (ms) values according to Intensity Change (0, +10, -10) and Sequence Position (P, O, O+1, O+2) revealed a significant tendency for long drift of time on the present data set. A number of variables could contribute to a slightly more variable data set, a reduced number of trials, participants' engagement to follow instructions, fatigue. Taking in consideration the well-documented observation that intervals tend to shorten due to the tendency to speed up along the trial, difference scores ($ITI_n - ITI_{n-1}$) were used to minimize the effects of outliers or long-term drifts variability (Pfordresher & Dalla Bella, 2011; Ammirante & Thompson, 2012). For this relative measure, ITI difference scores of less than zero would mean that the current ITI (i.e., ITI_n) is shorter than the previous one (i.e., ITI_{n-1}), a score of zero would mean the current ITI is exactly the same as the previous one, and a score above zero would mean that the current ITI is longer than the previous. Results hereby reported use ITI different scores (ms).

A repeated-measures ANOVA with Intensity Change (3) and Sequence Position (4) was performed, and results indicated a significant main effect of Sequence Position, $F(3, 63) = 4.39, p = .01$. Interestingly, when comparing the effect of intensity change on the intervals after the perturbation with the interval preceding the change, it was observed that oddball significantly affected timing of tapping only at position O+1 and O+2 ($p = .01, p = .03$). Results also indicated that the interaction between Sequence Position and Intensity change was only significant for the condition where the auditory feedback was louder than standard tones ($F(3, 19) = 5.65, p = .006$), and not for softer tones ($p = .47$) (Figure 13). This was confirmed by pairwise comparisons that indicated that at positions O+1 and O+2 the condition with loud tone was significantly different from control ($p = .03, p = .02$,

respectively) whereas the soft-oddball condition did not differ from the control condition ($p = .75, p = .30$).

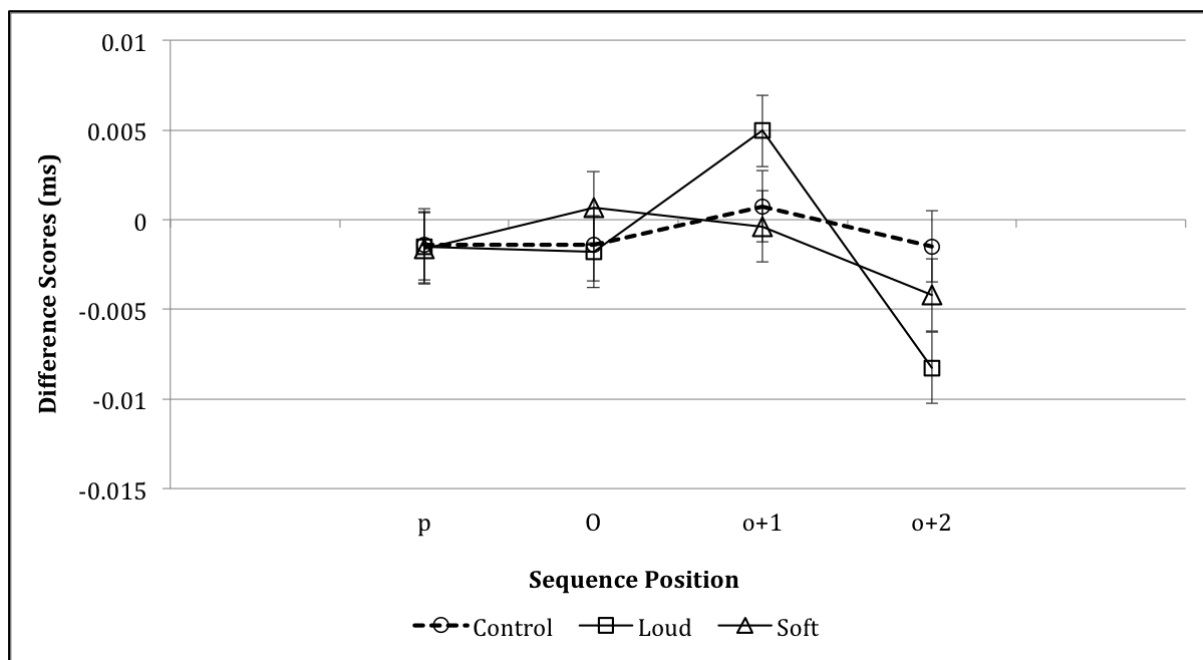


Figure 13. Interaction of Sequence Position and Intensity Change.

Variability

Coefficient of Variation (CV) values were averaged across trials for each condition and subjected to repeated-measures ANOVA with Sequence Position (4) and Intensity Change (3) as within subject factors, and years of training as a continuous between-subjects covariate. Results showed that accuracy was not affected by the unexpected intensity change as none of the factors reached statistical significance, including Sequence Position ($p = .77$), and the interactions with years of musical training ($p = .27$).

Tap Velocity (TV)

Mean TV scores averaged across conditions were entered into a 3 (Intensity) x 4 (Sequence Position) repeated-measures ANOVA. Results revealed that, although a main

effect of Sequence Position did not reach significance ($p = .11$), pairwise comparisons analysis showed that tap velocity at position O+1 was significantly different from previous interval ($p = .02$). None of the other conditions evaluated reached significance.

Discussion

Experiment 4 tested the hypothesis that unexpected changes in feedback intensity significantly interact with the timing of tapping. Specifically, an unexpected increase in intensity significantly disrupted timing but not an unexpected decrease in intensity. This finding does not support the prediction that *any* unexpected disruption in feedback content interacts with timing. Rather, the findings suggest that other mechanisms such as arousal and attention might have a role in such interactions. That is, expectations may interact with arousal and attention, such that these factors jointly influence timing.

The results here reported are supported by recent studies that showed that only unexpected louder tones affected piano performance (Furuya & Soechting, 2010). Specifically, researchers noted that an increase in intensity interacted with inter-keystroke intervals and finger contact duration, whereas decreasing tone intensity did not significantly disrupted piano performance. They also found that louder tones affected timing of keystrokes only at the 4th stroke after the perturbation, which suggested that intensity changes were not immediately compensated. This finding showed that the effect of louder tones did not affect the interval immediately after the perturbation, as was the case in Experiments 1 to 3, but only at position O+1 and O+2.

We also found that perturbations in intensity did not significantly interacted with tap velocity. Furuya and Soechting (2010) also noted inconsistent effects of intensity changes on keystroke velocity. However, Ulrich and Mattes (1996) demonstrated that louder tones tend to elicit more forceful and faster reaction times in comparison to softer tones. The discrepancy between this study and our results may be for methodological choices. While

Ulrich and Mattes (1996) used loud tones of 103 dB, in the present experiment increase in intensity changes were equivalent to 82 dB of intensity. This considerable difference may explain the different results.

So far, the evidence suggests that content changes, regardless of whether they consist of changes in pitch, timbre or (increased) intensity, significantly interact with the timing of motor actions. The consistency between the effects among different conditions suggests that content perturbations elicited a quick compensatory mechanism not significantly affected by the size or nature of the change. In general, the ITI for the oddball was shorter than the ITI for adjacent taps. Therefore, the instability generated by the oddball seemed to be restricted to local disruptions as corrections generally occurred after a few taps, thus not affecting global timing and variability of the performance.

At this point it is inevitable to question the nature of the mechanisms involved in the interaction between feedback content and timing. We do not expect to explore all the possible systems underlying this interaction, but one of the first questions worth investigating is whether attention is required for this interaction to take place or whether the interaction between feedback content and timing is supported by automatic mechanisms³.

Support for an automatic process would be found in a study that showed that timing shifts below perceptual thresholds elicited correction mechanisms (Repp, 2000). Repp suggested in his recent review that (phase) correction responses may be driven by a nonlinear subconscious process that registers expectancy violations (Repp & Su, 2013). We cannot suggest that the effect elicited by perturbations in feedback content is ‘phase correction’ by definition, given that *a*) it is thought that phase correction responses are only elicited in synchronization when a timing cue is used as reference for motor correction (Repp & Keller,

³ Attention refers to top-down, voluntary attention, whereas automatic as involuntary attention, bottom-up sensory processing.

2004) *b*) temporal perturbations were not introduced in the sequence. However, it is plausible that violations of expectation caused by unexpected changes in the auditory feedback significantly interact with timing mechanisms.

Studies that measured event-related brain potentials (ERP) suggest that task-irrelevant pitch changes of 1% are enough to elicit mismatch negativity (MMN), which are potentials elicited by stimuli that do not match the predictable pattern elicited by regular event, whether or not attention is engaged (Berti, Roeber, Schroger, 2004; Koelsch, Heinke, Sammler & Olthoff, 2006). Not only pitch but also timbre and intensity changes seem to elicit mismatch negativity, suggesting an automatic detection of these attributes by the nervous system (Goydke, Altenmuller, Moller & Munte, 2004; Muller-Gass et al., 2007).

Conversely, the hypothesis that attentional resources are involved in the process of unexpected feedback content perturbations can be gathered in an extensive body of literature showing that tasks that involve attention can be greatly disrupted by concurrent tasks (dual-task). Brown (2008) noted that temporal perception could be significantly disrupted by concurrent nontemporal tasks demands (Brown, 2008; Brown & Boltz, 2002; Grondin, 2010). Based on the theory that postulates the existence of a limited attentional pool, studies have shown that concurrent tasks compete for attentional resources. Takano & Miyake (2007) found that automatic mechanisms of motor timing correction were not affected by dual tasks, whereas compensatory mechanisms that require attention were greatly inhibited by concurrent tasks.

In short, automatic tasks are not greatly affected by attentionally-demanding tasks, whereas correction mechanisms that require attention can be significantly disrupted by concurrent tasks. Experiment 5 tested whether the inclusion of a perceptual task that consumes additional memory and attentional resources inhibits the effect of unexpected content perturbation on timing.

Experiment 5: The role of attention

To evaluate whether automatic or attentive processes are engaged by the perturbations of auditory feedback, Experiment 5 repeated the protocol adopted on Experiment 3 (pitch, timbre, pitch & timbre changes) and asked participants to categorize the type of change applied on that trial. It has been established, particularly in visual research, that detection is a pre-attentive and parallel process in which information is decoded automatically, whereas identification requires serial processing and attention (Straube & Fahle, 2011; Mondy & Coltheart, 2000). Therefore, it was expected that the additional task would introduce an attentional cost for the conjunction search and categorization, which in turn would significantly interact with the effect of feedback perturbation if the process demands attentional resources. On the other hand, little effect would be noted if automatic processes were operant.

Methods

Participants

A new sample of 25 undergraduate students (17 females, 8 males) was recruited at Macquarie University and received credit points for their participation. Participants' average age was 23.3 years ($SD = 4.7$, range 19-39 years), and the number of years of formal music training was in average 2.9 years ($SD = 3.9$). None of the participants reported any form of hearing or motor impairment, and two had participated previously in a tapping experiment. All participants gave informed consent.

Materials, Equipment, Stimuli and Procedures

The equipment, stimuli and data analysis in the present experiment were identical to Experiment 2. Likewise, the basic procedure remained the same as in the described experiment, with the exception of the identification question.

Participants were instructed to maintain a steady beat at the tempo provided by the pacing signal during the synchronization phase. However, at the end of each trial participants were asked to inform whether there was any change in the feedback tones (as in Experiment 2) and, if so, which of the attributes were manipulated by selecting one of the following options: Pitch; Timbre; Pitch and Timbre; Did not occur (Figure 11). Answers to the questions were not analyzed, as the goal was not to verify whether participants were able to discriminate timbre and pitch but to introduce a cognitive demand on the task. We expected that this modification would require additional attention and memory processes possibly affecting timing.

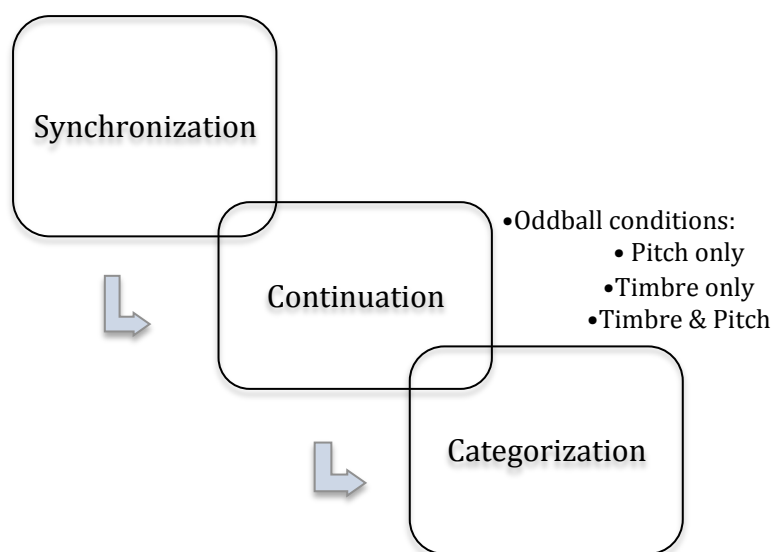


Figure 11. Procedure in Experiment 5.

Results

ITI values were average across initial pitch and target position for each participant and condition, and subjected to repeated-measures ANOVA with 3 factors: Pitch Change (0, 6), Timbre (piano, harp, organ) and Sequence Position (P, O, O+1, O+2). The main effect of

Sequence Position was significant, $F(3, 72) = 4.66, p = .01$. However, pairwise comparison analysis revealed that position immediately after the perturbation did not differ significantly from the adjacent ITIs. This suggests that overall effect of feedback perturbation was reduced when identification was required.

Nonetheless, further analysis indicated a significant interaction between Pitch Change and Sequence Position, $F(3, 72) = 9.79, p = .001$, and pairwise comparison analysis confirmed that the condition where pitch was perturbed was significantly different from the control condition at oddball position ($p = .002$) and position O+1 ($p = .02$), which suggests that the effect of unexpected pitch perturbations was preserved. This finding was confirmed by analysis of the interaction Pitch, Timbre and Sequence Position, $F(6, 144) = 3.65, p = .007$. Multiple comparisons analysis revealed that conditions Pitch Only and Pitch & Timbre were significantly different from the control condition at oddball position ($p = .02, p = .005$, respectively) and position O+1 ($p = .007, p = .01$).

Interestingly the interaction of Timbre and Sequence Position did not reach statistical significance, $F(6, 144) = 2.18, p = .08$. Pairwise comparison analysis revealed that there were no differences between control condition and the timbre changes at the oddball position (control = harp, $p = .89$; control = organ, $p = .11$, harp = organ, $p = .14$). There was also no difference in the following positions analyzed, which may suggest that including an attentional demand on the task reduced drastically the effect of unexpected timbre changes on timing (Figure 12).

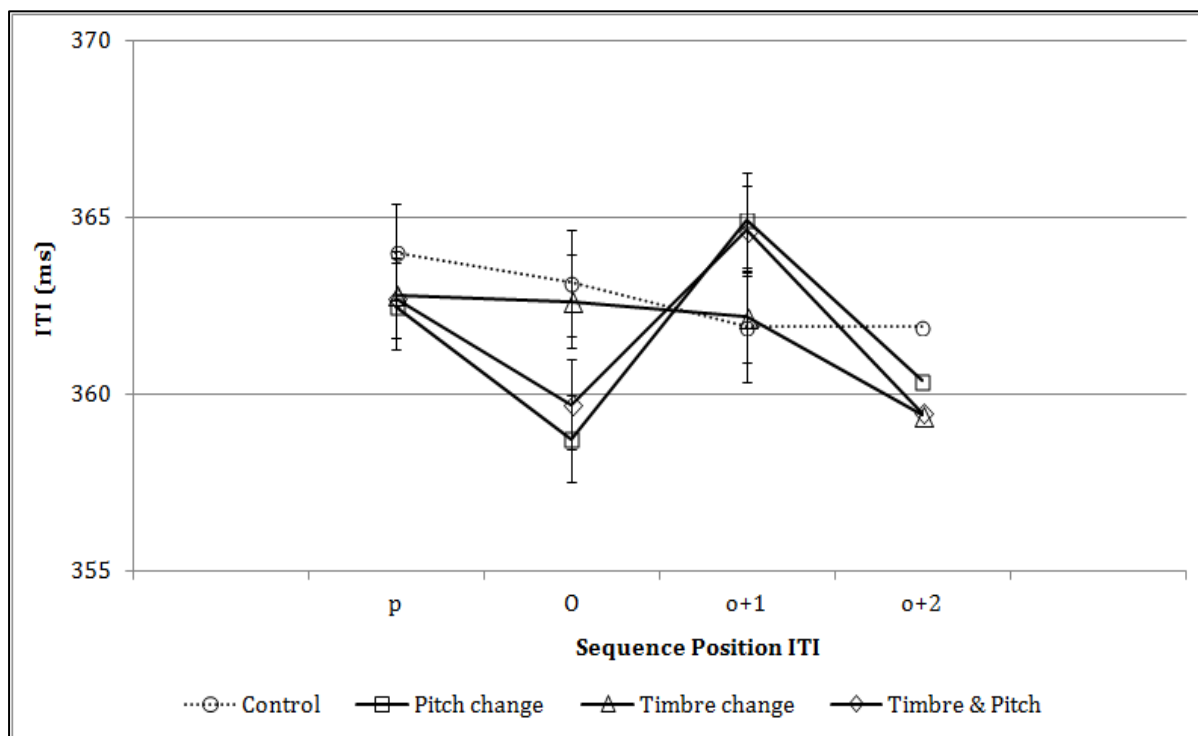


Figure 12. Main effect across conditions in Experiment 5.

Variability

Each participant's CV values were averaged across trials for each condition and subject to repeated-measures ANOVA with 3 factors (pitch change, timbre, sequence position) and years of training as a continuous between-subjects covariate. Results showed that variability was not significantly affected by the oddball (main effect of Sequence Position, $F(3, 69) = 1.30, p = .28$), given that none of the factors reached statistical significance. The interaction of Sequence Position x Training was not significant either ($F < 1$). This result indicates that participants were precise on their tapping despite evident timing perturbation induced by the unexpected event at oddball position, and replicated the result of Experiment 2.

Tap Velocity (TV)

Mean TV scores according to Pitch change (2), Timbre (3) and Sequence Position (4) were entered into repeated-measures ANOVA. There was no significant main effect of TV given that none of the factors reached significance (Sequence Position: $F(3,72) = 1.36, p = .26$). This result suggests that unexpected perturbations in the presence of a distracting task did not significantly interact with movement trajectory.

Discussion

The present experiment investigated whether the effect of unexpected feedback perturbations observed in previous experiments was based on automatic or attentive processes. Effects of oddballs on timing were different in the presence of an additional task than when there was no additional task.

In both conditions in which pitch was manipulated (pitch only, pitch & timbre), the effect of the unexpected change was reduced but resistant to the additional attentional cost imposed by the categorization task. On the other hand, in the condition where only timbre was manipulated, the effect of content change was suppressed. In this condition, the timing of intervals did not differ from the control condition, suggesting that the additional attentional demand significantly interfered with effect of perturbations on timing.

Firstly, the observation that the effect of unexpected changes persisted in conditions where pitch was manipulated suggests that the link between pitch and timing mechanism was resistant to top-down interference. This finding supports the hypothesis that the interaction between feedback pitch content and timing relies on automatic process, and may suggest that pitch may be processed faster or be resistant to top-down control. Support for this argument can be found in an ERP study that showed that latency was shorter for pitch deviants than timbre deviants (Goydke et al. 2004). Further investigations would be greatly benefited by measures of event-related brain potential to confirm that unexpected pitch changes are indeed

processed pre-attentively, hence resisting in a great degree to interference from concurrent tasks.

The suppression of the effect of unexpected timbre change may be related to task difficulty. Perceptual studies have shown a degree of interaction between timbre and pitch (Krumhansl & Iverson, 1992), which may have in turn increased the difficulty in categorizing timbre changes leading to additional attentional demand. Mondy & Coltheart (2000) mentioned that if subjects are aware that they will be required to judge or identify features in the task, they are more likely to focus extra attention to the manipulation. In this experiment, perhaps participants noticed the difficulty of the task, and in turn paid more attention to timbre changes, which could explain the suppression. Further studies are necessary to verify whether this result would be replicated with more salient timbre changes. Taken together, findings partially support the hypothesis that the relation between feedback content and timing mechanisms rely on automatic processes.

General Discussion

The aim of this series of experiments was to test the hypothesis that unexpected transient perturbations of feedback content interact with timing mechanisms. Results indicate that unexpected changes in pitch, timbre and increased intensity significantly disrupt timed movements. In particular, the interval immediately after the unexpected change was significantly shorter than adjacent taps, whereas the following tap tended to be overcompensated. This disruption did not affect variability over the course of the trial, as intervals tended to return to the tempo established by the metronome after 3-4 taps suggesting a local perturbation. These findings were consistent across experimental conditions and indicated that the size of pitch distance, type of perturbation or number of attributes manipulated, did not interfere with the magnitude of the effect. Additional evidence showed that the interaction between feedback content and timing was also not related to musical

training and relies on a partially automatic process, as compensation was greatly suppressed in slow tempi and in certain conditions where additional attentional demands were imposed. Finally, it was noted that perturbations on feedback content directly interacted with finger trajectory, as tap velocity was significantly affected by unexpected changes.

These results corroborate the prediction that expected motor and perceptual outcomes of the movements are integrated in an internal representation of timing. We showed that, nontemporal information, such as pitch, timbre and intensity, are part of this internal representation, as suggested by the forward models (Miall & Wolpert, 1996; Schubotz, 2007; Davidson & Wolpert, 2005; Bubic et al., 2010; Shadmehr, Smith & Krakauer, 2010; Mates & Aschersleben, 2000; Hommel, Mussel, Aschersleben & Prinz, 2001). A rich body of evidence has supported this model, showing that unexpected changes in the predicted outcome greatly interfere the representation of the action (Schubo, Prinz & Aschersleben, 2004). Along the same arguments, Mates and Aschersleben (2000) suggested that the various components deriving from the tap (tactile, kinesthetic, auditory) would be integrated in a central representation of time.

Our results did not support studies that indicate there is dissociation between the representation of feedback content and timing. For instance, experiments that applied random pitch changes in piano performance tasks (Finney, 1997), or arbitrary and meaningless feedback during speech (Howell, 2007), suggested that the manipulations did not interact with timing of events. One critical aspect of these studies is that the feedback provided was completely unrelated with the action, therefore, not providing an accurate representation of the action planned. Other investigations that combined phase shifts and pitch changes found no effect of content change on timing (Repp, 2003, 2002, 2004), leading to the conclusion that correction mechanisms are “insensitive” to pitch changes and are only activated by perturbations of feedback onset (Repp, 2003). Pfordresher (2006) proposed a model that

suggests that feedback content perturbations interfere only with sequence errors, not with timing. This model nevertheless, is based on serial shifts effects, which is greatly related to serial order and motor planning of sequences, which may have a strong effect of global expectations.

Taken together, the experiments described in this chapter support the assumption proposed by the internal forward model that expectancy is intrinsic to actions and that perceptual outcomes of rhythmic movements are integrated in the representation of timing. The modified oddball paradigm adopted in these experiments was an important tool to detect this interaction. Unlike previous studies that used serial shifts (Pfordresher, 2006 for review), or combined pitch and temporal manipulations (Repp, 2003; Repp & Penel, 2004; Repp, 2005), this paradigm successfully isolated the effect of a single transient perturbation of feedback content in timing of discrete movements. This was important in order to examine the effect of local expectancies in the representation of timing.

In conclusion, findings here reported add support to the idea that nontemporal attributes, such as pitch, timbre and intensity, interact with timing mechanisms. Further studies are required to examine the mechanisms involved in this interaction and whether expectancies are also intrinsic to continuous rhythmic movements.

Chapter 3:

An examination of the role of auditory feedback in event and emergent timing mechanisms

ABSTRACT

The present chapter investigates the role of expectation in timing by comparing the effect of unexpected feedback content perturbations two distinct timing tasks: finger tapping and circle drawing. Research suggests that rhythmic movements rely on two dissociable timing mechanisms, event and emergent timing, which differ substantially on how timing cues, such as auditory feedback, interact with movement. Experiment 1 evaluated the effect of unexpected perturbations on timing of finger tapping whereas Experiment 2 replicated the protocol for circle drawing. Results from the two experiments were then compared in order to reveal similarities and differences between event and emergent timing mechanisms. Debates on the degree of dissociation between emergent and event timing are discussed.

An Examination of the Role of Auditory Feedback in Event and Emergent Timing Mechanisms

Determining the timing of events, understanding the temporal relation between different stimuli, and anticipating when the next event will occur, are crucial cognitive processes that are deeply involved in a variety of everyday activities. For instance, walking down a crowded street involves timing one's own movements so as to navigate successfully while avoiding any collisions with others. To hit a ball with a tennis racquet, to tackle a player in rugby, to dance, to participate in an exercise class, to play the piano, and to sing 'Happy Birthday', are all examples of activities in which precise timing of bodily movements and the capacity to predict and respond to the timing of events are essential.

Studies have recently demonstrated that there are two distinct timing mechanisms responsible for the control of fine coordinated movements in music, sports, and dance. Discrete rhythmic movements, which are periodic actions preceded and followed by a period of no or little motion (e.g. finger tapping) are thought to rely on event timing. On the other hand, continuous rhythmic movements (e.g., circle drawing) seem to depend on emergent timing (Hogan & Sternad, 2007; Huys et al., 2008). Event timing requires an explicit representation of a temporal interval to be produced based on an internal clock-like mechanism, whereas emergent timing arises from the dynamic control of nontemporal parameters of the produced movement, such as velocity, thus not requiring an explicitly defined mental representation of time (Zelaznik, Spencer & Ivry, 2000; Ivry, Spencer, Zelaznik & Diedrichsen, 2002; Repp & Steinman, 2010).

The proposal that movements are based on two distinct timing mechanisms has been supported by a series of studies that demonstrated that patients with cerebellar lesion exhibited increased variability for event timing (intermittent circle drawing) but not for

continuous circle drawing (Ivry, Spencer, Zelaznik & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen & Ivry, 2003; Spencer, Ivry & Zelaznik, 2005). Neuroimaging findings also suggest that event and emergent timing recruit different brain areas (Schaal, Sternad, Osu & Kawato, 2004; Spencer, Verstynen, Brett & Ivry, 2007). Finally, mathematical models of movement control are consistent with the possibility that the motor system relies on two different timing mechanisms (Huys, Studenka, Rheaume, Zelaznik & Jirsa, 2008).

Research suggests that event and emergent timing mechanisms diverge in fundamental ways with respect to motor control. Specifically, auditory feedback affects these two types of movements differently, suggesting that they rely on distinct mechanisms. Zelaznik and Rosenbaum (2010) introduced auditory feedback at the end point of each cycle during circle drawing. Results indicated that the presence of a clear perceptual signal that demarcated each cycle induced a change in the strategy adopted by some participants to complete the circle drawing task. That is, auditory feedback induced event timing even in continuous tasks. This suggestion aligns with the proposition that event-timing mechanisms are recruited when movements require synchronization with an external source, i.e. a clear temporal goal (Zelaznik & Rosenbaum, 2010; Repp & Steinman, 2010; Elliott, Welchman & Wing, 2009). Taken together, existing research suggests that clear temporal cues (provided by auditory, tactile and visual information) can sometimes elicit an internal representation of time, and may determine the timing mechanism adopted in a task.

To further investigate the role of auditory feedback in event and emergent timing, we examined the effect of unexpected perturbations of feedback content on timing of finger tapping and circle drawing. Experiment 1 focused on the effect of unexpected changes in feedback content on timed tapping, whereas Experiment 2 examined the effect of unexpected changes in feedback content on timed circle drawing. Based on the assumption that expected motor and perceptual outcomes are integrated in the motor command (Schubotz & von

Cramon, 2003; Hommel et al., 2001; Wolpert & Flanagan, 2001; Aschersleben & Prinz, 1995; van der Steen & Keller, 2013), these experiments tested whether feedback would be integrated in the representation of timing not only in event timing, as suggested in Chapter 2, but also in emergent timing. It was predicted that feedback perturbations would significantly disrupt the timing of both event and emergent timing. However, if this prediction were not confirmed, data would indicate that continuous and discrete movements are based on distinct timing and expectancy mechanisms.

Experiment 1: Event timing

Results described in Chapter 2 indicate that timing of tapping is significantly influenced by unexpected changes in feedback content, such as pitch, timbre and an increase in intensity. Results showed that the intertap interval immediately following the unexpected perturbation was significantly shorter than adjacent taps, suggesting that participants tended to speed up after the perturbation. What remain unclear, however, are the underlying processes responsible for this interaction.

A number of mechanisms may underlie these effects. First, it is useful to consider the possibility that nontemporal attributes of sound, such as pitch and timbre, are represented spatially, or at least analogously to the representation of physical space. Theory and research on the connection between pitch and space have a long history. For example, theories of tonality – such as tonal pitch space – are based on the idea of evaluating psychological distances between tonal events (Lerdahl, 2001; Smith & Cuddy, 2003; Plomp & Levelt, 1965; Parncutt, 1989; Bigand, Parncutt & Lerdahl, 1996 for review). Briefly, these models assume that tonal music is represented by a multidimensional space in which distances between two pitches, chords, or keys determine their degree of psychological relatedness. Spatial representations of music are also assumed in *Melodic Motion Theory* (Ammirante & Thompson, 2012). Melodic Motion Theory is based on the idea that various attributes of

melody imply movement through space. For example, changes in pitch contour are experienced as subject to the same physical constraints as a change in direction for biological motion (Boltz, 1998). Thus, when an isochronous sequence of tones involves a change in pitch or pitch contour, as regularly occurs in all melodies, listeners perceive a subtle (illusory) change in the tempo of the sequence. Ammirante and Thompson (2010, 2012) found that this illusion arises at the level of motor timing, as the tempo of tapping was significantly faster when larger pitch changes were presented. Based on this theory, it would be predicted that any change would interact with timing, and moreover, that the pitch distance would be directly associated with the magnitude of the change. Previous findings did not support this prediction however.

Another possibility is that the interaction between feedback content and timing is mediated by *expectancy*. Expectancies allow the motor system to prepare an appropriate response in advance so as to coincide with the event and not only react to it. Such complex processes require an internal system that generates accurate predictions of the causal relationship between our actions and their consequences (Wolpert & Flanagan, 2001). This prediction system is termed internal forward model. This model postulates that expectancies are intrinsically related to actions, and that the expected motor and perceptual outcomes are integrated in the motor command (Schubotz & von Cramon, 2003; Hommel et al., 2001; Wolpert & Flanagan, 2001; Aschersleben & Prinz, 1995; van der Steen & Keller, 2013). Therefore, it could be assumed that highly expected pitch changes would be greatly integrated in the representation of timing hence not inducing any temporal changes in timing of events.

In an attempt to disentangle the various possible mechanisms involved in this interaction, the following experiment tested the effect of feedback content change in four conditions. In Condition 1, pitch changes were introduced every four tones of the sequence,

ensuring that they were highly predictable and expected for participants. In Condition 2, one of the expected changes was displaced by 1-semitone. In Condition 3, one of the expected changes was removed such that the feedback pitch unexpected remained the same. This manipulation allowed an independent assessment of the effects of expectancy violation and pitch change. In Condition 4, all feedback tones were identical except for one unexpected pitch change (oddball).

It was predicted that highly expected pitch changes in Condition 1 would not elicit a timing disruption if expectancy mechanisms (and not pitch change, per se) were involved in the interaction between feedback and timing. If highly expected changes still evoke a timing disruption, however, then it would suggest that any pitch change is distracting. Regardless of whether or not they are expected, pitch changes may attract attention toward the spectral content of the change and away from the timing of the feedback tone, thereby disrupting the ability to maintain steady and precise timing for subsequent taps. Condition 2 examined the effects of combining an additional level of expectancy violation to the effects of pitch change; Condition 3 isolated the effect of expectancy violation in the absence of pitch change: if expectancy alone is responsible for timing disruption, then an unexpected non-change should elicit timing disruption. Finally, Condition 4 provided a baseline for assessing unexpected feedback changes for which expectancy and pitch change coincide. The results for this baseline condition could then be compared with the results for other conditions, and with the results described in Chapter 2 for the same manipulation.

Methods

Participants

Twenty-five undergraduate students (20 females, 5 males) were recruited from the department of Psychology at Macquarie University and received partial course credit for their participation. The average age was 20.1 years ($SD = 6.4$ – range 18 to 44), and participants

had a variety of the number of years of formal music training, ranging from 0 to 13 years ($M = 4.02$; $SD = 4.5$), nonetheless only one participant reported being currently involved with musical activities for at least 2 hours weekly.

None of the participants reported any form of hearing or motor impairment, and none had participated previously in a tapping experiment. This project was approved by Macquarie University Human Research Ethics Committee. All participants gave informed consent and were debriefed about the goals of the experiment after their testing.

Materials and Equipment

Stimulus presentation and data collection were done using Macbook *Pro 9.2* laptop computers running custom software written in Python. The tones were produced by a Roland RD-250s digital piano and were presented over Sennheiser HD 515 headphones at 74 dB SPL.

Stimuli and Procedure

The experimental design followed the synchronization-continuation paradigm (Stevens, 1886). Participants first synchronised 8 taps with metronome tones, which were 20 ms square-wave clicks of 1000 hertz in frequency and 74 dB in intensity, presented at a fixed interonset interval of 600 ms. After 8 taps the metronome stopped and the participant attempted to continue tapping at the same pace, with each tap triggering a feedback tone. All feedback tones had a piano timbre. Participants were instructed to maintain the tempo set by the pacing signal to the best of their abilities until the end of the trial.

The feedback tones in the continuation phase were organized such that the first tone in every group of 4 tones was a piano tone of 392 Hz frequency (G4) and the other 3 tones were 261.63 Hz (C4), as depicted in Figure 1. This combination of feedback tones was repeated for 20 taps in the continuation phase (5 cycles).

Similar patterns of feedback tones were also presented in conditions 2 and 3 (i.e., a pitch change every fourth tone). However, in Condition 2 the expected pitch change (to G4) was unexpectedly displaced upward by 1 semitone (to G#4) at the 9th position of the continuation phase. In Condition 3, the expected pitch change (to G4) unexpectedly did not change (remained at C4) at the 9th position of the sequence. That is, the oddball was an *unexpected non-change*. Condition 4 replicated the protocol used in the experiments described in Chapter 2: all feedback sounds were C4 piano tones and there was only one unexpected pitch change (oddball) during the sequence of feedback tones (G#4). In Conditions 1-3, the cycle of four feedback tones implied a metric structure (repeated groupings of four tones) that was reinforced in all four conditions by introducing a slight increase in intensity for the first tone within each group of four tones (+10 dB).



Figure 1. Stimuli for each of the 4 conditions. The oddball occurs at the 9th position.

Participants were given 4 practice trials (all Condition 1) in order to familiarize them with the task and to ensure that they developed expectations for the feedback tones. Each condition was randomly presented 20 times, consisting of 80 trials in total per participant. Trials where intertap intervals (ITIs) were above or below 60% of the mean ITI for the trial were discarded and re-done immediately. Participants completed first the tapping and then the circle drawing task. With breaks offered between blocks, the task took approximately 40 minutes.

Data Analysis

The synchronization phase ensured that the tempo of tapping was consistent across participants, but only the taps in the continuation phase were subjected to statistical analysis. To account for accelerations that can occur at the transition between synchronization and continuation phases (Flach, 2005) the first 5 taps in the continuation phase were discarded, and the remaining 15 taps were subjected to analysis.

ITIs were defined as elapsed time between taps (in milliseconds). To evaluate general interference effects of oddballs on timing we analyzed participants' coefficient of variation (CV), which is defined as the standard deviation of ITIs within a trial divided by the mean ITI (SD/Mean). The average coefficient of variation was calculated across all trials for each condition.

The analysis focused on 3 ITIs before and 3 ITIs after the oddball presentation. Initial analysis indicated that there was not a significant difference among the three intervals before the oddball. Therefore, for each trial an average of 3 ITIs ratio preceding the oddball was calculated and labeled as ITIp (where P = *pre-oddball*). The following ITIs were coded O, O+1, O+2 (where O = oddball). For the purpose of illustration, target ITIs were aligned and average across positions.

ITI (ms) values were averaged across trials for each participant and for each condition and subjected to a 4 x 4 repeated-measures ANOVA with 2 factors: Condition (4 levels) and Sequence Position (4 levels). The Greenhouse-Geisser correction was applied to p values where appropriate.

Results

This experiment tests the relative importance of pitch changes and expectancy violation on the timing of tapping by examining whether pitch changes interact with the timing of motor actions or whether timing is only affected by the presence of an unpredicted event. ITI (ms) values were analyzed and results indicated a significant main effect of Sequence Position, $F(3,72) = 7.71, p = .001$. Pairwise comparisons revealed that the sequence position immediately following the oddball tone was significantly shortened in comparison to all the other positions analyzed ($O < P, p < .005$; $O < O+1, p = .006$; $O < O+2, p = .02$). There was a main effect of Condition, $F(3,72) = 11.47, p < .005$. Across the taps that were analyzed, the mean ITI was larger in Condition 4 than in the other conditions. However, this main effect is qualified by a significant interaction between Sequence Position and Condition, which revealed that the effect of the oddball was quite different in the four conditions, $F(9,216) = 11.77, p < .005$. For Condition 1 (expected pitch change), there was no significant shift in the timing of taps (see Figure 2). This finding suggests that an *expected* pitch change does not affect the timing of motor actions. On the other hand, there was a significant effect of the oddball for other conditions.

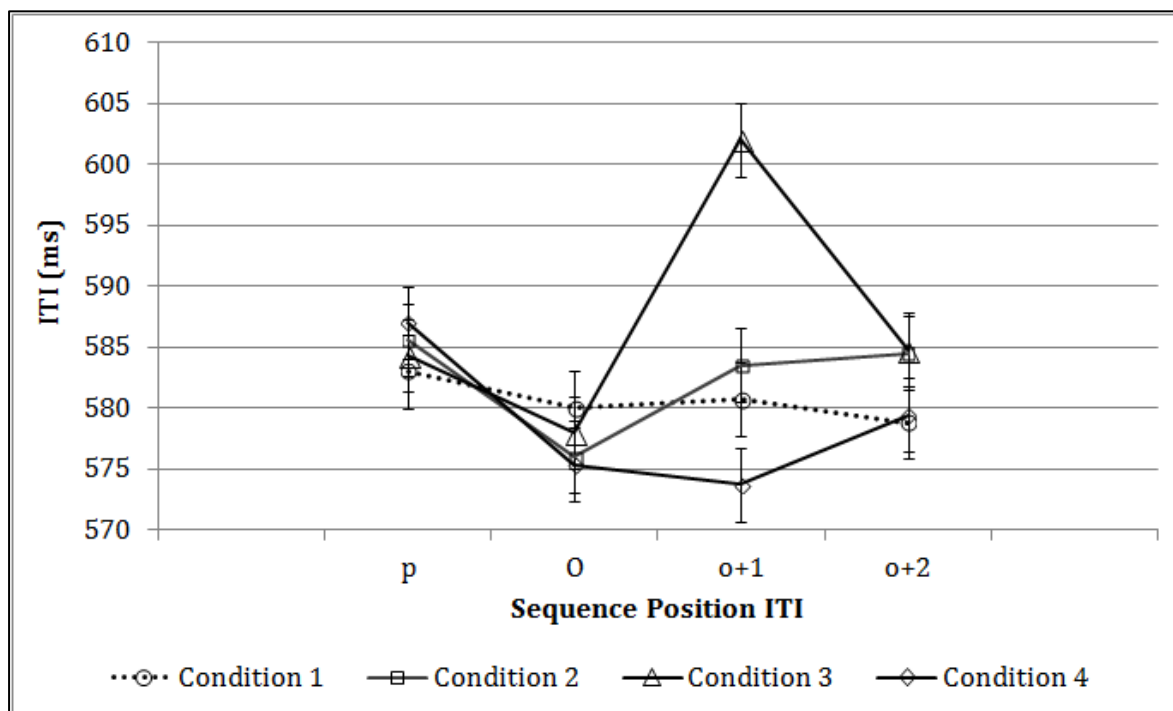


Figure 2. Main effect of Sequence Position and Conditions.

Coefficient of Variation (CV)

To further evaluate the effects of oddballs on timing we analyzed participants' coefficient of variation (CV). Each participant's CV values were averaged across trials for each condition and subjected to a repeated-measures analysis (ANOVA) with 2 factors (Condition, Sequence Position). There was a significant interaction between Condition and Sequence Position, $F(3, 72) = 4.93, p = .004$. Further analysis comparing the independent effect of each condition revealed that variability significantly increased after the oddball under Condition 3, suggesting that compensation was introduced after the perturbation ($F = 11.001, p = .003$). The coefficient of variation did not significantly change across trials in the other conditions. None of the other factors reached statistical significance.

Discussion

Experiment 1 examined the hypothesis that expectancy mediates the interaction between feedback content and the timing of tapping, predicting that unexpected changes of

feedback should significantly interact with timing, whereas highly predictable pitch changes should not affect timing. Results confirmed this prediction by showing that unexpected auditory feedback triggered by the action significantly influenced the timing of tapping. Data revealed that unexpected feedback shortened the intertap interval immediately after the perturbation and induced a compensation of the second timing interval. The disruption of timing was observed in conditions where pitch changes were as small as 1-semitone, and also where an expected pitch change was omitted. These findings, therefore, suggest that expectations are intrinsic to timing and support the hypothesis that expected motor and perceptual outcomes are integrated in an internal representation.

Additional support to this hypothesis was obtained by showing that expected pitch changes did not influence timing of taps. Again, these results did not corroborate the hypothesis that nontemporal attributes of sound, such as pitch and timbre, are represented spatially, as suggested by the *Melodic Motion Theory* (see Ammirante & Thompson, 2010, 2012). We did not find an association between pitch distance and the timing disruption. One possible explanation for this discrepancy is the absence of melodic contour in the stimuli used in the experiments reported in this thesis.

Experiment 1 supported the hypothesis of integration between feedback and timing in event timing. However, it is not known whether unexpected changes in feedback content interact with *emergent* timing mechanism. This question was addressed in Experiment 2.

Experiment 2: Emergent timing

The role of auditory feedback in emergent timing has not yet been sufficiently explored. Thus far, research has focused on the effect of the presence of different types of feedback, such as auditory (Zelaznik & Rosenbaum, 2010), tactile (Studenka, Zelaznik & Balasubramaniam, 2012), on emergent timing mechanism but it is still unknown whether feedback content perturbations would interact with timing of continuous movements.

Experiment 2 tested whether unexpected perturbations on feedback content disrupt the timing of continuous movements, such as circle drawing. Based on the hypothesis that expected motor and perceptual outcomes are integrated in an internal representation, it was predicted that feedback perturbations would significantly disrupt timing of emergent timing. On the other hand, if data fails to show an effect of content perturbation on emergent timing, findings would support the suggestion that emergent and event timing are based on distinct mechanisms.

Methods

Participants

Twenty-four undergraduate students (13 females), average age 20.0 years ($SD = 3.9$ – range 18 to 36) were recruited from the department of Psychology at Macquarie University and received partial course credit for their participation. Participants had a variety of the number of years of formal music training, ranging from 0 to 8 years ($M = 2.45$; $SD = 2.5$), however only one participant was currently involved in music activities. None of the participants reported any form of hearing or motor impairment, and one had participated previously in a tapping experiment. All participants gave informed consent and were debriefed about the goals of the experiment after their testing.

Materials, Equipment, Stimuli and Procedure

The present experiment is identical to Experiment 1, with the exception of the task performed. Participants were instructed to repeatedly move their finger in a clockwise circle direction in time with the metronome and maintain the tempo set by the pacing signal to the best of their abilities until the end of the trial. Participants traced an unfilled circle template of 5 cm in diameter displayed on the screen, and were instructed to synchronise every time the path of the finger crossed an intersection at 270 degrees of the circle with the metronome

(Figure 3). Participants were told that timing accuracy was more relevant than drawing accuracy, and they were free to draw a circle at a preferred size.

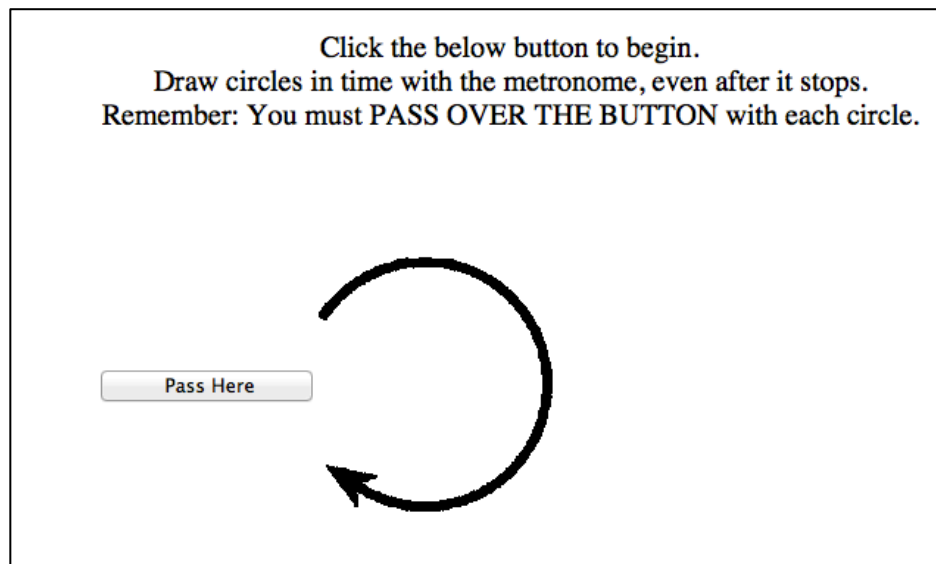


Figure 3. Circle template presented in the circle drawing task. Reduced scale.

Results

To measure timing in the circle drawing task, inter-response interval (IRI) was defined as elapsed time between passes through the intersection. IRI (ms) values were averaged by condition and entered into a repeated-measures ANOVA with Condition (4) and Sequence Position (4) as within subjects factors. Results indicated a significant main effect of Sequence Position, $F(3,69) = 5.79$, $p = .004$, however pairwise comparisons revealed that unexpected changes seemed to have interfered only positions O+1 ($O+1 > P$, $p = .005$; $O+1 = O$ $p = .07$; $O+1 > O+2$ $p = .003$), which suggests that feedback changes did not interfere with the interval immediately after the oddball presentation perhaps given that the motor plan had been already in place, and disruption therefore, interfered with the construction of the motor plan of the following movement. It is also interesting to note that, unlike in event timing where unexpected changes tend to elicit a shortening of the interval immediately after the

perturbation, in emergent timing movements seems that oddball increased the interval after the perturbation.

More importantly, results indicated a main interaction of Condition and Sequence Position, $F(9,207) = 2.69$, $p = .02$, and post hoc tests revealed that Condition 1 ($F(3,21) = 2.35$, $p = .10$) and Condition 2 ($F(3,21) = 2.87$, $p = .06$) did not reach significance. Only Conditions 3 and 4 significantly interacted with intervals in the sequence position ($F = 3.7$ $p = .02$; $F = 6.00$ $p = .004$, respectively), as displayed in Figure 4.

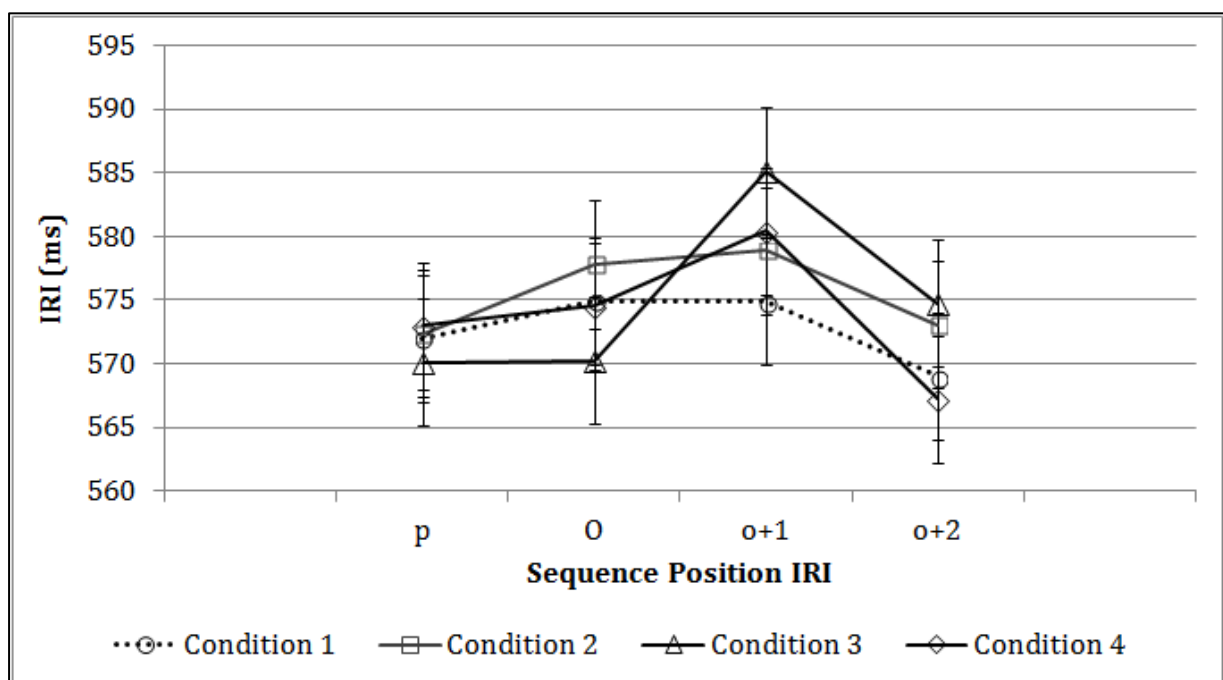


Figure 4. Inter-response intervals (ms) displayed across conditions and sequence position.

To further examined whether the availability of auditory feedback on the continuation phase of the circle drawing task indeed induced a shift to event timing strategies, it was tested whether lag one autocorrelations were present in the task. Lag 1 scores were average across trials and One-way ANOVA with Lag and Conditions as factors was performed. Mean lag one values were negative for all conditions, and t-test one-sample confirmed that

autocorrelation values were significantly different from zero, $t(95) = 9.77, p < .005$. This indicates that the auditory feedback served as an external temporal cue therefore induced event timing.

Variability

Each participant's CV values were averaged across trials for each condition and subject to repeated-measures ANOVA with 2 factors (Condition, Sequence Position). Results suggested that variability did not change significantly after the perturbation across conditions and sequence position tested, as all factors did not reach significance ($F < 1$).

Comparing variability scores between performances on tapping (Experiment 1) and circle drawing (Experiment 2), it was shown that tapping is significantly more accurate than circle drawing, $F(1,23) = 41.81, p < .005$. Interestingly, correlation analysis indicated that variability in circle drawing and tapping tasks were not correlated ($r = -.32, n = 24, p = .11$).

Discussion

Experiment 2 tested whether unexpected perturbations on feedback content would disrupt timing of continuous movements, such as circle drawing. Based on the assumption proposed by the forward models that expected motor and perceptual outcomes of one's actions are integrated in an internal representation, it was predicted that feedback perturbations would significantly disrupt timing of event and emergent timing. Results confirmed this initial prediction by showing that timing of intervals in the circle drawing task were significantly affected by unexpected changes.

One way to explore whether a common system underlies different motor tasks is by examining lag one autocorrelations. According to the Wing and Kristofferson (1973) event timing based model, lag one autocorrelation analysis reveals the variability imposed by the internal clock and motor delay intervals. Research has used this model to determine whether event timing strategies were employed to perform a certain task, as it has been suggested that

negative lag one correlations are typical of event timing mechanisms whereas non-negative lag one represents emergent timing strategies (Zelaznik & Rosenbaum, 2010; Baer, Thibodeau, Gralnick, Li & Penhune, 2013). It was found that negative lag one autocorrelation was significant in the present task, which supports studies showing that external temporal cues are used to define a temporal goal and determine the preferred timing mode adopted.

Interestingly, it was noted that not all conditions interfered with timing of continuous movements, as conditions 1 and 2 did not disrupted timing intervals. In these conditions, a highly expected pitch change was introduced every four tones (condition 1) and a semitone change was introduced in one of this tones in condition 2. The fact that these conditions did not interfere with timing in the circle drawing task suggest that continuous movements are more resistant to interference and suggests a crucial role of expectancy. This suggestion is corroborated by the observation that unexpected perturbations of feedback content in conditions 3 and 4 interacted with timing, but only at position O+1 and O+2.

Recent studies support our findings as it has been consistently demonstrated that continuous movements have longer recovery times after a phase shift perturbation (Elliot, Welcham & Wing, 2009), which indicates that movements based on emergent timing have a “large inertia in that, once the limb is moving, it is very difficult to adjust this movement pattern” (Studenka, Zelaznik & Balasubramaniam, 2012, p. 1098; Repp & Steinman, 2010).

Findings here reported corroborate recent suggestions that perceptual events (in this case, auditory feedback) are essential to define temporal goal and play a fundamental part in the internal representation of time, which may indicate an important role in establishing the timing mechanism adopted to complete a certain timing task.

General Discussion

The aim of these experiments was to investigate the role of feedback in event and emergent timing by testing whether perturbations of feedback content would significantly

interact with timing of discrete and continuous movements. Experiment 1 was successful in demonstrating the crucial role of expectancy in the interaction between feedback content and timing. Results have shown that unexpected changes of feedback content, hence nontemporal aspects of the feedback, such as pitch, timbre and intensity, significantly interact with timing of tapping. It was possible to observe that expected pitch changes occurring at predictable positions did not interact with timing of intervals, which suggests that the results reported in this thesis are associated to violation of expectations.

It was shown for the first time that unexpected changes in feedback content interacted with timing of continuous movements. This result adds support to hypothesis that expectancy mechanisms are intrinsic to timing of motor actions. However, it was observed that the effect of unexpected changes on timing differed between tapping and circle drawing. For the tapping task, the oddball led to a decrease in intertap interval at the interval immediately following the change in feedback tone. On the other hand, unexpected changes interacted with timing by increasing the inter-response interval on the second position after the perturbation.

These results are supported by studies showing that continuous movements are slower to adjust following changes in the sensory input in comparison to discrete movements (Repp & Steinman, 2010; Elliott, Welchman & Wing, 2009). Repp (2008) suggested that the difference in the interference effect of unexpected events in the two tasks is related to a greater “maintenance tendency” in continuous movements. This tendency is thought to be associated with the inertia associated to the movement (Repp, 2008; Repp & Steinman, 2010; Studenka et al., 2012).

Another interpretation for these results is the association of different expectancy processes. It has been recently suggested that emergent timing is based on “strong anticipation” processes (Marmelat & Delignieres, 2012). According to this hypothesis based

on dynamic system approach, strong anticipations arise from the close alignment between the action and its sensory outcome. In this case, the goal of the system is to maintain smooth and uninterrupted rhythmic movements based on global and often long term expectations. Therefore, it is possible that the decoupling between motor actions and the external environment linked to strong expectations leads to a suppression of immediate interactions between unexpected events and the motor planning.

On the other hand, event timing seems to be associated with “weak anticipation” processes. This expectancy mechanism is required in dynamic environments where unpredicted events require rapid and efficient correction in order to maintain accurate responses. Therefore, it can be said that weak anticipations entail local and short-term expectancies (van der Steen & Keller, 2013; Dubois, 2003; Stephen et al., 2008; Marmelat & Delignieres, 2012). It may be possible that weak anticipations facilitate the intervention of error correction mechanisms resulting in immediate interactions between unexpected events and timing.

Thus, further examinations are crucial to understand the importance of different aspects involved in rhythmic movements. Results here described corroborate suggestion that feedback is a key aspect influencing the timing strategy adopted to perform discrete and continuous movements in synchrony with external events. One question that arises is whether training would be a significant element in this equation, and may be another important aspect of timing. This question is addressed in the next sections.

Chapter 4

Timing and expertise: evaluating the effect of movement-based expertise (sports and music) on emergent and event timing mechanisms

ABSTRACT

Training in a movement-based skill may be defined as the process of aligning internal predictions of motor and perceptual outcomes with the dynamic conditions of the environment and the body, and the capacity to adjust rapidly to any misalignment. As a result, skill and training significantly enhance timing accuracy. This chapter evaluates the effect of expertise on emergent and event timing. Experiment 1 compared the performance of elite athletes, musicians and controls in circle drawing and tapping tasks. The goal of this test was to verify whether intense training in event-based tasks (e.g. music) would only interact with tapping, or whether training in music would also interact with emergent-based tasks. Experiment 2 replicated the paradigm but including auditory feedback at the continuation phase of the task. This modification was applied in order to examine whether experts would be differently impacted by auditory feedback.

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**Timing Skills and Expertise: Evaluating the Effect of Movement-Based Expertise
(Music and Sports) on Event and Emergent Timing Mechanisms**

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Author note

Authors contribution: I was the major contributor to this co-authored paper. In particular, I was responsible for the experiment preparation, data collection, analysis and manuscript preparation. Paolo Ammirante designed Experiment 1, conducted and advised the process of data analysis and manuscript preparation. Bill Thompson and Ronald Ranvaud provided feedback and suggestions regarding the writing of the manuscript.

I also received technical support from Alex Chilvers, who was responsible for stimuli preparation and experiment programming, and also helped with data collection in Experiment 1.

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Abstract

Introduction: Movement-based expertise, such as dance, music, and athletic sport, rely on precise timing of bodily movements and the capacity to predict and respond to the timing of events. However, whereas music often involves rhythmic actions that adhere to regular cycles of timed events (meter), many athletic sports involve predominantly fluid and continuous movements that are not timed in a cyclical manner. It has been proposed that accurate temporal control of discrete movements rely on event timing whereas continuous actions involve emergent timing. We examined whether movement-based expertise would interact with the timing mode adopted to produce and maintain accurate rhythmic movements. We predicted that expertise and training would reinforce one predominant timing mode supporting the hypothesis that expertise plays an important role in determining the timing strategy employed to maintain temporal accuracy of actions.

Materials and Methods: Timing accuracy was evaluated in groups of participants with movement-based expertise (musicians and athletes) and groups of participants with no movement-based expertise on the prototypical event and emergent timing task, finger tapping and circle drawing, respectively. For each task, participants first synchronised with a metronome and then continued reproducing the movements at the same rate established by the metronome. In Experiment 1, no auditory feedback was provided in the continuation phase of the trials whereas in Experiment 2 every action triggered a feedback tone.

Results: Analysis of the continuation phase indicated that athletes performed significantly more accurately than musicians and controls in the circle drawing task, whereas musicians were more accurate than controls in the finger tapping task. Interestingly, musicians were also more accurate than controls in the circle drawing task, and there was no reliable difference between musicians and athletes on the tapping task. When auditory feedback was presented results showed that there was no statistical difference between the performance of

athletes and the other groups in the circle drawing task, whereas musicians outperformed controls in the drawing and tapping tasks. Further analysis showed that musicians and controls changed timing strategy in the presence of auditory feedback and adopted an event timing strategy to perform the circle drawing task. In contrast, athletes employed emergent timing to complete the drawing task, even when auditory signals marked the temporal intervals.

Discussion: Results revealed that movement-based expertise engage both timing mechanisms, however extensive training reinforces one predominant timing mode. Additionally, it was shown that expertise is a crucial factor to determine the timing strategy employed to maintain accuracy of rhythmic movements, suggesting that the distinction between event and emergent timing is not an all-or-none process.

Keywords: emergent timing, event timing, expertise, training, music, sports

Movement-based expertise, such as dance, music, and athletic sports, rely on precise timing of bodily movements and the capacity to predict and respond to the timing of events. However, whereas music often involves discrete rhythmic actions that adhere to regular cycles of timed events (meter), many athletic sports involve fluid and continuous rhythmic movements that are not timed in a cyclical manner. Recent studies have suggested that timing control of discrete actions (i.e., events preceded and followed by a period without motion) and continuous movements depend on different timing strategies or processes (Robertson et al., 1999; Zelaznik et al., 2002; Huys et al., 2008; Zelaznik & Rosenbaum, 2010; Studenka et al., 2012). It is thought that timing of discrete movements is event-based, involving a clock-like neural process and an explicit internal representation of the time interval delineated by each discrete movement. In contrast, activities that involve smooth and continuous rhythmic movements are based predominantly on emergent timing, where timing regularity arises from the control of parameters such as movement velocity and trajectory control in the absence of a representation of time interval.

An increasing body of evidence has shown that event and emergent timing are distinct and dissociable systems. Behavioral studies have shown that temporal variability in finger tapping tends not to correlate with variability in continuous circle drawing (Robertson et al., 1999; Zelaznik et al., 2005), and that event-timed movements are significantly more accurate and adjust faster to timing perturbations than emergent-timed movements (Elliot et al., 2009; Repp & Steinman, 2010). There is also neurological (Spencer et al., 2003; Spencer et al., 2005; Ivry et al., 2002) and neuroimaging evidence (Schaal et al., 2004; Spencer et al., 2007) suggesting that event and emergent timing processes recruit different brain areas.

Although these mechanisms are based on distinct processes, recent results have demonstrated that the event/emergent distinction is not an all-or-none mechanism and the specific circumstances under which a given timing strategy is adopted are largely unclear

(Studenka et al., 2012; Baer et al., 2013). It has been suggested, for instance, that the presence of perceptual events marking the completion of time intervals can induce event timing processes even for tasks performed with continuous movements (Zelaznik & Rosenbaum, 2010; Studenka et al., 2012). Computational simulations and behavioral studies have indicated that task tempo and movement speed constraints (Huys et al., 2008; Zelaznik & Rosenbaum, 2010), as well as task order and practice (Jantzen et al., 2002, 2004), are important elements to define the preferred timing mechanism elicited in a certain task. The present work tested whether expertise and intense training in a given mode of timing (e.g., music or sports) would also be a determining factor in defining the dominant timing process engaged in a particular rhythmic action.

It is well known that highly trained musicians are exceptionally accurate in event-based timing tasks, such as finger tapping with an auditory metronome (Repp, 2005, 2010; Repp and Doggett, 2007; Baer et al., 2013). Musically trained participants tend to show smaller asynchronies between movement and onset of metronome click and lower tapping variability compared to nonmusician counterparts (Aschersleben, 2002, Repp, 2010). Musical expertise also seems to enhance the internal temporal representation of time as suggested by perceptual studies showing that training can significantly improve interval discrimination and perceptual sensitivity to timing perturbations (Buonomano & Karmarkar, 2002; Ivry & Schlerf, 2008; Repp, 2010). Not only musicians benefit from training in event-based timing tasks, but training and practice can also significantly improve accuracy in sensorimotor synchronization also for nonmusicians (Aschersleben, 2002).

On the other hand, we know very little about how expertise might influence the operation of emergent timing mechanisms. A recent study investigated whether musical training affects temporal variability in an emergent timing task by comparing the performance of musicians and nonmusicians in finger tapping and circle drawing tasks (Baer

et al., 2013). Whereas musicians were significantly more accurate than nonmusicians in the finger tapping task, performances did not differ between groups in the circle drawing test. This result is consistent with the view that emergent and event timing are distinct mechanisms; expertise in a predominantly event-based timing mechanism only interacts with tasks associated with discrete movements and not emergent timing-based tasks (Zelaznik et al., 2000; Zelaznik et al., 2005). Interestingly, it was also shown that musicians tended to use an event-based strategy even to perform the emergent task, which suggests that musical expertise significantly influenced the timing mechanism adopted to maintain accurate timing.

The main purpose of the present study was to investigate the dissociability of event and emergent timing mechanisms in movement-based experts from different domains. Based on the assumption that musical performance involves predominantly discrete rhythmic actions that rely on event timing and that athletic sports recruit primarily fluid and continuous rhythmic movements based on emergent timing, we examined whether movement-based expertise is associated with specific or general timing skills. If the difference between event and emergent timing processes is affected by expertise and training in a specific timing mode, we predicted that athletes should be more accurate in the emergent timing task whereas musicians should be more accurate in the event timing task. In contrast, if musicians and athletes do not differ in their performance in both tasks, this would suggest that the two timing processes are less separable in movement-based experts, or that training affects both event and emergent timing processes.

To test this hypothesis, Experiment 1 compared the performance of elite athletes, highly trained musicians, and controls on tapping and drawing tasks. The variability of inter-response intervals was measured in a synchronization-continuation paradigm. In Experiment 2, auditory feedback was presented in the continuation phase in order to assess the effect of the presence of salient perceptual events in determining the timing mode adopted to complete

the tasks. We were particularly interested in whether the presence of auditory feedback would induce the use of event timing strategies regardless of the expertise of the participants or whether the domain of expertise would be a relevant factor.

Experiment 1

Methods

Participants

Fifteen athletes were recruited through the Macquarie University Elite Athlete Scholarship Program. Athletes (8 females, 7 males) were on average 21.31 years old ($SD = 2.33$, range 18–26 years) and had been involved in athletic training for an average of 7.31 years ($SD = 3.45$). All athletes involved in the project were actively engaged in training and competing at State and/or National level. None of the athletes included had completed more than 2 years of musical training or were involved in any musical activities. Musicians ($n = 13$, 4 females) were recruited through the Departments of Music and Psychology at Macquarie University and local conservatories and universities. The average age of musicians was 21.38 years ($SD = 3.20$, range 18–28 years) and all participants had been involved in formal music training for at least 10 consecutive years ($M = 10.85$, $SD = 2.38$). Musicians played a range of instruments, including piano, guitar, and violin. Control participants ($n = 17$, 10 females) were on average 21.76 years old ($SD = 3.31$, range 18–31 years). None of the participants in the control group reported any formal athletic and music training. None of the participants reported hearing or motor impairment. Psychology undergraduate students were compensated with course credit, and all other participants received financial compensation for their participation. All participants provided informed consent and were debriefed about the goals of the experiment.

Materials, Stimuli and Procedure

Stimulus presentation and data collection were done using a Macbook *Pro 9.2* laptop running custom software written in Python and tasks were completed using an Apple single-button mouse. The task widely used to represent event timing is finger tapping whereas circle drawing is thought to typify emergent timing task (Repp & Steinman, 2010). The paradigm adopted for both tasks was synchronization-continuation (Stevens, 1886). For each trial, participants first synchronised their movements (circle drawing or tapping) with isochronous metronome click for 18 clicks. The signal tones were 40 ms square waves clicks of 480 Hz presented at 74 dB. After the synchronization phase, the metronome stopped and participants were instructed to continue to produce 36 more movements at the tempo set by the metronome. Within each trial, one of two metronome tempi was used: slow (75 BPM) or fast (100 BPM).

In the event timing task, participants tapped with their index finger at the tempo set by the metronome and continued when the cue was removed. No auditory feedback was provided. In the emergent timing task, participants repeatedly moved their finger in a circle in time with the metronome and in a clockwise direction, and continued the task in the absence of the external timing cue. Participants traced an unfilled circle template of 5 cm in diameter displayed on the screen, and were instructed to synchronise every time the path of the cursor crossed an intersection at 270 degrees of the circle with the metronome. Participants were told that timing accuracy was more relevant than drawing accuracy, and they were free to draw a circle at their preferred size. For the tapping task, participants repeatedly tapped on the mouse with their index finger of the right hand at the tempo set by the metronome. Participants had 5 practice trials at 100 BPM before each experimental block. Trials were blocked by task, and order of presentation was counterbalanced between participants. Within each block, a total of 20 trials were presented (10 at each tempi). With breaks offered between trials at participants' discretion, the experiment took approximately 50 minutes.

Data Analysis

Only responses in the continuation-phase were analyzed as the synchronization phase was used only to establish the pacing. In order to allow for acceleration commonly observed in the transition from the synchronization to continuation phase (Flach, 2005), only the final 30 movements were analyzed. For the tapping task, inter-response interval (IRI) was defined as elapsed time between taps (in milliseconds) and for the circle drawing task, IRI was defined as elapsed time between passes through the intersection. To measure timing accuracy we analyzed participant's coefficient of variation (CV), which was defined as the standard deviation of IRIs within a trial divided by its mean IRI (SD/Mean). Average CV was calculated across all trials for each condition and individual. Lower CV scores indicate greater accuracy. CV scores were averaged by task and tempo for each participant. In addition to CV, lag 1 autocorrelation was calculated to examine strategies adopted on the tasks. In general, event timing tasks are associated with negative lag one covariation whereas emergent timing tasks result in positive lag one covariation (Baer et al., 2013; Zelaznik & Rosenbaum, 2010).

Results

CV was entered into a mixed design ANOVA with Task (circle drawing, tapping) and Tempo (fast, slow) as within-subject factors and Group (athletes, musicians, controls) as between-subject factors. Results indicated a significant main effect of Task, $F(1,42) = 251.01, p < .005$, demonstrated that participants were more accurate in the tapping task ($M = .07$) than circle drawing ($M = .23$). It was also verified that there was no statistical difference between fast and slow tempi, $F(1,42) = 1.16, p = .28$, and no significant interaction between Task and Tempo, $F(1,42) = 2.25, p = .14$.

Between-subjects analysis revealed a significant difference between Groups, $F(2,42) = 18.42, p < .005$, which was confirmed by a significant interaction between Group and Task, $F(2,42) = 16.48, p < .005$. Independent sample t-tests revealed that on the circle drawing task athletes were significantly more accurate than musicians, $t(26) = 2.19, p = .03$, and controls, $t(30) = 7.00, p < .005$, while musicians were significantly more accurate than controls, $t(28) = 3.37, p = .002$. On the finger tapping task, musicians were significantly more accurate than controls, $t(28) = 2.23, p = .03$, however, the performance between musicians and athletes did not reach significance, $t(26) = .61, p = .54$. Athletes' performance on the tapping task also did not differ from controls, $t(30) = 1.87, p = .07$ (Figure 1).

Given to the significant interaction between Task and Group, we analyzed the correlation between CV on both tasks for each of the groups tested. Results indicated that the variability in the finger tapping task was not significantly correlated with the variability in the circle drawing task for all groups: musicians ($p = .55$), athletes ($p = .08$) and controls ($p = .11$).

One generally accepted indicator of the timing strategy adopted in a given task is found through the analysis of lag 1 autocorrelation. Tasks that adopt a event timing strategy exhibit lag one autocorrelation values between $-.5$ and 0 , whereas tasks believed to engage primarily emergent timing strategies are associated with a non-negative lag one (Zelaznik & Rosenbaum, 2010; Delignieres & Torre, 2011). Analysis of lag 1 autocorrelation values indicated that there was a significant difference between tasks, $F(1, 43) = 4.13, p = .04$, but the interactions between Task with Group or Tempo did not reached significance. Between-subjects analysis indicated that experts and controls tended to adopt similar strategies in either event or emergent tasks, given that lag 1 autocorrelation values was not statistically different among groups, $F(2, 43) = .51, p = .60$.

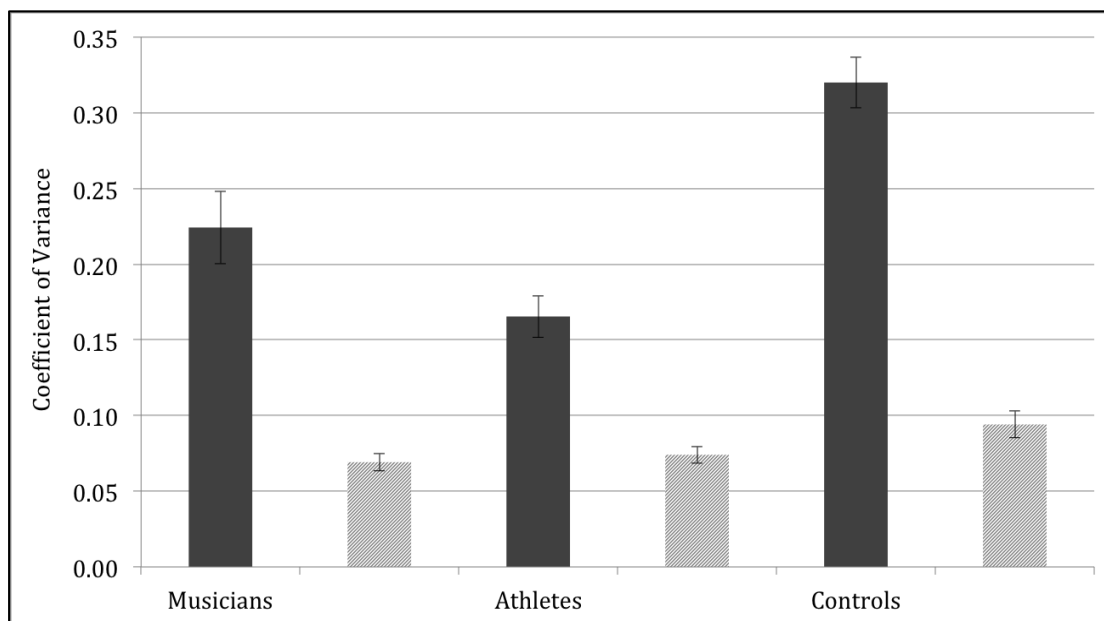


Figure 1. CV by Group and Task. Dark grey bars represent the average CV at circle drawing for each group; light grey patterned bars represent CV at the finger tapping task.

Discussion

Results of the present experiment demonstrated that athletes were significantly more accurate on the circle drawing task than musicians and controls, which suggests that intense training in smooth and continuous movements based on emergent timing directly interacts with timing control of such activities. It was also confirmed that musicians tended to be significantly more accurate than controls in tasks involving temporal control of discrete movements, such as finger tapping (Repp, 2005; Repp & Doggett, 2007; Baer et al., 2013). However, between-group comparisons indicated that musicians were also significantly more accurate than controls in the circle drawing task and that there were no reliable differences between musicians and athletes in the tapping task. These findings suggest that movement-based expertise engage both timing mechanisms, nevertheless, reinforcing one predominant timing mode.

Past research has suggested that formal music training only enhanced accuracy in event timing tasks but not emergent-based tasks (Baer et al., 2013). Methodological differences may have contributed to the discrepancy between our results and Baer's, as perhaps the devices used in the present experiment imposed high motor demands rather than timing specific demands. On the other hand, our results could also support the hypothesis that event and emergent timing mechanisms are less separable than previously claimed. The hypothesis that the dissociation between event and emergent timing is not a one-or-all process (Repp & Steinman, 2010; Studenka et al., 2012) indicates that the circumstances where the different timing modes are employed are open for investigation. We suggest that expertise and training are particularly important elements in determining the timing mechanism engaged in maintaining accurate timed actions.

In the following experiment we sought to further explore the hypothesis that movement-based expertise would interact with both timing mechanisms, yet reinforce one predominant timing mode. Previous studies have proposed that the presence of salient feedback marking the completion of time intervals elicits timing behavior consistent with event timing, even in continuous movement-based tasks (Studenka et al., 2012; Zelaznik & Rosenbaum, 2010). Studenka and colleagues (2012) showed that the introduction of discrete tactile events presented at the completion of a cycle induced event timing in a typically emergent timing task. This finding corroborated a previous study that suggested that event timing can be elicited by the insertion of auditory feedback clearly establishing temporal goals (Zelaznik & Rosenbaum, 2010). However, in real life situations actions are greatly associated with feedback (e.g., tactile, visual, proprioceptive, auditory), which are fundamental for motor control and improvement of accuracy and precision of timed actions (Aschersleben, Gehrke & Prinz, 2001). Therefore, in the following experiment we tested whether the presence of auditory feedback would also elicit event timing in the completion of

the drawing task in participants with intense training and experts in emergent-based movements. In other words, would elite athletes also use event timing strategies to perform continuous rhythmic movements? We predicted that, in the presence of auditory feedback, musicians and controls would adopt event timing to perform the continuous movements, whereas athletes would not change strategies in the presence of feedback. Confirmation of this prediction would suggest that expertise and training indeed reinforce one predominant timing mode, which would be resistant to certain interferences. On the other hand, if the introduction of discrete events elicits event timing also in elite athletes, findings would corroborate the hypothesis that event timing is dominant in the presence of salient events clearly representing temporal goals.

Experiment 2

Methods

Participants

A total of 31 elite athletes (10 females) were recruited from Macquarie University through the Elite Athlete Scholarship Program. Athletes' average age was 21.06 years old ($SD = 3.69$, range 18–32 years) and they had been involved in athletic training for an average of 8.31 years ($SD = 5.55$). None of the athletes were involved in the first experiment and none had had more than 2 years of musical training. From this group, 13 athletes were experts in sports that involve rhythmic paced movements (e.g., swimming, rowing, squash, badminton, dragon boating) whereas 18 elite athletes were experts in sports do not essentially require rhythmically paced movements (e.g., ice hockey, rugby, mountain biking, basketball, snowboarding). Musicians ($n = 17$, 15 females) were recruited through the Departments of Music and Psychology at Macquarie University and local conservatories and universities. The average age of musicians was 20.72 years ($SD = 3.52$, range 18–29 years). Musicians were all currently involved in music activities for a minimum of 2 hours/week and all had

been involved in formal music training for at least 10 consecutive years ($M = 11.94$, $SD = 2.68$). None of the participants were involved in the previous study. Musicians played a range of instruments, including piano, guitar, and violin. Control participants ($n = 10$, 10 males) were postgraduate or professional computer programmers recruited through the Computer Science Department at Macquarie University. Participants were on average 31.58 years old ($SD = 7.21$, range 22–49 years), and had an average of 10 years of specific training ($SD = 6.07$). None reported any formal athletic training or being currently involved in formal music training. All participants provided informed consent and were debriefed about the goals of the experiment. None of the participants reported hearing or motor impairment. Participants received financial compensation for their participation.

Materials, Stimuli, Procedure and Data Analysis

Stimulus presentation and data collection involved the same equipment as in the previous experiment, with the exception that participants completed the tasks using laptop's touch pad instead of a computer mouse to facilitate performance on the circle drawing task. Procedures and data analysis followed the protocol established in Experiment 1. The main change was the introduction of auditory feedback at the continuation phase of the task. For each trial, after participants synchronised their movements (circle drawing or tapping) with an isochronous metronome click for 18 clicks, the metronome stopped and participants were instructed to continue to produce 36 more movements at the tempo set by the metronome. For the tapping task, participants repeatedly tapped on the touch pad with their index finger of the right hand at the tempo set by the metronome. Every tap triggered a feedback tone of 40 ms duration at 480 Hz frequency and presented at 74 dB. In the emergent timing task, participants repeatedly traced a circle clockwise with their index finger in time with the metronome and continued the task in the absence of the external timing cue. Participants were told to pass the cursor over a crossing intersection at 270 degrees of the circle in

synchrony with the metronome. In the continuation phase, every time the cursor trajectory crossed the intersection the auditory feedback was provided.

Results

To measure timing accuracy, CV scores were averaged by task and tempo for each participant, and entered into a mixed design ANOVA with Task (circle, tapping), Tempo (slow, fast) as within factors and Group (athletes, musicians, controls) as between-subjects factor. Analysis revealed a significant main effect of Task, $F(1,55) = 4.60, p = .03$, and a paired sample t-test confirmed that the performance on the finger tapping task ($M = .05$) was significantly more accurate than on the circle drawing ($M = .10$), $t(57) = 6.87, p < .005$. There was also a main effect of Tempo, $F(1,55) = 35.61, p < .005$, confirmed by an interaction between Task and Tempo ($F = 17.69, p < .005$).

Between-subjects analysis indicated that there was a significant main effect of Group, $F(2,55) = 3.23, p = .04$, but only a marginal statistical interaction between Task, Tempo and Group, $F(2,55) = 2.81, p = .06$. Further analysis comparing the performance of the different groups on the circle drawing task showed no statistical difference between the performance of athletes and musicians ($p = .24$), and no difference between athletes and controls ($p = .07$). However, results showed that musicians were significantly more accurate than controls in the circle drawing task ($p = .01$), confirming results from Experiment 1. Analysis on the tapping task performance indicated that musicians were significantly more accurate than controls ($p = .04$), whereas no other significant difference was observed among the performance of the other groups (athletes and controls, $p = .14$; musicians and athletes, $p = .33$). See Figure 2.

We also compared the performance of athletes experts in sports that involve rhythmic movements ($n = 13$) with experts in other 'non-rhythmic' sports (e.g. soccer, rugby, volleyball; $n = 18$) in order to examine whether the expertise could influence their performance in the timing tasks. An independent sample t-test indicated that there was no

statistical difference between both athlete groups on either the circle task, $t(29) = 1.40$, $p = .17$, or the finger tapping task, $t(29) = .31$, $p = .75$.

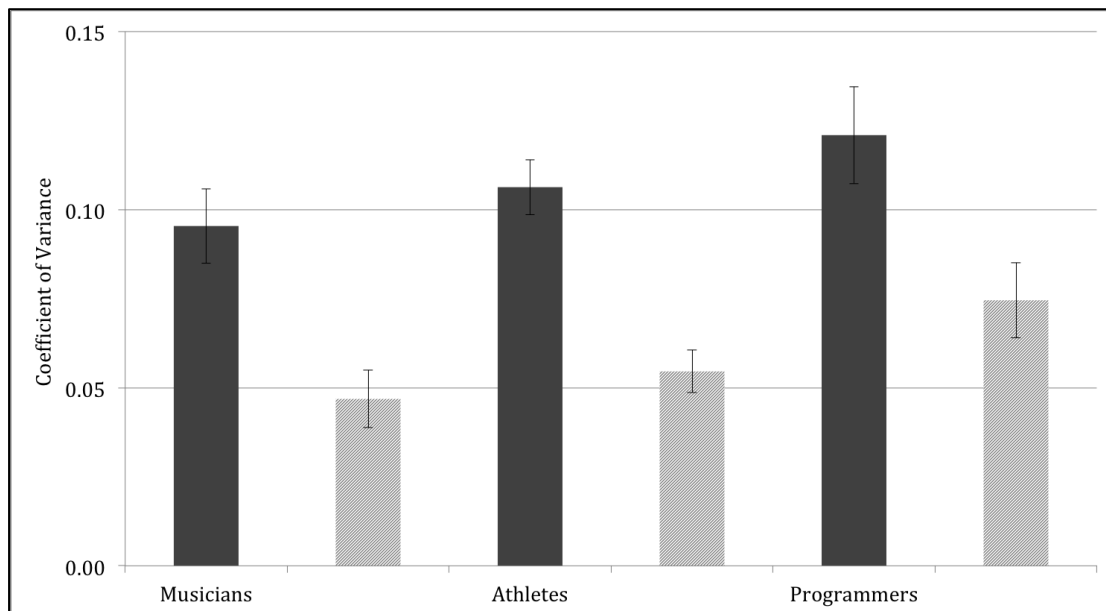


Figure 2. CV by Task and Group. Dark grey bars represent average CV for the circle drawing task in Experiment 2, light grey patterned bars represent average CV for the finger tapping task.

Previous research has suggested that the introduction of a perceptual event, such as tactile or auditory feedback, strongly induce event timing strategies even for tasks performed with continuous smoothly produced movements (Zelaznik & Rosenbaum, 2010; Studenka, Zelaznik & Balasubramaniam, 2012). However, it has been shown that training can interact with timing strategies adopted to maintain accuracy in timing tasks (Baer et al., 2013). One generally accepted indicator of the timing strategy adopted in a given task is found through the analysis of lag 1 autocorrelation. Tasks that adopt a event timing strategy exhibit lag one autocorrelation values between $-.5$ and 0 , whereas tasks believed to engage primarily emergent timing strategies are associated with a non-negative lag one (Zelaznik &

Rosenbaum, 2010; Delignieres & Torre, 2011). To determine the effect of the auditory feedback on the timing strategy adopted by musicians, athletes and non-experts, lag 1 autocorrelation scores from Experiment 1 and 2 were entered into a repeated-measures ANOVA with Task (2) and Tempo (2) as within-subjects factors and Group and Experiment as between-subjects factors. Results indicated significant interactions between Task and Experiment, $F(1,96) = 10.54, p = .002$, and between Task and Group, $F(5,96) = 3.38, p = .007$, and a significant main effect of Group, $F(5,96) = 2.55, p = .03$. Post hoc analysis of the interaction between Task and Experiment revealed that the introduction of the auditory feedback significantly evoked a change in the strategy in the circle drawing task ($p < .0005$) but not in the tapping task ($p = .76$).

To further examine whether participants' expertise was a factor in determining the strategy adopted, pairwise comparisons between Task and Experiment for each group were performed, as displayed in Figure 3. The analysis revealed that musicians generally adopted an emergent timing strategy to perform the circle drawing task in the absence of feedback ($M = .02$). With the introduction of the auditory feedback results indicated that musicians tended to change the strategy to event timing strategies to perform the same task ($M = -.007$), although the difference between lag 1 values in both conditions did not reach significance, $F(1,96) = 1.29, p = .25$. The introduction of auditory feedback also seemed to have affected the strategy adopted by the control group, as it was observed that the lag 1 values in the circumstance where no auditory feedback was provided was non-negative ($M = .05$), whereas the presence of salient perceptual events in the completion of the timing interval significantly induced event timing processes to complete the circle drawing task ($M = -.04$), $F(1,96) = 8.97, p = .003$. On the other hand, results indicated that athletes tended to adopt an emergent timing strategy to perform the circle drawing task in the absence ($M = .10$) as well as in the presence of auditory feedback ($M = .04$). This evidence suggest that for this particular

population highly trained in rhythm continuous movements, the presence of a perceptual event marking the timing intervals did not interact with the timing strategy adopted to maintain accurate of rhythmic movements.

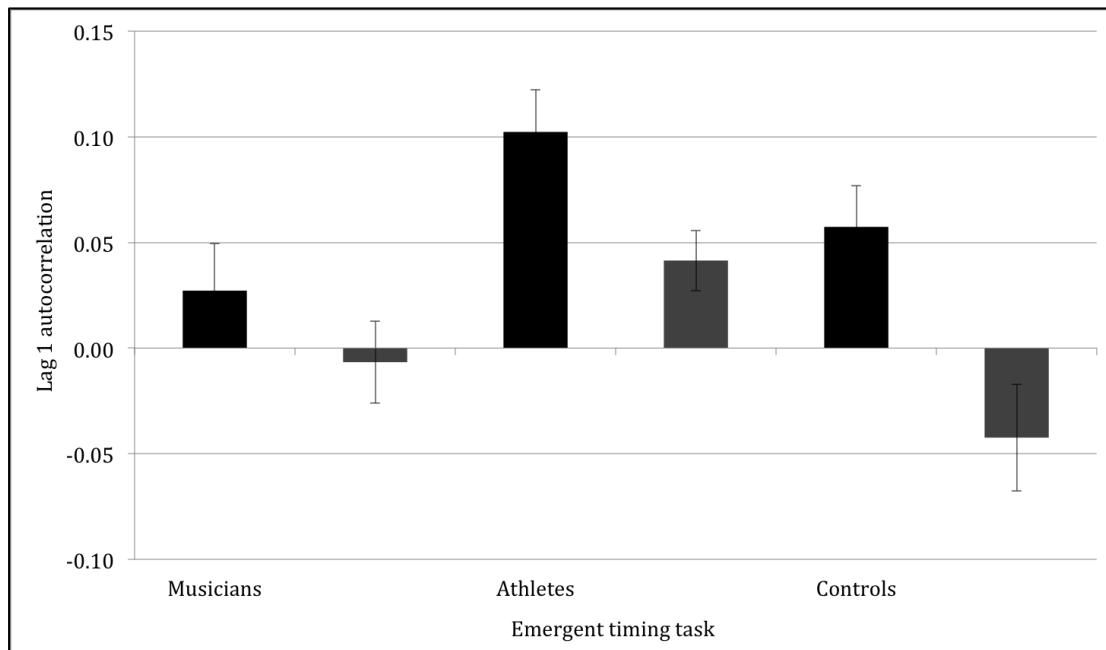


Figure 3. Lag 1 Autocorrelation by Group and Experiment on the emergent timing task. Black bars: average Lag 1 autocorrelation values in Experiment 1 (no auditory feedback); Dark grey bars: average values in Experiment 2 (with auditory feedback).

Discussion

We found that the introduction of a feedback tone marking each response interval at the continuation phase of the circle drawing task elicited event timing strategies for musicians and controls, whereas it did not induce a change in strategy for the athletes, who continued to employ emergent timing to complete the task. This finding supports the hypothesis that the distinction between event and emergent timing is not an all-or-none process, and expertise and training are significant factors to determine the timing mode adopted to control timing accuracy of rhythmic movements. This result corroborates a growing body of evidence that

the distinction between these timing mechanisms is subject to influence of order effect and practice (Jantzen et al., 2002, 2004; Zelaznik & Rosenbaum, 2010), differences in feedback (Studenka & Zelaznik, 2011), rate (Huys et al., 2008), as well as expertise and training in a given mode.

These results suggest that expertise and training reinforce a predominant timing mode, however, it was also demonstrated that movement-based expertise engages both timing mechanisms. It was shown that musicians were significantly more accurate than controls in both timing tasks, confirming results presented in Experiment 1. Taken together, these findings suggest that the control of complex rhythmic movements, such as those involved in music performance and sports activities, engage both types of movements, hence interacting with event and emergent timing mechanisms. This perspective is aligned with studies showing that event and emergent timing coexist and may be employed in different stages of a timing task, although one timing mode may be dominant in particular tasks (Repp, 2008; Repp & Steinman, 2010; Zelaznik et al., 2005).

Interestingly, Experiment 2 showed no difference in the performance of athletes, musicians or controls in the circle drawing task. This result contrasts with those reported in Experiment 1, which could be due to methodological choices or the different timing strategy adopted by musicians and controls to complete the task. A study conducted by Elliot et. al. (2009) concluded that event timing is preferred in synchronization tasks given that smooth continuous actions are more variable and slower to adjust after perturbations in the sensory input. Thus, it is reasonable to assume that the presence of feedback, which primed the use of event timing for musicians and controls, may have contributed to the difference in results.

General Discussion

The present work provides relevant new information on the distinction between event and emergent timing mechanisms by showing that expertise and training are fundamental

elements to determine the dominant timing mode employed in different tasks. Results suggested that movement-based activities engage both timing modes, although one timing mechanism is often dominant. These results corroborate the notion that the circumstances under which a given timing mode is engaged are complex, suggesting that the dissociability between event and emergent timing is not an all-or-none process.

It was demonstrated that athletes tended to be significantly more accurate than musicians and controls in the circle drawing task, whereas musicians were more accurate than controls at the tapping task in the absence of auditory feedback. These results indicate that intense training and expertise improve timing accuracy in a dominant timing mode, corroborating the idea that music performance relies predominantly on event timing (Baer et al., 2013), and that athletic activities employ predominantly smooth and continuous movements based on emergent timing. These findings are important new information that training does interact with accuracy in smooth and continuous movements, a subject relatively less explored in the literature of timing and expertise. It is well known that music training enhances tapping accuracy and can significantly improve interval discrimination and perceptual sensitivity to timing perturbations (Aschersleben, 2002, Repp, 2010; Buonomano & Karmarkar, 2002; Ivry & Schlerf, 2008). We also showed that expertise and training in motor activities predominantly based in emergent timing can improve timing control of smooth and continuous movements, which could have important implications in motor rehabilitation and pedagogy.

More importantly, it was also noted that movement-based expertise engages both timing mechanisms. This important finding suggests that emergent and event timing are not completely dissociable mechanisms as initially assumed, adding evidence in accordance with a growing volume of work that suggest that both emergent and event components significantly influence timing performance and that a number of factors interact with these

timing mechanisms (Repp, 2008; Repp & Steinman, 2010; Studenka et al., 2012; Jantzen et al., 2002, 2004). Therefore, we conclude that discrete movements rely predominantly on event timing and continuous rhythmic movements rely more heavily on emergent timing, and expertise and training reinforce a dominant timing mode.

We suggest that expertise and training, rate (Huys et al., 2008), instructions (Huys et al., 2010), practice and order effect (Jantzen et al., 2002, 2004), feedback (Studenka & Zelaznik, 2011; Zelaznik & Rosenbaum, 2010), kinematics (Robertson et al., 1999; Ivry et al., 2002), are all elements that are integrated and uniquely contribute to the generation of an internal representation of time (Coull & Nobre, 2008; Zelaznik, Spencer & Ivry, 2002). The following step in understanding the distinction between event and emergent timing is, perhaps, to comprehend the nature of the internal representation of time underpinning these two timing processes and the contribution of different cognitive and motor aspects to the production and maintenance of accurate rhythmic actions.

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Chapter 5

Understanding the role of music training in the development of event and emergent timing skills in children and adolescents.

ABSTRACT

The present chapter aims to expand the discussion on the role of skill and training in timing by addressing the question of whether the interaction between expectancy and timing is formed through years of intense training. To examine the role of training on the development of timing mechanisms, Chapter 5 described the results of an experiment that tested whether school-age children of 10 to 14 years old with formal music training would perform significantly more accurately than age-matched students with little or no musical training (< 2 years). Results are discussed in relation to the current knowledge about the development of timing skills and the role of music training.

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Rhythmic Movements and Music Training: a Developmental Study

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Authors contribution: The first author was responsible for the experiment preparation, data collection, analysis and manuscript preparation. Bill Thompson and Ronald Ranvaud provided feedback and suggestions regarding the writing of the manuscript.

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Abstract

Introduction: When people sing and clap along with the music in a concert, or play music and dance together, they engage in forms of temporal entrainment. Temporal entrainment refers to the natural, spontaneous and automatic rhythmic synchronization of movements to the beat of the music. Recent studies and theories have supported the hypothesis that discrete and continuous rhythmic movements rely on two dissociable timing mechanisms, event and emergent timing. However, little is known regarding the role of training in the development of these timing mechanisms. In the present study, we examined the effect of music training in the accuracy of sensorimotor synchronization of finger tapping and circle drawing in children of 10 to 14 years of age, both musicians and nonmusicians. We predicted that music training would reinforce one dominant timing mechanism, and therefore, would have its largest effect on the event-based tasks, supporting the hypothesis that training reinforces a dominant timing mechanism.

Materials and Methods: We compared the accuracy of the performance of fifty-seven 10-, 12- and 14-year-old students (31 musicians, 26 nonmusicians) in the finger tapping and circle drawing tasks. For each task, participants initially synchronise their movements with a metronome pacing and then maintained the same rate but without the metronome.

Results: Analysis of the continuation phase of the trials revealed that musicians tended to be significantly more accurate than nonmusicians in the finger tapping task. Musicians also showed better performance on the circle drawing task, although the effect was not as strong as in the tapping task. Correlation analysis confirmed that music training and years of formal training were associated with better performance in the finger tapping task, however, such effect was only present when participants had an average of at least of 4 years of training. On the other hand, accuracy in the circle drawing task was greatly associated with the age of the participants.

Discussion: These results suggest that music training reinforces the link between music training and event timing along the years of training and that the natural maturation of the motor system is crucial for the development of accurate smooth and continuous rhythmic movements. Additionally, it was also demonstrated that musicians were more accurate than nonmusicians in the circle drawing task, although its effect was not as large as in tapping, which suggests that although there is a dissociation between event and emergent timing mechanisms, training in movement-based activities, such as music, may engage both timing systems, one being predominant.

When people sing and clap along with the music in a concert, or play music and dance together, they engage in forms of temporal entrainment. Temporal entrainment refers to the natural, spontaneous and automatic rhythmic synchronization of movements to the beat of the music, or when we coordinate our actions with another person when playing music in an ensemble or when dancing another person (Phillips-Silver & Keller, 2012). Most people are able to synchronise rhythmic movements with the music with relative ease and spontaneity, and with imprecise precision, even without any form of formal training in music, sports or dance. This apparently trivial phenomenon, however, is only possible given to a complex set of timing skills that are gradually developed.

In order to tap, sing, drum or dance with music, it is essential to be able to detect and extract the beat of the music. The beat (or pulse) is the basic unit of metrical structure that is established by the occurrence of regular, and hence predictable, musical sounds (Jackendoff & Lerdahl, 2006). Studies have shown that the basic neural substrates that allow for the processing of duration and detection of beat regularity are already functional at birth (Winkler, Haden, Ladining, Sziller, Honing, 2009; Kushnerenko, Ceponiene, Fellman, Huotilainen, Winkler, 2001; Ceponien et al., 2002; Cheour et al., 2002), and that infants as young as 2 to 4 months old are able to extract beat duration and detect small tempo differences in isochronous sequences (Demany, McKenzie & Vurpillot, 1977; Baruch & Drake, 1997; Chang & Trehub, 1977; Trehub & Hannon, 2006). However, whereas the basic and essential perceptual mechanisms for processing of musical rhythm are established throughout the first year of life, the ability to produce rhythmic movements in synchrony with music matures gradually.

The literature suggests that infants start producing spontaneous rhythmic movements in response to stimuli with a clear and stable beat, particularly music, from the age of 5 months (Eerola, Luck & Toiviainen, 2006; Zentner & Eerola, 2010). However, there is little

evidence that children are able to produce rhythmic movements that are timed to or synchronised with the music before the age of 4 years (Zentner & Eerola, 2010; Morgan, Killough & Thompson, 2013; Provasi & Bobin-Begue, 2003; Drake, Jones & Baruch, 2000; McAuley, Jones, Holub, Johnston & Miller, 2006). Importantly, Drake and colleagues (2000) noted that although 4-year-old children can reproduce rhythmic patterns and synchronise to the music, they are only able to do so within a restricted range of tempi. This range gradually develops and expands between the ages of 4 and 10 years, suggesting that there are age-specific synchronization regions and that the ability to process and produce discrete movements at different time span improves gradually with age reaching stable levels at adolescence (around 15 years of age) (Baruch, Panissal-Vieu & Drake, 2004; Drake, Jones & Baruch, 2000; McAuley et al., 2006; Trainor & Corrigan, 2010; Drawing, Achtersleben & Li, 2005).

It is important to note, however, that the majority of studies to date that have investigated the development of the ability to synchronise rhythmic movements with music have adopted tasks that engage primarily discrete movements, such as finger tapping, foot tapping and clapping. Discrete rhythmic movements are periodic actions preceded and followed by a period without motion, and the literature suggests that music performance engages predominantly this type of rhythmic movements. However, there are a variety of rhythmic movements in music that require smooth and continuous rhythmic movements, such as arm movements involved in the control the bow of a violin or percussion mallets, or dance movements that may involve a variety of fluid and continuous movements that are precisely synchronised with the beat of the music. Continuous rhythmic movements, typically represented by tasks such as circle drawing, are periodic smooth and continuous movements that lack clear action endpoints (Huys et al., 2008). Besides the evident kinematic difference between these two classes of rhythmic movements, recent research has demonstrated that

different brain areas and cognitive processes are associated with the production and maintenance of temporal control of discrete and continuous movements (Spencer et al., 2003; Schaal et al., 2004; Zelaznik, Spencer & Ivry, 2005; Studenka, Zelaznik & Balasubramaniam, 2012; Robertson et al., 1999; Zelaznik et al., 2002; Zelaznik & Rosenbaum, 2010; Repp & Steinman, 2010). It has been proposed that discrete movements are event-based, involving a clock-like neural process and an explicit internal representation of the time interval delineated by each discrete movement. In contrast, activities that involve smooth and continuous rhythmic movements are based predominantly on emergent timing, where timing regularity arises from the control of parameters such as movement velocity and trajectory control in the absence of an explicit representation of time interval (Robertson et al., 1999; Zelaznik et al., 2002; Huys et al., 2008; Zelaznik & Rosenbaum, 2010; Studenka et al., 2012).

It is still unclear whether the formal training and practice could play a significant role in establishing and reinforcing the dissociation between event and emergent timing. Research has shown that early exposure to music, social context, culture, and enriched experiences with music from young age significantly impact the development of timing skills (Kirschner & Ilari, 2013; Kirschner & Tomasello, 2009; Gerry et al., 2009; Trehub & Hannon, 2009; Hannon, Soley & Levine, 2011). It has been shown that formal music training in music significantly enhances accuracy in sensorimotor synchronization. Drake et al. (2000) demonstrated that children from 6-10 years who received music training were significantly more accurate at rhythmic production tasks than age-matched counterparts (Drake et al., 2000). Drake (1993) also showed that 7-year-old children who had music classes performed as well as untrained adults in tasks that required ability to reproduce rhythmic patterns. Studies have also shown that musically trained adults tend to show smaller asynchronies between movement and onset of metronome click, and lower tapping variability when compared to nonmusicians counterparts (Aschersleben, 2002, Repp, 2010). Finally, it has

been recently suggested that music expertise interacts with timing strategies adopted to perform timing tasks, as musicians tend to use even timing to perform circle drawing and tapping tasks (Baer et al., 2013).

On the other hand, it remains to be explored whether music training interacts with accuracy in continuous rhythmic movements. A recent study has suggested that music training improved temporal accuracy in tapping tasks, but not drawing, supporting the hypothesis that music performance relies on event timing (Baer et al., 2013). Conversely, recent investigations have proposed that the dissociation between event and emergent timing is not as rigid as initially proposed and that a number of elements interact with the event-emergent timing dissociability, including learning and practice (Jantzen et al., 2002, 2004; Studenka et al., 2012). In the present study, we investigated whether formal music training enhances accuracy in event-based tasks (e.g., finger tapping), in particular, whether years of training would be related with the amount of the effect on event-based timing. We also tested whether music training would interact with accuracy in emergent-based tasks (e.g., circle drawing). For that, we examined the performance of children and adolescents from 10 to 14 years of age, in a range of years of music training. We hypothesized that, given to the strong association between music performance and clock-like mechanisms, formal music training would reinforce event-timing strategies and therefore have its largest effect on the discrete movements task. We predicted that years of music training would be directly associated with the effect in the accuracy of finger tapping. However, if musicians also perform more accurately than nonmusicians in the circle drawing task, this would suggest that music training would engage both timing mechanisms, in a different level, or that the dissociation between event-emergent timing is less separable than previously thought.

Methods

Participants

Fifty-seven students (32 females, 25 males) were recruited at a private co-educational¹ school at the Northern area of Sydney/Australia that offers music as co-curricular activity. Eighteen students were from Year 5 (13 females, 5 males) at primary school, and had average age of 10.3 years ($SD = 0.5$). From these, 10 had music training ($M = 2.2$ years $SD = 1.7$) and 8 had no music training (< 2 yrs). Nineteen students (11 females, 8 males) were recruited from Year 7 with an average of 12.3 years of age ($SD = 0.5$), of which 11 were musicians ($M = 4.1$ years $SD = 2.1$) and 8 were nonmusicians (< 2 yrs of training). Finally, 20 students were recruited from Year 9 (9 females, 11 males) with an average of 14.3 years of age ($SD = 0.5$), which 11 were musicians ($M = 5.7$ years $SD = 3.2$) and 9 were nonmusicians (< 2 yrs of training). All musician students were enrolled in music classes and involved in at least 2 hours of weekly activities, whereas nonmusicians were not involved in any musical activity. None of the participants reported any form of hearing or motor impairment. This experiment was approved by Macquarie University Human Research Ethics Committee. Parents and caregivers were informed and debriefed about the goals of the experiment and consent their child's participation in this study. Participation was voluntary.

Materials and Equipment

Stimulus presentation and data collection were accomplished using Macbook *Pro 9, 2* computers running custom software written in Python. The tones were produced by a Roland RD-250s digital piano and were presented over Sennheiser HD 515 headphones at 74 dB SPL. Circle drawing and tapping tasks were completed with the right hand using laptop's mouse pad.

Stimuli and Procedure

The continuation-tapping paradigm was adopted for both tasks (Stevens, 1886). For each trial, participants first synchronised their movements (circle drawing or tapping) with a

¹ Mixed-gender education

metronome click for 18 clicks. The signal tones were 40 ms square waves clicks of 480 Hz of frequency and 74dB. After the synchronization phase, the metronome stopped and participants continued to produce 36 more movements at the tempo set by the metronome. Within each trial, one of two metronome tempi was used: slow (75 BPM) or fast (100 BPM).

In the event timing task, students tapped with their index finger at the tempo set by a metronome tone and continued when the cue was removed. In the continuation phase, every tap triggered a feedback tone, which was identical to the metronome tones. In the emergent timing task, participants repeatedly moved their finger in a circle clockwise direction in time with the metronome and continued the task in the absence of the external timing cue. Participants traced an unfilled circle template of 5 cm in diameter displayed on the screen, and every time the path of the finger crossed an intersection at 180 degrees of the circle (9 o'clock), the auditory feedback tone was presented. Participants were instructed that timing accuracy was more relevant than drawing accuracy, and they were free to draw a circle at a preferred size.

For the tapping task, participants repeatedly tapped on the mouse pad with their index finger of the right hand at the tempo set by the metronome. Mouse pad was configured at high sensitivity, therefore, not producing any additional sounds in response to the taps.

Participants had 5 practice trials at 100 BPM before each experimental block. Trials were blocked by task, and order of presentation was counterbalanced between participants. Within each block, a total of 16 trials were presented: 8 at slow tempo and 8 at the fast tempo. Trials where inter-response intervals were above or below 60% of the mean IOI for the trial were discarded and re-done immediately. With breaks offered between trials at participants' discretion, the task took approximately 30 minutes.

Data Analysis

Taps in the synchronization phase were used for the purpose of ensuring that tempo was consistent between participants therefore, only taps in the continuation-phase were analyzed. It is well established that accelerations commonly occur at the transition between synchronization and continuation phases (Flach, 2005). Thus, the first 5 movements in the continuation phase were discarded and the final 31 cycles were subjected to analysis.

For the tapping task, inter-response interval (IRI) was defined as elapsed time between taps (in milliseconds) and for the circle drawing task, IRI was defined as elapsed time between passes through the intersection. To measure timing accuracy we analyzed participant's coefficient of variation (CV), which was defined as the standard deviation of IRIs within a trial divided by its mean IRI (SD/Mean). The average coefficient of variation was calculated across all trials for each condition and individual. This measure contains all sources of variability, such as long-term drift through the trial. Lower CV scores indicate greater accuracy. CV scores were averaged by task and tempo for each participant and entered into ANOVA with Task (circle drawing, tapping) and Tempo (fast, slow) as within-subjects factors, and Age (10, 12, 14) and Group (musicians, nonmusicians) as between subjects factor.

Results

Results indicate a significant difference between the student's performance on the timing tasks, Task, $F(1, 51) = 271.89, p < .005$; participants were significantly more accurate in the tapping task ($M = .07$) than in the circle drawing ($M = .20$). Furthermore, analysis suggest that there was a significant interaction between Task and Tempo, $F(1, 51) = 27.07, p < .005$, which revealed that participants tended to be more accurate when drawing a circle at a slow tempo ($M = .19$) than a fast tempo ($M = .23$), whereas this interaction between tempo and task was not observed in the tapping task ($M_{fast} = .070, M_{slow} = .072$).

Between-subject analysis indicated that there was a significant main effect of Group, $F(1, 51) = 6.59, p = .01$. More specifically, data revealed that there was a significant interaction between Group and Task for the finger tapping, $F(1, 51) = 8.31, p = .006$, which demonstrated that musicians tended to perform significantly more accurately on the tapping task ($M = .06$) than nonmusician students ($M = .08$). On circle drawing task, results showed that, although musicians ($M = .19$) tended to be more accurate than nonmusicians ($M = .23$), the difference in the accuracy levels was only marginally statistically significant, $F(1, 51) = 3.67, p = .06$. The Age of participants was also a significant factor in determining the accuracy in the performance of the timing tasks, Age $F(2, 51) = 3.38, p = .04$, which was confirmed by the correlation analysis. Results revealed a correlation between participant's age and accuracy in the circle drawing task ($r^2 = .29, n = 52, p = .02$), but not with tapping ($r^2 = .29, p = .02$), whereas Group and Years of Training of the participants were significantly correlated with participant's performance on the tapping task, Group ($r^2 = .35, n = 52, p = .007$) and Years of Training ($r^2 = .41, p = .002$), not for circle drawing (respectively, $p = .06$ and $p = .08$). These findings suggest that formal music training significantly enhanced accuracy in the performance of the event-based task, whereas age, thus the natural maturation of the motor system plays a crucial part in the accuracy in the emergent timing task (Figure 1). It was interesting to note, however, that music training improved the performance on the tapping task for 12- and 14-years old students ($p = .003; p = .05$, respectively), but not for the 10-year-old participants ($p = .06$)

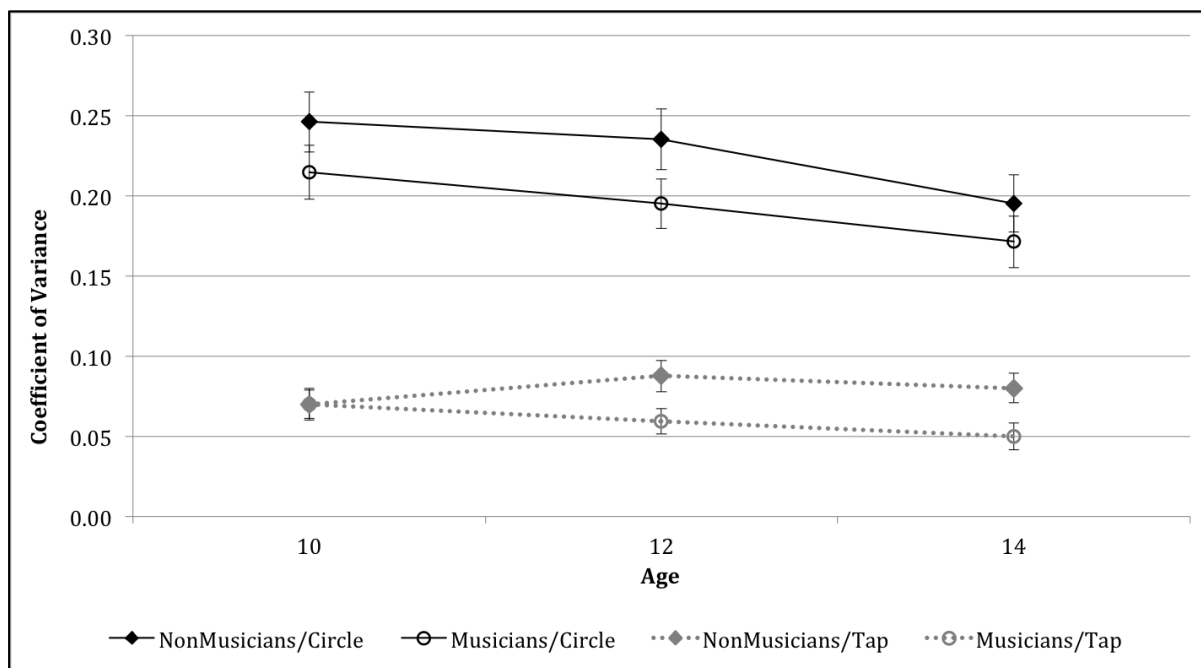


Figure 1. Coefficient of Variation compared between Task, Age and Group. Filled marks and dashed lines represent performance on circle drawing task, whereas unfilled marks and straight lines represent results from tapping task.

There was a significant correlation between tapping and drawing tasks ($r^2 = .30$, $p = .02$), which suggest that participants adopted a similar timing strategy to complete both task probably induced by the auditory feedback presented in the continuation phase of the trials (Zelaznik & Rosenbaum, 2010). Autocorrelation lag one analysis revealed that both circle drawing and finger tapping tasks were performed in event timing mode as mean lag 1 values for circle drawing and finger tapping did not differ ($M_{tapping} = -.04$, $M_{drawing} = -.05$, $p = .44$). Interestingly, ANOVA tests suggested a significant interaction between Task, Group and Age $F(2, 450) = 3.74$, $p = .02$, which was confirmed in a post-hoc analysis that indicated that 12-year-old nonmusicians used emergent timing to perform the circle drawing task, whereas age-matched musicians adopted an event timing strategy to perform the same task, $F(1, 450) =$

8.84, $p = .003$. In the other age groups, all participants performed both tapping and circle drawing with event timing mechanisms.

Discussion

To better understand the role of music training on the development of emergent and event timing skills we explored the question of whether formal music training would interact with accuracy in the performance of two tasks that represent the distinct timing mechanisms, finger tapping and circle drawing. Results indicated that students with formal music training were indeed significantly more accurate than nonmusician counterparts in the finger tapping task. This finding was confirmed by a significant correlation between years of training and accuracy in the tapping task, suggesting that formal music training interacted significantly with event timing mechanisms. However, findings also revealed that students with music training performed more accurately than nonmusicians in the circle drawing task, although the effect was not as strong as in the tapping task. This result is opposite to Baer et al. (2013) who reported that musicians and nonmusicians (adults) did not differ in the circle drawing task. It can be hypothesized that through experience, practice, and years of formal training, one predominant timing mode is reinforced and emphasized.

A result in favor of the suggestion that training reinforces a dominant timing mechanism and strengthens the interactions between event timing and music performance is that the effect of music training in the accuracy in the tapping task was only evident in students of 12 and 14 years of age, not having a significant impact in the performance of 10-year-old participants. Students in the youngest group tested had on average 2 years of music training, whereas 12- and 14-years old musicians had on average 4 and 6 years of training, respectively. This result indicates that the effect of music training on event-based task may be mediated by years of training and experience in one given timing mode. Van Mier (2006), showed that children of 4 and 5 years olds performed both discrete and continuous tasks

using event timing strategies, and it was only after the age of 6 that children were able to draw circles with smooth and continuous movements. Taken together, these results suggest that the dissociation between event and emergent timing may be gradually established, and greatly mediated by learning and training.

It was interesting to note that the accuracy in the performance of nonmusicians in the tapping task did not enhance significantly across the different age groups, which suggests that the level of accuracy is already high in 10-year-old children and there may not be a lot of room for significant natural improvement. Drake (1993) showed that 5 years old children exhibit imprecise accuracy in tasks such as reproduction of simple rhythmic patterns, arguing that certain timing skills do not improve significantly with age, but can be significantly affected by music training. On the other hand, results showed that participant's age was significantly associated with accuracy in the circle drawing task, suggesting that the natural development of the motor system is crucial for the improvement of the timing control required to perform rhythmic continuous movements. More importantly, results suggest that the development of the set of timing skills required to perform accurately synchronised continuous movements may not be completely stable at adolescence and could continue improving with age.

Evidence here described suggest that the effect of music on event timing is associated with years of formal music training, which suggests that the dissociation between event and emergent timing is reinforced by training, practice and learning. It was also demonstrated that music training interacted with the performance of circle drawing, although to a lesser effect, supporting the suggestion that the dissociability between event and emergent timing is less separable than previously suggested.

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Chapter 6

An examination of the role of formal music training in the development of timing skills: case study

ABSTRACT

Drawing on the results described in Chapter 5, this chapter further explored the interaction between training and timing skills by describing a case study of an exceptionally talented 12-year-old musician. The highly trained young musician had double the years of formal training than age-matched musicians. To verify the effect of training on accuracy of tapping and circle drawing tasks, the performance of the prodigy was compared with age-matched musicians and nonmusicians. Results were discussed in relation to the impact of training and the limits imposed by the natural maturation of the motor system. This chapter was submitted as part of a book where the subject of discussion was “musical prodigies”, which explains the particular focus on prodigies throughout the chapter.

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Development of Timing Skills

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Author note

Authors contribution: I was the major contributor to this co-authored paper. In particular, I was responsible for the experiment preparation, data collection, analysis and manuscript preparation. Bill Thompson and Paolo Ammirante both assisted with the experimental design and provided feedback and suggestions regarding the writing of the manuscript.

I also received technical support from Alex Chilvers, who was responsible for stimuli preparation and programming of the experiment.

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Abstract

Music is intimately connected with the experience of rhythmic movement. This unique relation between music and movement depends on a complex set of timing skills that are developed throughout childhood. However, extraordinary cases of rhythmic prodigies seem to violate the natural process of development, thus challenging the normal course of motor development. This chapter examines existing literature on timing skill in order to identify some milestones of the natural development of timing skills that are essential for the production of accurate rhythmic movements. Secondly, we consider the effect of the amount of formal music training and weekly practice for the development of timing skills involved in discrete and continuous rhythmic movements by describing a preliminary study with a prodigy musician and age-matched musicians and nonmusicians. The findings are discussed in relation to motor timing skills and music performance, as well in consideration to current models of ‘talent identification’ commonly adopted in music, sports, and dance.

Keywords: Timing – Training – Development – Prodigy – Music Performance

Music makes us move. The relation between music and movement is ubiquitous (Brown, 2003) and may be characterized as a unique, spontaneous, and universal phenomenon (Honing, 2012). This apparently trivial phenomenon results from a complex set of timing skills that are spontaneously developed. People without any formal music training can generate a steady beat or coordinate their movements with an external one, often with impressive precision. Children and adults clap and dance along with music with relative ease and spontaneity. Although recent studies suggest that some animals (particularly species characterized as *vocal imitators*) can move in synchrony with external rhythmic stimuli (Patel, Iversen, Bregman & Schulz, 2009; Hattori, Tomonaga & Matsuzawa, 2013), humans are uniquely skilled in their ability to intentionally and precisely synchronise movements to music (Jackendoff & Lerdahl, 2006; Grahn & Rowe, 2013; Bispham, 2006).

Despite the seemingly effortless nature of rhythmic movements, they entail a number of complex timing skills. These skills are progressively acquired and consolidated throughout development and enhanced with prolonged exposure and formal training. Informal interaction with music over the course of normal development significantly impacts the level of competency with which people engage with music of that culture (Hannon & Trainor, 2007). However, on the other side of the spectrum, there are few and rare cases of children that achieved extraordinary levels of competency in a small amount of time. These cases have fascinated throughout history, and extraordinary young musicians, such as W.A. Mozart, F. Mendelssohn, L. Beethoven, and Stevie Wonder, have been recognized as prodigies.

Among cases of prodigies in the domain of rhythm production (prodigy drummers), Buddy Rich's is well-documented. His rhythmic abilities expanded extremely rapidly such that by the age of 3 he was integrated into and even took top billing in his parents' vaudeville act as "Traps, the drum wonder" (Figure 1), becoming the second-highest paid child performer in the world by the age of 4 (Tormé, 1991). A newspaper review describes him as

having “the ability of a veteran jazz drummer” at the age of five (Tormé, 1991, p. 14). A surviving recording from 1929 (age 12) incorporates extremely rapid drum rolls and complex rhythmic patterns between hands and feet, showing that Rich had exceptional motor control at an early age and was clearly motivated by the physical challenges associated with playing the drums.



Figure 1. Buddy Rich as “Traps, the drum wonder” circa 3-years-old. Photo from Mel Tormé’s *Traps The Drum Wonder*.

Systematic studies of rhythmic prodigies are scarce, therefore it is difficult to access and verify whether their level of performance relies on technical skills and fluent and precise mechanical coordination, or whether it encompasses expressive components such as improvisation, creativity, and stylistic choices. A recent preliminary study conducted by Sowinski and colleagues (2009) revealed that a 5-year old prodigy drummer was significantly more accurate than adult nonmusicians at synchronizing with a metronome. The

study concluded that the prodigy's synchronization abilities were likely due to extraordinary motor control skills, as his result did not differ from adults on perceptual tasks.

What are the elements that contribute to outstanding rapid motor development observed in rhythmic prodigies, such as Buddy Rich, and elite athletes like Michael Phelps, who established a national record at the age of 10 and was the youngest man ever to set a swimming world record (age 15) (Phelps & Cazeveuve, 2012)? Several models have been proposed to understand the complex set of skills and environmental factors that contribute to such rapid development. Gagne's model establishes two types of abilities that compose the spectrum of skills of a prodigy¹: natural and systematically developed abilities (1995). This model identifies sensorimotor abilities as one of the five aptitude domains that are described as starting points for the development. Natural abilities are characterized as spontaneous skills that are revealed throughout the early years of life, and that are established without any systematic learning, training or practice and that soon show a large individual difference that cannot be solely explained by experience and training (formal or informal) (Gagne, 1995). One line of studies has focused on these natural abilities to explain genetic factors that may contribute to such rapid growth and maturity of these skills at young age (Friedman et al., 2008; Vandervert, 2009, Winner, 2000). Precocious talent identification is a common practice among many sports modalities that claim that early identification of gifted athletes allow close monitoring and preparation through the developmental process, hence increasing the changes of a successful carrier (Vandorpe et al., 2012). Perceptual-motor measurements involving motor coordination skills, such as temporal control of rhythmic movements, are

¹ According to Gange (1995, p.110) prodigy is a term that describes "extremely precocious talent". In his model, he adopts the terms talented and gifted, where giftedness is defined as "the possession and use of untrained and spontaneously expressed natural abilities" (p. 106) and talent is defined as "the superior mastery of systematically developed abilities (or skills)" (p. 107). Throughout this chapter, we adopt Feldman's (1993, p. 188) definition of prodigy as "a child (typically younger than 10 years old) who is performing at the level of a highly trained adult in a very demanding field of endeavor".

usually adopted as one of the tests to identify young athletes and predict future success in a variety of sports (Vandorpe et al., 2012).

It is also widely accepted that environmental factors (e.g., socioeconomic status, parental behavior), as well as training, learning, and exposure interact with the child's development (Gagne, 1995; Wider, 2000; Ericsson, 2006). Particularly in the area of music performance — perhaps in an attempt to demystify folk psychology ideas such as ‘inspiration’ and ‘inborn gift’ in relation to music performance — research in music psychology has greatly focused on the role of formal training in the development of music related skills (Sloboda, 2000). A study of 257 young musicians between 8 and 18 years was conducted by Sloboda et al. (1996) to understand factors involved in high achievement of performing musicians. This study found a strong correlation between level of achievement and the amount of daily practice, supporting the view that formal practice is a crucial determinant aspect of musical achievement. It was also shown that high achieving musicians started music lessons early in life. Further studies developed by Sloboda's lab also showed that musicians at the start of their professional carriers have accumulated around 10,000 hours of practice (Sloboda, 2007; Ericsson, Krampe & Tesch-Romer, 1993). Lehmann (1997) examined 14 historical musician prodigies and noted that all of them started music lessons before the age of nine and, for most of them, their music teachers were their own parents, which corroborates the perspective that formal practice, age of beginning of musical lessons, and parental engagement are key elements for music expertise (Howe & Sloboda, 1991).

The “10,000 hours” theory (Ericsson, 2006) has been criticized for its relatively simplistic approach to explain music expertise and prodigy (Hambrick et al., 2013) and current theories and studies suggest that a complex set of factors contribute to the development of such extraordinary skills at young age (Heller, Perleth & Lim, 2005; Baker & Cote, 2003; Ivaldi, 2011; Moore, Burland & Davidson, 2003; Campitelli & Gobet, 2011).

Current theories and investigations propose a more holistic approach, suggesting that, to advance in the study of the development of expertise skills, we have to identify as many potentially relevant factors as possible and deeply comprehend the natural development of the skills in place.

In the following sections of this chapter we explore the current literature in order to identify crucial developmental processes by which the unique ability to produce rhythmic movements is established throughout the normal stages of development. Much of this literature focuses on timing skills involved in accurate synchronization of rhythmic movements with external stimulus, such as a metronome, rather than self-paced rhythmic movements. Synchronization ability is crucial in ensemble music performance, athletic sports, and dance, and is defined by Gagne (1995) as being part of the natural abilities that can deeply relate to these movement-based activities. On the other hand, rhythmic talent may also involve the ability to take the lead in interactive contexts, which should place greater demands on self-paced timing. Although precision in both synchronization and self-paced timing can be used to index timing ability, they may engage somewhat different strategies (Semjen, Schulze, & Vorberg, 2000). Another important distinction made throughout the chapter is between discrete and continuous forms of movement, which appear to be based on different mechanisms and brain areas (Robertson et al., 1999; Zelaznik, Spencer & Ivry, 2005). Therefore, discrete and continuous rhythmic skills are examined separately in this literature review.

We also empirically examined the role of training and amount of weekly practice in of timing skills essential for music performance. A case study is described where the performance of a prodigy musician is compared with age-matched musicians with half of the years of training. We were interested in examining whether the amount of practice would be associated with better performance in finger tapping and circle drawing tasks.

The natural course of development of motor timing skills

Synchronization of rhythmic movements with music relies on a number of complex perceptual and motor processes that are refined across the life span. In order to clap, tap, sing, drum or dance with music, it is essential to be able to detect and extract the beat of the music. The beat (or pulse) is the basic unit of metrical structure that is established by the occurrence of regular, and hence predictable, musical sounds (Jackendoff & Lerdahl, 2006). Studies have shown the basic neural substrates that allow for the processing of duration and detection of beat regularity is already functional at birth (Kushnerenko, Ceponiene, Fellman, Huottilainen, Winkler, 2001; Ceponien et al., 2002; Cheour et al., 2002). Winkler and colleagues (2009) recorded electroencephalogram activity in healthy full term newborns 2 and 3 days postpartum while listening to two different sequences of a rock drum accompaniment pattern. In one of these sequences the downbeat of the sequence was occasionally omitted. Results showed that the brain of the newborns detected the omission of the beat (Winkler, Haden, Ladinig, Sziller, Honing, 2009).

Studies have also demonstrated that the perception of rhythm is developed very early in infancy, as by 2 months infants show increased interest in novel rhythmic information and are able to discriminate the tempi of beat patterns (Demany, McKenzie & Vurpillot, 1977; Baruch & Drake, 1997; Chang & Trehub, 1977; Trehub & Hannon, 2006). Studies with infants are generally based on the habituation/dishabituation paradigm, in which gaze duration is used as a measure of an infant's interest. Using this method, Baruch and Drake (1997) demonstrated that infants as young as 2 to 4 months old are able to extract the duration of the interval of events and detect small tempo differences in isochronous sequences. These results indicate that, like adults, infants use relative duration, size, and order of temporal patterns to discriminate rhythmic structures (Trehub & Hannon, 2006).

Interestingly, there are compelling suggestions that learning and enculturation rapidly shape the development of timing perception (Trehub & Hannon, 2006; Hannon, Soley & Levine, 2011; Hannon & Trehub, 2005a, 2005b; Bergeson & Trehub, 2006). For instance, 6-month-old infants show an enhanced perception for subtle changes in the timing of rhythmic patterns typical of Western tonal music but not unconventional ones, suggesting that prolonged exposure to culture-specific rhythmic patterns influences how listeners perceive meter (Trehub & Hannon, 2009; Hannon, Soley & Levine, 2011; Hannon & Trehub, 2005a, 2005b; Soley & Hannon, 2010). Enriched experiences with music and movement provided by Kindermusik classes also accelerate preferences for duple meter in 7-month-old infants (Gerry et al., 2009). One study even showed that the way that parents move and rock infants in time with the beat of the music influences infant's rhythmic perception. Phillips-Silver and Trainor (2005) presented 7-month old infants with unaccented, metrically ambiguous rhythms. One group of infants was bounced in the arms of the experimenter on every second beat of the music, whereas another group was bounced every three beats. Results showed that the group that was bounced every second beat preferred to listen to a version of the rhythm with accents on every second beat, whereas the infants bounced on every third beat preferred the sequence with accents on every third beat. This remarkable finding demonstrated that movement directly influences perception of meter and that the connection between movement and rhythmic is established very early in life.

When it comes to infants' own rhythmic response to music, studies have demonstrated that by 5 months of age infants start producing spontaneous rhythmic movements in response to isochronous stimuli, such as music (Zentner & Eerola, 2010). However, studies suggest that from 5 to 24 months of age infants exhibit periodic spontaneous movements, particularly in response to music, but there is no evidence that these

rhythmic movements are timed to or synchronised with the music (Zentner & Eerola, 2010; Morgan, Killough & Thompson, 2013).

The ability to produce discrete, self-paced rhythmic movements, such as finger tapping, seems to be evident only at the age of 2-3, where children start exhibiting a spontaneous regular rate when asked to tap or clap at their most comfortable tempo (Eerola, Luck & Toiviainen, 2006; Provasi & Bobin-Begue, 2003; Drake, Jones & Baruch, 2000; McAuley, Jones, Holub, Johnston & Miller, 2006). Interestingly, it is at the age of 2-3 that children develop a concept of time (Droit-Volet, 2002; Droit-Volet & Wearden, 2002).

It seems to be accepted in the current literature that, although children can produce spontaneous and stable rhythmic movements at a preferred rate by 2 and 3 years of age, the capacity to intentionally coordinate discrete movements in time with music is only developed by the age of 4 (Drake, Jones & Baruch, 2000; Repp, 2005). Importantly, Drake and colleagues (2000) noted that at this age children can synchronise and discriminate temporal information within a restricted range of tempi centered around 300-400 ms. This range gradually develops and expands between the ages of 4 and 10 years, suggesting that there are age-specific synchronization regions and that the ability to process and produce discrete movements at different time span improves significantly with age (Baruch, Panissal-Vieu & Drake, 2004; Drake, Jones & Baruch, 2000; McAuley et al., 2006; Trainor & Corrigan, 2010).

However, there are some documented cases of early synchronization ability. A well-known but apocryphal example involved the jazz drummer Buddy Rich. At 18 months, he attended a music rehearsal with his parents, who were vaudevillian performers. After being handed a pair of drumsticks, Rich tapped along with the tempo of the music, even following the tempo changes (Tormé, 1991). More recently, Merker, Eckerdal, and Madison (2009) documented a 12-month girl who maintained beat-for-beat synchrony with her mother for 19

consecutive beats using maracas. Interestingly, the infant had participated in “baby rhythmicity” classes in her first year of life. Thus, in these cases, precocity in synchronization was associated with early exposure to rhythmic music.

Social context and enculturation are also important factors in the acceleration of the development of timing skills. Children as young as 2.5 years old show more accurate synchronization to rhythmic patterns when drumming with a teacher than when drumming along with a recorded version of the stimuli (Kirschner & Tomasello, 2009). It has also been shown that Brazilian children were more likely to engage in spontaneous drumming in a social context compared to German children (Kirschner & Ilari, 2013), suggesting that early exposure to rhythmic movements within a cultural context influences the development of the ability to synchronise with music and with a musical partner (Phillips-Silver & Keller, 2012).

The literature examined so far focuses primarily on discrete movements, such as finger tapping, foot tapping or clapping, and has not considered continuous movements. Discrete rhythmic movements are periodic actions interrupted by contact with a rigid surface (e.g. finger tapping), whereas continuous rhythmic movements, e.g., circle drawing, are periodic smooth and continuous movements that lack such clear action endpoints (Huys et al., 2008). Besides the obvious kinematic difference between these two classes of rhythmic movements, recent research and theory has demonstrated that different brain areas and cognitive processes are associated with the production and maintenance of temporal control of discrete and continuous movements (Spencer et al., 2003; Zelaznik, Spencer & Ivry, 2005; Studenka, Zelaznik & Balasubramaniam, 2012; Robertson et al., 1999; Zelaznik et al., 2002; Zelaznik & Rosenbaum, 2010; Repp & Steinman, 2010). Music performance is strongly associated with discrete movements, however the motor coordination required to control the bow of a violin or cello relies on continuous movements.

A dissociation between discrete and continuous movements is also evident developmentally. Children's first scribbling attempts can be observed by 15 months, and at 2 years they start to learn to draw geometric shapes. But an important observation is that error correction and movement planning are not yet fully developed at this age, which suggests that it takes time for the development of motor control to perform smooth and continuous movements with accuracy (Rueckriegel et al., 2008; Bo et al., 2008). To examine developmental changes in the motor strategy adopted to perform discrete and continuous tasks, Van Mier (2006) measured the number of times children stopped while drawing zigzagging (discrete) and wavy (continuous) lines. Results showed that children of 4 and 5 years of age performed both tasks in a discrete manner, stopping almost as much in the wavy lines task as in the zigzag one. Only children over 6 were able to draw a circle continuously. This study reveals an important developmental distinction between discrete and continuous movements in motor control, suggesting that the proficiency to plan and control motor actions in a smooth and continuous manner requires more time to mature (Van Mier, 2006; De Boer; Peper & Beek, 2012).

Timing accuracy, visuo-motor coordination, and spontaneous limb entrainment improve considerably from the age of 8 years (Pellizer & Hauert, 1996; Getchell, 2006; Robertson, 2001; Bazile, Siegler & Benguigui, 2013). Bo and colleagues (2008) tested spatial and temporal variability in self-paced continuous and discontinuous (discrete) tasks with children ranging from 5 to 10 years old, and found that younger children exhibited the highest temporal variability for discontinuous circle drawing (in which there is a pause after each circle that is drawn). On the other hand, 10 year-olds showed similar temporal variability between continuous and discontinuous conditions, showing that the timing mechanisms that control discrete and continuous movements are fully functional and stable by the age of 10.

The body of work reviewed so far indicates that there are gradual and lengthy processes of development and natural maturation of motor control required to produce stable rhythmic movements that are synchronised with dynamic stimuli or self-paced. As suggested, the capacity to synchronise rhythmic discrete movements is only limited at the age of 4 and the timing mechanisms employed in the production of smooth and continuous movements are not yet fully developed by the age of 6. With this information in mind, it seems even more outstanding to note cases like Buddy Rich, who performed professionally at the age of 4. Is training associated with the development of such extraordinary timing abilities?

The role of training: a case study

According to the view shared by Sloboda et al. (1996), amount of practice is key to determining the acquisition of musical skills and achieving high levels of competency. The effect of effective music training is unquestionably important to the development of musical abilities and has been associated with increased accuracy in rhythmic production tasks in children and adults (Trainor, 2005; Drake et al., 2000; Aschersleben, 2002; Repp, 2010), and significantly improved interval discrimination and perceptual sensitivity to timing perturbations (Buonomano & Karmarkar, 2002; Ivry & Schlerf, 2008; Repp, 2010). However, we were particularly interested in understanding the effects of weekly training and years of formal music training in the accuracy of timed actions. Technical abilities are one essential component of skilled musical performance, in which the fluent coordination of motor output (intensity, duration, precise synchronization between different hands or different players) is important requirements of high quality technique (Sloboda, 2000).

Based on evidence that the amount of formal and effective training is directly associated with musical achievement (Sloboda et al., 1996; Sloboda, 2007) we predicted that the performance of a prodigy musician (12 years old, 8 years of formal music training, practicing 2 hours daily) on two self-paced timing tasks would be significantly better than

age-matched musicians and nonmusicians. If this prediction was confirmed, results would corroborate the vital effect of amount of training to the development of skilled music performance, suggesting that this paradigm could be used as a tool to identify rhythmic prodigies, as adopted in the synchronization study conducted by Sowkinski, Dalla Bella and Laskowska (2009). On the other hand, if results do not confirm this prediction, it could be suggested that a number of other elements, such as early exposure, natural abilities, intrapersonal context, and other environmental factors, could be associated with skilled musical performances.

In this preliminary study, participants were 12 years old students (11 females, 9 males) with music training that ranged from 0 to 8.5 years. Participants were grouped according to the extent of their music training. The nonmusician group consisted of 8 students with less than 2 years of music training and not currently involved in any musical activities; the musicians group consisted of 11 students with an average of 4 years of music training and all were currently involved in musical activities for at least 2 hours per week. The prodigy musician had 8.5 years of formal music training and was involved in an average of 2 hours of daily musical activities.

The main criterion to define the prodigy participant in this study was the age of his higher achievements according to the Australian Music Examination Board (AMEB). He started music lessons at the age of 3, formal piano lessons at 4 years old and double bass at 8 years. Recitals, workshops, and competitions were part of his musical activities already at 4 years old. In only four years of formal training in double bass, he achieved grade 6 in the AMEB performance examination, which is usually reached in the senior years of secondary school at age 17–18 (Geake, 1996). Currently, he holds a highly competitive music scholarship in a prestigious music school in Sydney, Australia, and has participated in several government and university programs for gifted students. By the time of this study he was 12

years old and was about to start Level 3 (Associate/Licenciate Diploma) of the Australian Music Examination Board diploma in music.

All participants completed two self-paced tasks: finger tapping and circle drawing synchronization. Students were instructed to time their movements as precisely as possible to coincide with a metronome and continue the task after the metronome stopped until the end of the trial (synchronization-continuation paradigm). The synchronization phase served only to ensure that tempo was consistent between participants. Auditory feedback was provided in the continuation phase; these sounds were identical to those generated by the metronome in the synchronization phase. For the tapping tasks, participants were told to use their right index finger and tap at the same pace established by the metronome, whereas for the circle drawing experiment participants used their right index finger to trace a small circle template using the mouse pad of a laptop. This circle template was presented as a guide and participants were free to draw a circle at a preferred size. Only data from the continuation phase were subject to analysis.

Results revealed that musicians were significantly more accurate in the (discrete) finger tapping task than nonmusicians. On the other hand, musicians and nonmusicians performed at similar levels of accuracy in the (continuous) circle drawing task. Accuracy in the discrete task (excluding the prodigy) was significantly correlated with years of formal music training. This finding reinforces the view that there is dissociation in the mechanisms of motor control involved in the production of discrete and continuous accurate rhythmic movements. Results also suggest that it may be that music training predominantly helps to refine discrete movements such that increased training has no significant effect on continuous movement skill, as proposed by the event-timing model (Repp & Steinman, 2010; Zelaznik & Rosenbaum, 2010; Baer et al., 2013). However, it is also possible that our group differences were not sufficient to reveal the effects of training on continuous movements.

On the other hand, when we compared the performance of the prodigy musician with age-matched musicians, results indicated that there was no statistical difference in the level of accuracy. Similarly, the prodigy was not more accurate than age-matched musicians at the circle drawing task. Taken together, these results indicate that, within the same age group, more years of formal training and hours of weekly training did not enhance mechanical precision in the execution and maintenance of accurate timing of finger movements.

This finding is somewhat surprising because, compared to the other musically trained children, the prodigy had double the number of years of music training and practiced significantly more frequently. This additional workload did not seem to have improved accuracy in a finger tapping task, suggesting that there may be limits to the impact of music training on the development of timing skills in children. These limits may be associated, for instance, with the gradual process of maturation of the motor system. Alternatively, there may be a ceiling effect that is reached quickly through music training. In support of the latter possibility, studies have shown that children are exceptionally accurate at tapping tasks. Drake (1993) reported that 5 year-old children were remarkably accurate in reproducing simple rhythms and 7-year-old musician children performed similarly to adult nonmusicians in a number of rhythm production tasks. Therefore, we can suggest that some timing abilities may be quite well developed naturally at a young age, and there may be little room for improvement through musical training at that stage of development.

Therefore, if motor precision and timing control did not differ between the performances of a prodigy musician and age-matched musicians, what could be the elements that distinguish skilled musical performances? Perhaps, the amount of formal training and practice is important to the development of elements such as the ability to express and communicate emotion through music.

Music is an affective form of expression and communication of emotional content, and as such, it is often labeled by listeners as sad, solemn, happy, etc. (Gabrielsson & Juslin, 1996). Performers are responsible for translating the intended musical content and projecting different emotional cues in a way that is readily decoded by trained and untrained audiences. Expressive skills demand stylistic knowledge and the manipulation of emotional cues such as articulation, timbre, intensity, vibrato, and tempo variations (Gabrielsson & Juslin, 1996). Expressive timing is defined as modulation of timing into acceleration-deceleration patterns that reflect musical segmentation and melodic gestures, and is often automatically performed by musicians (Repp, 1998). Expressive timing is often regarded as one of the most fundamental aspects of musical performance and it has been shown that listeners use expressive timing patterns to decode intended expressions (Juslin & Madison, 1999).

Mechanical performances that strictly adhere to notated durations sound robotic and unexpressive, and the absence of expressive timing leads to an artificial quality in music because listeners expect timing variation in music (Repp, 1998). Indeed, an analysis of the timing patterns of performances of a Beethoven minuet from several different pianists revealed that the ongoing pulse varied continuously in every performance analyzed (Repp, 1990). In other words, outstanding musical performances are not related to precise mechanical timing but rather to the ability to interpret composers' intentions and convey emotion through music.

Therefore, we suggest that the outstanding achievements obtained by the prodigy musician at such young age reflect a much more complex set of musical abilities that certainly include the capacity to express himself through music. Thus, beyond early timing precision and motor skill, skilled rhythmic performance may involve an ability to take a leading role in choosing stylistically appropriate and flexible tempi that are engaging to both listeners and performers. For example, conductor Lorin Maazel led the NBC orchestra at age

eleven, Buddy Rich became a bandleader at age eleven (Tormé, 1991), and jazz drummer Tony Williams was playing professionally by thirteen and joined Miles Davis' band at seventeen. Davis referred to Williams' drumming as

the center that the group's sound revolved around . . . He changed the way he played every night and played different tempos for every sound every night . . . you had to be real alert and pay attention to everything he did, or he'd lose you in a second, and you'd just be out of tempo and time and sound real bad (Davis, 1990, p. 264).

Conclusion

Early mastery of skills is still a complex topic of discussion and disagreement in the field of gifted education, which is reflected in the large variety of definitions and models that aim to account for this complex and not yet fully understood capacity. We explored only the surface of rhythmic prodigies and by no means did we intend to examine all the possibilities explanations present in the current literature. By examining the natural course of the development of timing skills involved in the production of rhythmic movements crucial for athletic sports, dance, and music, we were able to better understand the developmental complexities associated with acquiring and mastering timing skills at young age. The drummer prodigy Buddy Rich, who became second-highest paid child performer in the world by the age of 4, exemplifies the importance of early exposure, high level of natural sensorimotor abilities, self-motivation, and environmental factors.

The preliminary study presented in the chapter provides additional evidence that musical training does influence the development of accurate discrete rhythmic movements (e.g., finger tapping). But more importantly, it was demonstrated that within the same age group, additional workload reflected by the amount of weekly practice and years of formal training did not translate into higher accuracy of timed actions. We propose that the evaluation of technical skills, such as precise motor control, does not depict nor predict

skilled music performers. Therefore, future studies should aim to build a more holistic battery of tests, which includes technical and mechanical skills, but also abilities to take a leading role in choosing stylistically appropriate and flexible tempi. This observation may be particularly important for areas such as sports and dance that tend to use technical and motor skills as a tool to recruit promising athletes and dancers.

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Chapter 7

Conclusion

ABSTRACT

The final chapter revisits the theoretical framework motivating the three main hypotheses in light of the experimental findings reported in the thesis. I then discuss the implications of the findings for current theories of timing, and identify the limitations of the research. Future directions for research are also proposed.

Skilled performances such as dance, music, and athletic sport, require precise timing of bodily movements and the capacity to predict and respond to the timing of events. This thesis considered two types of timed movements: Discrete and continuous. It has been proposed that discrete and continuous movements rely on distinct timing mechanisms, namely event and emergent timing (Robertson et al., 1999; Zelaznik et al., 2002; Zelaznik et al., 2005; Spencer et al., 2003; Huys et al., 2008; Studenka et al., 2012; Degallier & Ijspeert, 2010). Event timing is thought to require an explicit internal representation of temporal intervals, whereas emergent timing arises from the dynamic control of nontemporal parameters of the produced movement, and hence does not require an explicitly defined mental representation of time (Zelaznik et al., 2002; Repp & Steinman, 2010). A central theme of this thesis is that expectancy and skill play a significant role in the distinction between event and emergent timing and the circumstances under which they operate. Expectancies are intrinsic to the representation of rhythmic actions and their consequences, and skill strengthens the alignment between expectation and action.

Anticipating the moment a certain rhythmic stimulus will occur is crucial for sensorimotor synchronization. Expectancies now only allow the motor system to react to events in the environment; they also allow us to synchronise our actions with external signals such as music. Such complex processes require an internal system that generates accurate predictions of the causal relationship between our actions and their consequences (Wolpert & Flanagan, 2001). This prediction system is described in the forward model, discussed throughout the thesis. The forward model postulates that expectancies are intrinsically related to actions, and that the expected motor and perceptual outcomes are integrated into motor commands (Schubotz & von Cramon, 2003; Hommel et al., 2001; Wolpert & Flanagan, 2001; Aschersleben & Prinz, 1995; van der Steen & Keller, 2013). Based on these assumptions, the present body of work examined whether 1) expectancy mechanisms are

integrated in the temporal coordination of continuous and discrete rhythmic movements; 2) feedback content (e.g. pitch, timbre, intensity) is integrated in the representation of motor timing; and 3) skill and training influence the interaction between expectancy and timing, resulting in enhanced accuracy of timed actions. In the next session, I revisit and discuss these hypotheses based on the experimental findings described throughout the thesis.

Overview of Experimental Findings

Chapters 2 and 3 focused on Hypotheses 1 and 2 - that expectancy mechanisms are engaged for discrete and continuous motor timing, and that feedback content is integrated in the representation of timing of motor actions. In Chapter 2, five experiments based on the synchronization-continuation paradigm examined the effect of an unexpected change in the pitch, timbre and intensity on accuracy of finger tapping. As predicted, unexpected perturbations of feedback content significantly disrupted the timing of discrete movements. This finding supports the hypothesis that timing is associated with a central expectancy process that integrates expectations for both motor and perceptual outcomes (Schubotz & von Cramon, 2003; Schubotz, 2007; Hommel et al., 2001; Bar, 2007; Bubic et al., 2010; Nobre & Coull, 2010; Munhall et al., 2009).

One important characteristic of the results reported in Chapter 2 is that the effect of the unexpected change in feedback tones disrupted timing by shortening the interval immediately following the change. This pattern was noted in all experiments, suggesting that expectancy mechanisms interact with timing in the same way irrespective of the magnitude or nature of the manipulations. Studies using event-related potentials (ERPs), which is an electrophysiological index of brain processes with high temporal resolution, suggest that unpredicted sensory outcomes of voluntary actions are processed as deviant events (Waszak & Herwig, 2007; Nittono & Ullsperger, 2000; Nittono, 2006; Heinks-Maldonado et al., 2005; Adachi, Morikawa & Nittono, 2011). Unpredictable stimuli may also be viewed as

distractors, given that unexpected events comprise an involuntary attention shift from the task-relevant information (in this case, timing) to nontemporal information. As a result, unexpected events may be perceived as shorter in duration than expected events of the same duration because attention is directed towards the deviant content and hence away from time. In this way, expectancy can indirectly affect the internal representation of time (Brown, 1997; Grondin, 2010; Lejeune, 1998; Debener, Kranczioch & Engel, 2002; Horvath, Roeber, Bendixen & Schroger, 2008; Nittono, 2006; Coull, 1998; Tse, Intriligator, Rivest & Cavanagh, 2004). Therefore, a possible interpretation of the results presented in this work is that unexpected changes in feedback engage bottom-up attentional mechanisms that interact with timing mechanisms (Humphreys et al., 1999; Debener et al., 2002).

An alternative interpretation of the effect observed is that unexpected stimuli increase arousal and thus increase the speed of the internal clock (Penton-Voak et al., 1996; Ulrich, Nitschke & Rammsayer, 2006; Seifried & Ulrich, 2010; Matthews, 2011). The arousal hypothesis states that surprising events are perceived to last longer than standard stimuli. To test the hypothesis that results were associated with an arousal or alertness effect, Experiment 1 (Chapter 3) tested four conditions where the degree of expectedness and the type of change was manipulated. Results suggest that the effect observed was more likely to be related to violation of expectations than general changes in the level of arousal. It was also demonstrated that unexpected *non-changes* in the content of feedback also significantly interacted with representation of timing.

Taken together, the experiments described in this thesis support the assumption proposed by the internal forward model that expectancy is intrinsic to actions and that perceptual outcomes of rhythmic movements are integrated in the representation of timing. To the best of my knowledge, this is the first series of experiments to reveal a general effect of expectations about feedback content on motor timing. The modified oddball paradigm

adopted in these experiments was an important tool to detect this interaction (see also, Ammirante & Thompson; 2012; Ammirante, Thompson & Russo, 2011). Unlike previous studies that used serial shifts (Pfordresher, 2006 for review), or combined pitch and temporal manipulations (Repp, 2003; Repp & Penel, 2004; Repp, 2005), this paradigm successfully isolated the effect of a single transient perturbation of feedback content in timing of discrete movements. This was important in order to examine the effect of local expectancies in the representation of timing.

In Chapter 3, the role of expectancy mechanisms was further examined through manipulations of the content of feedback in tapping and circle-drawing tasks. Results revealed that unexpected changes in the outcome of the actions significantly interacted with timing of discrete and continuous movements, which corroborates the suggestion that expectancy mechanisms are intrinsically integrated with rhythmic movements. However, it was observed that the effect of unexpected changes on timing differed between tapping and circle drawing. For the tapping task, the oddball led to a decrease in intertap interval at the interval immediately following the change in feedback tone. On the other hand, unexpected changes interacted with timing by increasing the inter-response interval on the second position after the perturbation.

These results are supported by studies showing that continuous movements are slower to adjust following changes in the sensory input in comparison with discrete movements (Repp & Steinman, 2010; Elliott, Welchman & Wing, 2009). Repp (2008) suggested that the difference in the interference effect of unexpected events in the two tasks is related to a greater “maintenance tendency” in continuous movements. This tendency is thought to be associated with the inertia associated with the movement (Repp, 2008; Repp & Steinman, 2010; Studenka et al., 2012).

Another interpretation of the findings reported in Chapter 3 relates to the possibility that expectancy processes may differ for event and emergent timing. Specifically, it has been argued that emergent timing is based on “strong anticipation” whereas event timing is based on “weak anticipation” (Marmelat & Delignieres, 2012). According to this hypothesis, strong anticipations arise from the close alignment between the action and its sensory outcome. In this case, the goal of the system is to maintain smooth and uninterrupted rhythmic movements based on global and often long term expectations. It is possible that the strong expectations associated with continuous movements inhibit rapid responses to environmental changes, thereby delaying the effects of unexpected events on motor planning.

On the other hand, event timing seems to be associated with “weak anticipation.” This expectancy mechanism is required in dynamic environments where unpredicted events require rapid and efficient correction in order to maintain accurate responses. Weak anticipation is associated with local and short-term expectancies, facilitating rapid intervention by error correction mechanisms (van der Steen & Keller, 2013; Dubois, 2003; Stephen et al., 2008; Marmelat & Delignieres, 2012).

Chapters 4-6 evaluated Hypothesis 3 – that timing is enhanced by skill and expertise. These chapters describe a series of experiments on the role of skill and training in motor timing. It is known that training in a movement-based skill reinforces internal predictions of motor and perceptual outcomes (Pecenka & Keller, 2011). One result of this fine-tuning between expectancies and timing is improved accuracy and enhanced capacity to adjust rapidly to unexpected changes in the environment and the body. To test whether training improves accuracy in event and emergent timing, Experiment 1 (Chapter 4) compared the performance of elite athletes, musicians and controls in circle drawing and tapping. Results revealed that movement-based experts were more accurate than controls in both event and emergent timing tasks. Moreover, athletes were significantly more accurate than musicians in

the circle-drawing task, whereas musicians and athletes did not differ significantly in the finger-tapping task. These findings indicate that skill and training engage both event and emergent timing but may reinforce a dominant or preferred mechanism when performing a domain-specific task.

These results also support the possibility that event and emergent timing are not as dissociable as initially conceived, in that they may be influenced by similar factors, such as practice, tempo, feedback and training (Studenka et al., 2012; Reep & Steinman, 2010; Repp, 2008; Jantzen 2002, 2004; Huys et al., 2008; Zelaznik & Rosenbaum, 2010). On the other hand, the present findings contradict a recent study suggesting that musicians and controls perform similarly in a circle-drawing task (Baer et al., 2013). Interestingly, Baer reported that musicians adopted an event timing strategy to perform the circle-drawing task, whereas the musicians in this study adopted an emergent timing strategy to perform the same task (Experiment 1, Chapter 4). Although further research is needed to explain this discrepancy, it appears that skilled performers can flexibly adopt different timing strategies to perform the same task.

To further examine whether skill and training interact with timing and expectancy mechanisms, Experiment 2 (Chapter 4) presented auditory feedback tones in the continuation phase of the trial. Previous studies have reported that participants tend to adopt an event timing strategy to perform a circle-drawing task when discrete perceptual events (e.g. tactile or auditory feedback) mark the completion of each cycle (Zelaznik & Rosenbaum, 2010; Studenka et al., 2012). In this study, however, analyses of movements indicated that musicians and controls tended to use event timing to complete the circle-drawing task, whereas athletes adopted an emergent timing strategy when performing this task. These findings indicate that skill and training significantly interact with the timing strategies adopted to perform rhythmic movements.

One interpretation of these findings is that athletes relied on global expectancies to perform the circle-drawing task whereas musicians focused on the feedback tones in order to generate local expectancies. This interpretation is compatible with the view that global and local expectancies are both deeply integrated with timing mechanisms and may be flexibly engaged when performing rhythmic movements. It is not possible to distinguish the role of expectancy from the timing mechanisms engaged, but based on the assumption that training and skill strengthen the alignment between expectations and environmental events, it is reasonable to suppose that the two types of experts used expectancies in different ways when performing these tasks.

The alignment between expectancies and motor actions is strengthened through many years of intense training. To examine the role of training on the development of timing mechanisms, Chapter 5 described an experiment that tested whether school-age children of 10 to 14 years old with formal music training perform timed movements significantly more accurately than age-matched students with little or no musical training (< 2 years). Results suggested that musicians were significantly more accurate than nonmusicians in both tapping and circle drawing, although the effect of training was significantly stronger in the event-based task.

Findings demonstrated that accuracy in the finger-tapping task was significantly correlated with years of music training. However, training only improved accuracy in performance of students who had an average of at least 4 years of training, which indicates that the interaction between expectancy and timing mechanisms is built with years of intense practice. On the other hand, it was also observed that the participants' age was significantly correlated with accuracy in the circle-drawing task. That is, there were distinct effects of training and natural maturation of the motor system on the development of timing movement skill. It seems that the mechanisms underlying event-based tasks reach maturation earlier than

those involved in emergent-based movements. This hypothesis is supported by findings reported by Van Mier (2006) demonstrating that 4- and 5-year-old children perform both discrete and continuous movements using event timing, whereas emergent timing mechanisms are only established after 6 years of age.

Chapter 6 further explored the interaction between musical skill and timing accuracy by describing a case study of an exceptionally talented 12-year-old musician. The highly trained young musician had double the years of formal training than age-matched musicians and is considered a prodigy. To verify the effect of training on accuracy of tapping and circle-drawing tasks, the performance of the prodigy was compared with age-matched musicians and nonmusicians. Results suggested that musicians were significantly more accurate than nonmusicians in the finger-tapping task, but there was no statistical difference between the performances of the musicians compared with the prodigy. These findings suggest that, although music training enhances timing accuracy for discrete movements, such benefits may be limited by the maturity of the nervous system.

In summary, the results reported in this thesis support the hypotheses that expectancy is intrinsically related to rhythmic actions; that feedback content affects motor timing; and the expertise in a movement-based skill can enhance the precision of timed movements.

Limitations and Future Research

This thesis focused on the role of expectancy in motor timing by examining the effect of feedback and skill in accuracy of finger tapping and circle drawing. All experiments adopted the synchronization-continuation paradigm (Stevens, 1886), whereby participants first synchronised with a pacing signal and then continued the rhythmic action without an external referent. The continuation phase was subjected to analysis, with the synchronization phase serving only to ensure that all participants entrained to the same tempo. The advantage of focusing on the continuation phase is that it allowed a direct examination of the interaction

between the expected and actual perceptual outcomes of movement. In the continuation phase of the trial participants were aware that the feedback is triggered by their actions, which provides a sense of agency and control over sensory outcomes. In contrast, during synchronization participants merely time their movements with an external pacing signal that is independent of any actions.

According to the internal models theory, the match between predicted and actual sensory feedback is fundamental to infer this sense of agency (Wolpert & Flanagan, 2001). Empirical studies using a modified version of the synchronization-continuation paradigm have supported this idea (Knoblich & Repp, 2009; Repp & Knoblich, 2007). Although the goal of the thesis was not to examine the influence of perceptual and sensorimotor cues on sense of agency, the topic is a promising avenue for future research.

A second aspect worth mentioning is that the focus of all experiments was the interaction between expectancy and timing mechanisms, but it is also important to acknowledge that different error correction strategies may be involved in the adjustment required after the perturbation of feedback. According to Repp & Keller (2004), adaptations to tempo changes in sensorimotor synchronization rely on two error correction mechanisms, phase and period correction. Phase correction is largely automatic and promotes local adjustments during synchronization with external signals, whereas period correction is engaged when there is a change of tempo in the sequence requiring conscious perception of the changes. Both phase and period correction mechanisms are thought to be active during synchronization tasks, but only period correction is thought to operate during continuation tasks.

The compensatory processes observed in the present results are inconsistent with a period correction strategy, as there were no perturbations in tempo. Rather, the feedback perturbations introduced were transient perturbations of local content, preserving the

temporal relation between the action and the onset of the feedback. Therefore, it is unlikely that timing adjustments reflect period correction. However, it is possible that the results described in Chapters 2 and 3 can be interpreted with respect to the recently proposed ADAM model (van der Steen & Keller, 2013), whereby adaptation and anticipation mechanisms are both taken in consideration to analyze adaptations in sensorimotor synchronization.

Overview

This thesis explored the role of expectancy, feedback, and skill in the timing of discrete and continuous rhythmic movements. Results revealed that expectancy mechanisms are intrinsically associated with our sensory-motor representation of time. Feedback content (e.g. pitch, timbre, intensity) is part of the representation of motor timing, and can affect both event and emergent timing. The interaction between expectancy and timing is reinforced by training and skill, and movement-based skill influences the strategies adopted to make precise rhythmic movements.

The results also raise important questions for future studies. For example, music performance likely involves both event and emergent timing mechanisms, and local and global expectancy mechanisms may be uniquely engaged when playing a musical instrument. More generally, the real-world, dynamic environments associated with music performance may involve a complex and interactive set of mechanisms that have yet to be fully explicated. Although the results described in this thesis help to elucidate the role of expectancy in the representation of timed actions, considerably more research is needed before they can be fully incorporated into a comprehensive and integrative neurobiological model of timed movement.

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Appendix

Ethics Approval

Fwd: HS Ethics Final Approval - Ref No.5201100065

1 mensagem

FHS Ethics <fhs.ethics@mq.edu.au>
Para: Thenille Braun <thenille.janzen@mq.edu.au>

30 de janeiro de 2014 09:56

----- Forwarded message -----

From: Ethics Secretariat <ethics.secretariat@mq.edu.au>
Date: 4 March 2011 14:03
Subject: HS Ethics Final Approval - Ref No.5201100065
To: Prof Bill Thompson <bill.thompson@mq.edu.au>
Cc: thenillebraun@yahoo.com.br

Dear Prof Thompson,

Re: "Bodily movements in a musical context: the role of expectancy in performance expression"

Thank you for your recent correspondence. Your response has addressed the issues raised by the Faculty of Human Sciences Human Research Ethics Sub-Committee and you may now commence your research.

The following personnel are authorised to conduct this research:

Ms Thenille Braun Janzen
Prof Bill Thompson

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).
2. Approval will be for a period of five (5) years subject to the provision of annual reports. Your first progress report is due on 1st March 2012 .

If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:
http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Sub-Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Sub-Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Sub-Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:

<http://www.mq.edu.au/policy>

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,

Dr Katey De Gioia
Acting Chair
Faculty of Human Sciences Ethics Review Sub-Committee
Human Research Ethics Committee

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