MUSIC AND MOVEMENT:
THE INFLUENCE OF TEMPO ON THE MIRROR NEURON SYSTEM IN CHILDREN

by

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Abstract

BACKGROUND: The mirror neuron system (MNS) is a neurological network associated with action-perception coupling, and is influenced by previous experiences. Visual, auditory, multi-modal, congruent and incongruent stimuli have been shown to modulate the response of the MNS throughout the various stages of human development. The musical attribute of tempo may exert a specific influence on action perception but this has not been studied in children.

PURPOSE: The overarching purpose of this research is to explore the neurological interactions of music and action. This study asks the question, “How does the tempo of regular pulse influence perception of action in children?”

METHODS: This research reflected on music and the MNS within the framework of dynamic systems theory (DST). A literature review examined the research relevant to the study question. Finally, a pilot study compared the responses in the MNS of 10 children during exposure to stimuli with tempi of 40 beats per minute (BPM) and 173BPM by examining the relative power of the mu rhythm frequency band (8-13Hz) in the sensorimotor cortex.

RESULTS: Previous research suggests tempo significantly influences executed movements, cortical excitability, perception of emotion in music, and perception of synchrony in audio-visual stimuli. The pilot study identified significant mu suppression in the left sensorimotor cortex during visual conditions only, whereas the right sensorimotor cortex demonstrated significant mu suppression during auditory, visual and multi-modal conditions. In the left hemisphere, visual stimuli showed significantly greater mu suppression than auditory stimuli. In the right

hemisphere, visual stimuli with a tempo of 173BPM showed significantly greater mu suppression than auditory stimuli with a tempo of 40BPM. The covariates of age, musical experience and dance experience were identified to have significant interactions with conditions.

CONCLUSIONS: This pilot study provided the first evidence that visual stimuli result in stronger mu suppression compared to auditory stimuli in typically developing children, similar to that found in adults. Increased tempo was associated with stronger action-perception coupling for uni-modal stimuli. This study lacked statistical power to demonstrate differences between multi-modal stimuli exhibiting equivalent or differing tempi; further research with larger samples is needed to explore these influences.

Preface

Contributions

This research was conducted in collaboration with my thesis committee in UBC's Perception-Action Lab (Dr. Naznin Virji-Babul, Director). My role included developing the research question, hypotheses and methodological design, completing the ethics application, conducting the literature review, preparing the experimental stimuli, organizing technology requirements, recruiting participants, collecting and analyzing the data, and drafting this written document.

Ethics

This research study met the criteria for a Minimal Risks Human Ethics application, and thus an expedited review by the UBC Behavioural Ethics Board was conducted. Approval was granted for this study on February 7th, 2014 (Certificate # H14-00010).

Conflict of Interest Declaration

The researchers and members of the thesis committee report no conflict of interest.

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List of Abbreviations

A.....Auditory

ANCOVA.....Analysis of Covariance

ANOVA.....Analysis of Variance

BESA.....Brain Electrical Source Analysis

BPM.....Beats Per Minute

CI.....Confidence Interval

D.....Differing

DCD.....Developmental Coordination Disorder

DST.....Dynamic Systems Theory

E.....Equivalent

EEG.....Electroencephalography

F.....Female

fMRI.....Functional Magnetic Resonance Imaging

Hz.....Hertz

IRI.....Inter-Response Interval

L.....Left

M.....Mean/Male

MM.....Multi-modal

MNS.....Mirror Neuron System

ms.....milliseconds

MSI .....Mu Suppression Index

NR.....Not Reported

PICO..... .....Population, Intervention, Comparison, Outcome

R..... .....Right

RM..... .....Repeated Measures

S.....Semitone (musical)

SD.....Standard Deviation

SMC..... ..... Sensorimotor Cortex

SPSS..... .....Statistical Package for the Social Sciences

SW..... .....Shapiro-Wilk Test of Normality

T.....Tone (musical)

TD..... ..... Typically Developing

TMS..... ..... Transcranial Magnetic Stimulation

UBC..... .....University of British Columbia

UM..... .....Uni-modal

V.....Visual

Glossary

Absolute Power: In electroencephalography, absolute power refers to the total energy intensity at an electrode at a given point in time. Power is often separated into different frequency bands.

Aeolian: A Greek natural minor musical mode based on the interval pattern: Tone (T), Semitone (S), T, T, S, T, T.

Articulation (musical): Articulation in music refers to the technique by which a musical note or the transition and continuity between notes are played. Examples of articulation include staccato (a note of shortened duration) and legato (notes are smoothly connected).

Attack density (musical): Attack in music is a measure of the quality (thickness) of the sound of a note during its initial run from nil to peak amplitude. Attack density is the number of attacks that occur within in a specified time frame.

Cortical Excitability: The propensity of a specific area of the cerebral cortex to generate an output signal beyond a certain threshold (action potential).

Dorian: A Greek musical mode based on the interval pattern: T, S, T, T, T, S, T.

EEG: Electroencephalography. EEG is the recording of electrical activity (specifically synchronized voltage fluctuations) within the brain by placing electrodes along the scalp.

Emotional valence: The degree to which an emotion is perceived as positive or negative.

Fast Fourier Transforms: Fast Fourier transforms are mathematical algorithms used to convert time domain signals (e.g., EEG signal strength as a function of time) into frequency bands (e.g., EEG spectral content as a function of frequency band).

Frequency band: Frequency refers to the number of cycles per second, noted as Hertz (Hz). In electroencephalography, synchronized electrical activity is separated into frequency bands according to known biological significance, such as the 1-4Hz band known as Delta waves present during deep sleep.

Harmony (musical): Harmony refers to the simultaneous use of musical notes or tones.

Inion: An anatomical location at the posterior base of the human skull, specifically the most prominent part of the occipital bone.

Ionian: A Greek major musical mode based on the interval pattern: T, T, S, T, T, T, S. Ionian is considered the second clearest mode.

Lydian: A Greek musical mode based on the interval pattern: T, T, T, S, T, T, S. Lydian is said to be the clearest mode.

Locrian: A Greek musical mode based on the interval pattern: T, S, T, T, S, T, T. Locrian mode is said to evoke the darkest sensations.

Melody (musical): Melody refers to musical tones presented in a linear succession that are perceived by the listener as a single entity.

Mirror Neuron System: The mirror neuron system (MNS) is a neurological network that responds to action execution, observation, imitation, and imagery, as well as action sounds, language, and music. The MNS is implicated in the development of empathy.

Mixolydian: A Greek musical mode based on the interval pattern: T, T, S, T, T, S, T.

Mu Desynchronization: The interruption of a synchronous resting-state mu wave rhythm by activation of neurons, resulting in a decrease of power in the 8-13Hz range.

Mu Suppression Index: The Mu Suppression Index (MSI) is a logarithm transformation of the relative power ratio (baseline condition/experimental condition) in the 8-13 Hz frequency band (Mu wave rhythm). The MSI is an index of motor activity and a reflection of the mirror neuron system.

Mu Wave Rhythm: Over the sensorimotor cortex, the synchronized electrical rhythm of rest-state motor neurons cycling at a frequency of 8-13 Hz is known as the mu wave rhythm.

Nasion: An anatomical location between the eyes and just above the bridge of the nose. This location reflects the intersecting two nasal bones and frontal bone of a human skull.

Neural Entrainment: Neural entrainment is the phenomenon of neurons oscillating at the frequency of an external beat.

Phrygian: A Greek musical mode based on the interval pattern: S, T, T, T, S, T, T. Phrygian is considered the second darkest mode.

Pulse (musical): The pulse in music refers to a series of repeated identical short-duration stimuli (beats) at the most basic level. The pulse beat is generally what listeners will entrain to for tapping their foot during a piece of music.

Relative Power: In electroencephalography, relative power refers to the ratio of an individual's calculated power spectra from a baseline (often rest) and experimental condition. Relative powers are often used when analyzing multiple participants in an experiment, as absolute power varies greatly between individuals.

Rhythm (musical): Rhythm is the regulated repetition of strong and weak elements (such as sound and silence), a pattern recurring over time.

Sensorimotor Synchronization: Sensorimotor synchronization is the ability to synchronize movements to an external input, such as tapping your fingers to a musical beat

Tempo: Tempo is the speed or pace of a rhythmic entity (e.g., musical piece, dance performance, heart rate, breathing rate) that is measured in beats per minute (BPM).

Texture (musical): Texture refers to the overall sound quality of a composition; that is, the way all components such as melody, harmony, and rhythm are combined together.

Timbre (musical): Timbre refers to the quality of a note or tone and is also known as the tone colour or tone quality. Timbre is the characteristic that distinguishes the sounds of various instruments or voices even when they have the same pitch and loudness.

Time Frequency Analysis: In electroencephalography, a time frequency analysis is the methods and techniques used to manipulate signals obtained from electrodes in order to represent the characteristics of the signal at various time points and within various frequency bands. A Fast Fourier transform is an example of a time frequency analysis.

Transcranial Magnetic Stimulation: The stimulation of small regions of the brain through electromagnetic induction, delivered by a coil magnetic field generator. TMS can be used to measure the cortical excitability of the sensorimotor cortex.

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For You

1 Introduction

1.1 Music and Movement

Historically, music and movement have been inextricably linked to each other, often in convergence with emotional contexts.[1] When infants cry in distress we rock them gently and sing a calming lullaby. We clap, cheer, and chant in unison to motivate our favourite hockey team. We spontaneously tap our toes in time to the beat of a marching band passing by in an enthusiastic parade. Our understanding of the unique human ability to synchronize music and movement through rhythm[1,2] is evolving with research that investigates the potential of music to facilitate learning and performance of actions.

In a rehabilitation context, the associations of music and movement are increasingly recognized as facilitators of therapeutic interventions. The use of music to promote both motor skills and psychosocial well-being has been investigated in a variety of clinical populations. For example, tango dance programs have demonstrated physical (e.g., improved balance, mobility) and psychosocial (e.g., reduced depression, reduced stress) benefits for persons with Parkinson disease,[3,4] age-related macular degeneration,[5] and depression.[6] Music therapy for adults post-stroke demonstrates improvements in speech production, gross and fine motor skills, and mood.[7,8] Research has suggested that dance may improve alignment, balance, and perceptual-motor abilities in children with disabilities.[9] Exploratory studies investigating adapted dance as physical rehabilitation for children with developmental disabilities such as cerebral palsy, autism spectrum disorder, and

Down syndrome have described positive outcomes in both motor and psychosocial domains.[9-11]

Music has been suggested to facilitate rehabilitation by providing a comprehensive multi-sensory experience connecting and activating physiological, psychological, cognitive, communicative, and emotional functioning processes.[12,13] The neurological occurrence of action-perception coupling is one such process. Action-perception coupling is the continuous cycle of perceptions leading to actions, and actions leading to new sensory perceptions. How does music influence the neurological underpinnings of action perception and execution? The overarching purpose of this research is to explore the neurological interactions of music and action in typically developing children.

1.2 Action-Perception Coupling

Action-perception coupling is a phenomenon that is widely acknowledged in the literature; its theoretical underpinnings have evolved with ongoing research providing new evidence.[14] Recently there has been a surge of research providing neurophysiological evidence of action-perception coupling – oscillations (rhythmic electrophysiological activity) at a frequency of 8-13Hz (known as the mu rhythm) in a network of brain regions that are modulated by movement execution, imitation, observation and imagination. This network is called the “mirror neuron system” (MNS). Specific areas associated with the MNS include the sensorimotor cortex,

supplementary motor areas, fusiform gyrus, angular gyrus, inferior parietal cortex, Broca's area and Wernicke's area (See Fig. 1.1).[15]

The MNS responds to a variety of interactions and experiences of movement, music, language, emotion, and empathy.[1,16-27] One aspect of this response is examined by evaluating the power of the brain's mu wave rhythm under different conditions. At rest, the sensorimotor cortex (SMC) exhibits a synchronized wavelength of electrical potentials (mu wave rhythm) repeating at a frequency of 8-13Hz, or 8-13 cycles per second.[27] Time frequency analyses of electroencephalography (EEG) rhythms are used to calculate the absolute power of each frequency band, including the mu rhythm. Desynchronization of this mu rhythm occurs when neurons in the SMC are activated. This is observed under conditions such as executing or observing movements, and results in a decrease of the calculated mu rhythm power (See Figure 1.2).[27] Greater activation of neurons results in a greater desynchronization of the mu rhythm and a greater suppression of the mu rhythm power. Suppression of mu waves is now considered to be a neurophysiological index of motor activity and a reflection of the MNS, modulated by action execution and perception, audio perception, emotional valence, and empathic processes.[1,16-27]

1.3 Development and the Mirror Neuron System

Movement, empathy, and the MNS demonstrate age-dependent changes from childhood to early adulthood, with neurological reorganization being particularly prevalent during the transition to adolescence.[28-30] In this period neurons in the

frontal cortex continue to be myelinated, increasing the speed at which neural information can be transmitted.[28] In addition, frequently used neural connections are strengthened during this period while infrequently used connections are eliminated, a process referred to as neural pruning.[28] Functionally, these neurological changes are associated with changes in self-perception, movement anticipation, emotional face processing, and empathic tasks.[29,30] These known developmental changes highlight the need to explore external influences such as music on neurological networks at various time points along the developmental trajectory.

1.4 Perception of Tempo in the Mirror Neuron System

Experiences and interactions are posited to be processed in the MNS according to dynamic structures that are shared between movement and music such as rate, direction, step size, jitter, and smoothness (See Figure 1.3).[31] Musical attributes associated with these structures such as pulse, tempo, rhythm, articulation, melody, harmony, timbre (tone quality), attack density, and texture may exert varying levels of influence on movement, and should be investigated individually to determine the direct impact of each. Rhythm is one aspect of music that has been investigated and shown to affect experiences of movement and emotion (e.g., arousal levels, walking pace, spontaneous tapping of toes).[31-34] Tempo, measured in beats per minute (BPM), is a component of rhythm that is of particular interest considering its relationship to physiological processes such as heart and respiratory rates that are linked to a person's emotional state.[35-37] Behavioural research has shown that children demonstrate greater rhythmic abilities when asked to move in synchrony

with auditory stimuli exhibiting a preferred faster tempo (140 BPM) compared to a non-preferred slower tempo (75 BPM).[38]

Are these differences reflected in neurological networks during observation of action? Do different tempi (slow, fast) change how the MNS perceives movement?

This pilot study asks the question, **"How does the tempo of regular pulse influence perception of action in children?"**

1.5 Research Considerations

Tempo can be perceived through multiple modalities including *visual* and *auditory*. Observation and imitation of *visual* stimuli are well known to induce mu suppression in the MNS and have been researched in a variety of populations including infants,[39] children with autism,[40] and adults with Down syndrome.[41] The influence of *auditory* stimuli on the MNS has been investigated with action and non-action sounds, each demonstrate unique patterns of activation. Pineda et al.[42] found that action sounds elicited larger mu suppression over the left hemisphere, whereas non-action sounds elicited larger mu suppression over the right hemisphere. Pizzamiglio et al.[43] also found that action sounds primarily activated the left hemisphere, with increased neuronal activation in the motor cortex; however, they found that non-action sounds activated both hemispheres, with increased activation in the temporal and frontal lobes.

Music as an *auditory* stimulus has a range of influences on the MNS depending on many factors. Perception of stimuli may be modulated by musical experience. Hadjidimitriou et al.[17] reported that non-musicians demonstrated significant mu suppression during *visual* and *audio-visual* stimulation, but not during *audio*-only stimulation. Comparatively, musicians demonstrated significant mu suppression during *audio*, *visual,* and *audio-visual* stimulation.[17] In another study, Hadjidimitriou et al.[16] found that musicians demonstrate significantly greater mu suppression with *auditory* stimuli compared to novices, but the two groups demonstrate no significant differences between them for *audio-visual* stimuli. Experts in dance also have extensive experience with musical stimuli. Orgs et al.[44] investigated the influence of dance experience on the perception of *visual* stimuli. They found dancers demonstrated significantly greater mu suppression compared to controls while observing dance movements, but not while observing everyday movements such as walking.[44] Haslinger et al.[45] provide further support for modification of the MNS response as a function of musical experience, by demonstrating that pianists have stronger activation compared to novices during observation of *visual* and *audio-visual* presentations of piano playing. Behmer and Jantzen[46] also found significantly greater mu suppression in musicians compared to novices while not only observing musical performances (*audio-visual stimuli)*, but also while reading stationary sheet music (*visual stimuli)*. There is some evidence that musicians process musical stimuli in different neurological regions compared to non-musicians. Both Marinoni et al.[47] and Ohnishi et al.[48] found that musicians demonstrated activation of the left hemisphere while non-musicians demonstrated activation of the right hemisphere.

These studies indicate that the type of stimuli (*visual* or *auditory)* is important to consider when investigating the influence of tempo on the MNS. An EEG study by McGarry et al.[49] highlights the importance of also comparing *uni-modal* (visual, auditory) stimuli to *multi-modal* (audio-visual) stimuli. They demonstrated that *multi-modal stimuli* were associated with greater mu suppression in electrodes C3 (central, left hemisphere) and C4 (central, right hemisphere) compared to visual-only stimuli and audio-only stimuli.[49] Several studies have also investigated the influence of multisensory congruency as a modulator of action and the MNS.[50-52] D'Ausilio et al.[52] demonstrated a significant effect of matched and mismatched audio-visual stimuli on the reaction time of pianists. Reaction times were significantly longer when pianists received mismatched audio-visual stimuli compared to visual-only stimuli.[52] Reaction times were significantly shorter when pianists received matched audio-visual stimuli compared to visual-only stimuli.[52] The timing of the stimuli was also a significant factor – facilitation of reaction time occurred in a significantly earlier time window compared to interference.[52] Multi-modal stimuli that are *equivalent* in tempo may have a facilitating effect on the MNS while stimuli that are *differing* in tempo may have an interfering effect on the MNS.

The study question, "How does the tempo of regular pulse influence perception of action in children?" is examined in the contexts of *auditory* and *visual* stimuli, *uni-modal* and *multi-modal* stimuli, and *equivalent* and *differing* stimuli. The pilot study considers age, sex, dance and musical experience as potential confounding variables.

Chapter Two of this thesis discusses the neurological interactions of music and action within the framework of DST. Chapter Three presents a review of the available literature regarding tempo and the MNS. Chapter Four describes the methodology employed in designing and conducting the thesis research study, including participant recruitment and eligibility criteria, protocols and outcome measures, and the collection and analysis of data. Chapter Five reports on the research findings from the thesis research study. Chapter Six summarizes the findings, limitations, and implications of this research.

1.6 Purpose and Aims

The purpose of this research study is to compare the response of the MNS in children aged 10-12 years old during perception of auditory and visual stimuli with two tempi, and during perception of multi-modal stimuli exhibiting rhythms with equivalent and differing tempi. The ages of 10-12 years were chosen to capture the period starting the transition to adolescence. The tempi of 40BPM and 173BPM were chosen to reflect a large divergence of slow and fast, and to eliminate any concurrent beats during multi-modal stimuli.

The aims of this pilot study are:

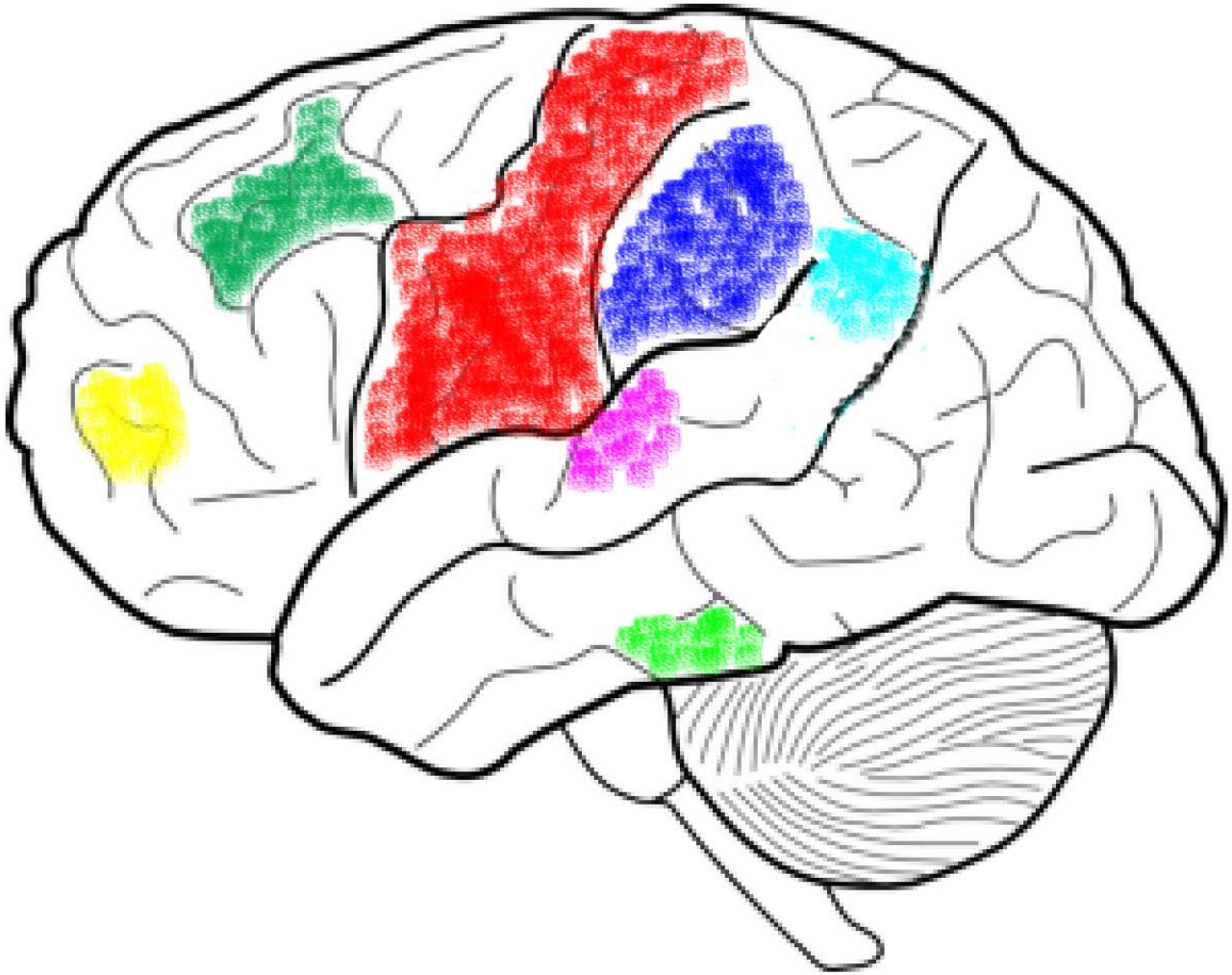
1. To evaluate the modulation of mu rhythm power during controlled presentation of auditory stimuli exhibiting tempi of 40 BPM and 173 BPM.
2. To evaluate the modulation of mu rhythm power during controlled presentation of visual stimuli exhibiting tempi of 40 BPM and 173 BPM.

3. To evaluate the modulation of mu rhythm power during controlled presentation of combined auditory (A) and visual (V) stimuli exhibiting rhythms with equivalent tempi (AV = 40 BPM; AV = 173 BPM).
4. To evaluate the modulation of mu rhythm power during controlled presentation of combined auditory and visual stimuli exhibiting rhythms with differing tempi (A = 40 BPM, V = 173 BPM; A = 173 BPM, V = 40 BPM).
5. To compare Mu Suppression Index (MSI) (change in mu rhythm power) scores in children for all conditions of uni-modal and multi-modal stimuli.

1.7 Hypotheses

1. The mean MSI will be significantly greater for the visual conditions compared to the auditory conditions.
2. The mean MSI will be significantly greater for the multi-modal conditions compared to the uni-modal conditions.
3. The mean MSI will be significantly greater for the equivalent conditions compared to the differing conditions.
4. There will be a significant effect of stimulus and tempo on the mean MSI.

Figure 1.1 Anatomical Brain Regions Associated with the Mirror Neuron System



Sensorimotor Cortex

Supplementary Motor Area

Broca's Area

Inferior Parietal Lobule

Angular Gyrus

Wernicke's Area

Fusiform Gyrus

Figure 1.2 Power-Frequency Plot Showing Mu Rhythm Suppression During Motor Activation

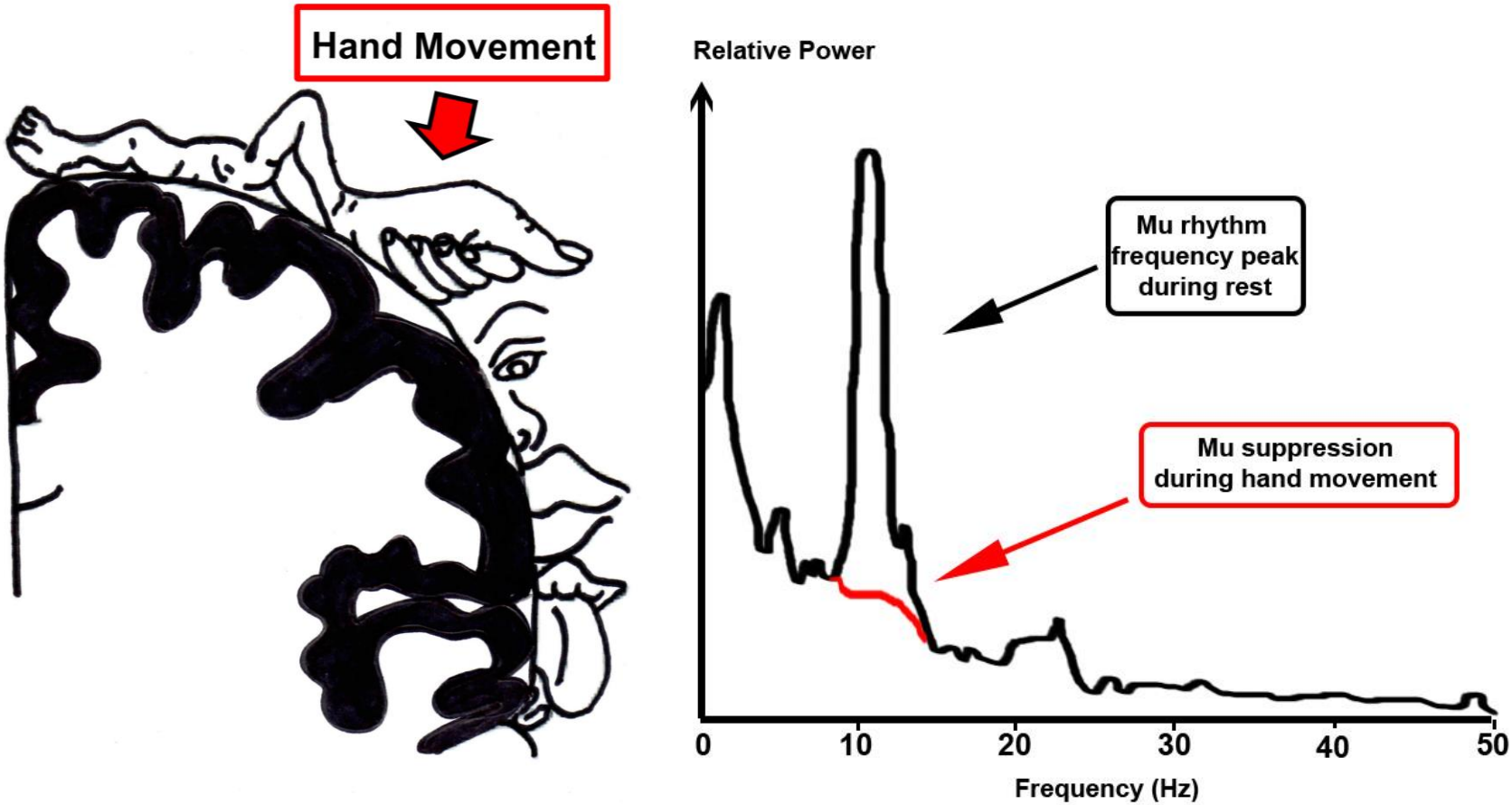
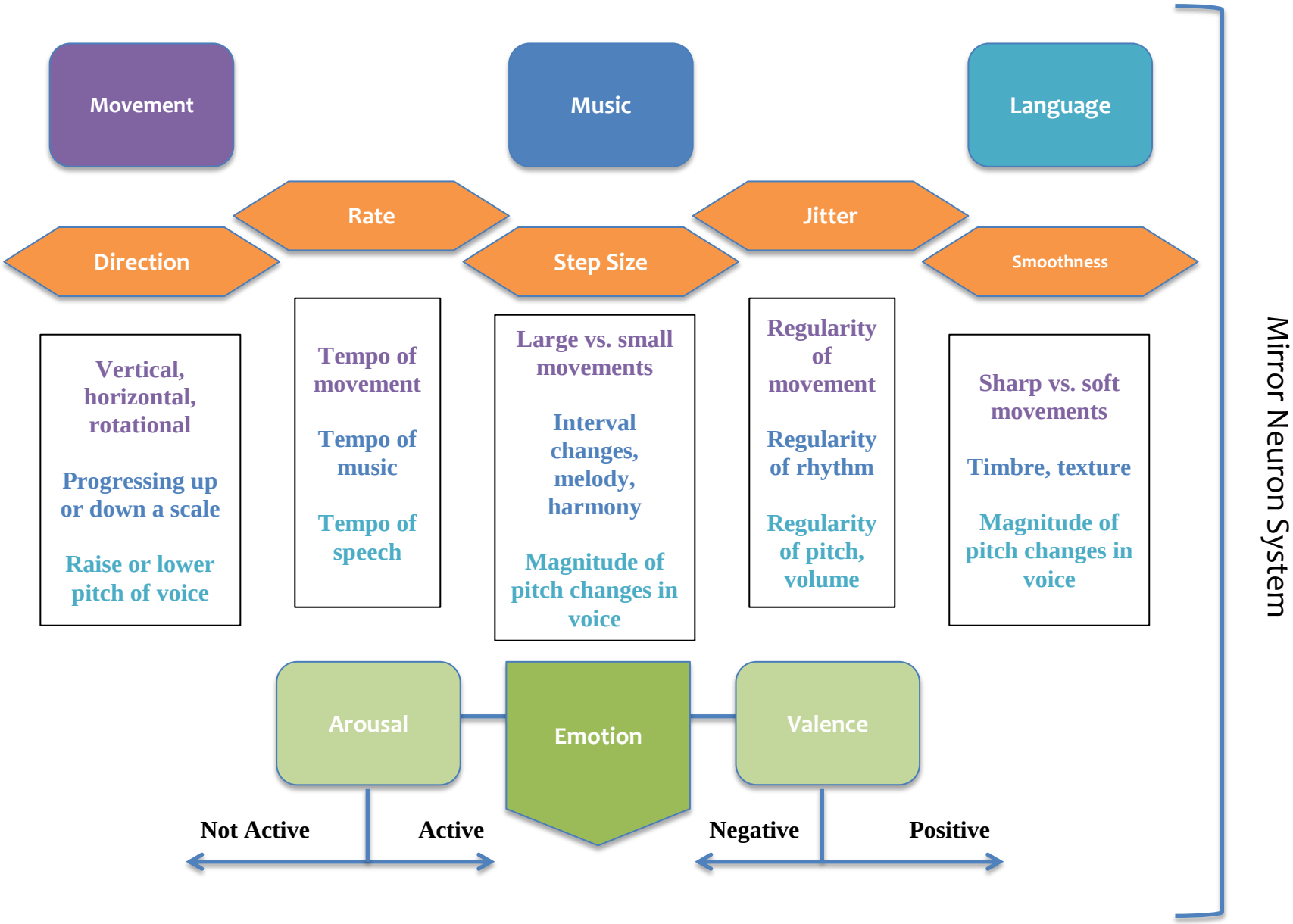


Figure 1.3 Schematic Representation of Concepts Associated with the Mirror Neuron System



2 Music and the Mirror Neuron System within Dynamic Systems Theory

2.1 Background

Dynamic systems theory (DST) is a broad theory of human development, initially described by developmental psychologist, Esther Thelen, and derived from the mathematical constructs of dynamical systems theory. The purpose of DST is to frame human development as a non-linear, complex, dynamic and continuous system by which both mechanisms (e.g., physiological processes) and outcomes (e.g., observable behaviours) can be explained.[53] The concepts of non-linearity and complexity refer to the notion that a system consists of many subsystems, each of which contributes to the overall emergent properties of the system without placing more importance on one over the others.[54] In contrast to an input-output model, DST considers operations of multiple factors (e.g., brain, body, task, environment) at multiple levels (from molecular to cultural) across multiple time scales (from milliseconds to years) in determining the state of a system at any given time in any given space. Small influences within a subsystem can have large effects on the overall system's mechanisms and producible outcomes, or have relatively little effect.[53]

DST states that systems are inherently dynamic and continuous. Subsystems and systems will self-organize towards a state of stability, yet as each component undergoes changes or transitions, the entire system will experience periods of instability, before organizing towards a new stable state.[55] The current state of a

system depends on the previous state, and will influence any future state of stability.[53]

Another characteristic of systems according to DST is the presence of rate limiting factors. In any given system, change in the outcomes of the system (i.e., observable behaviours) may be limited by any of the subsystems within the brain, body, environment or task.[56] For example, the capacity for a child to learn how to walk may be limited by the integrity of his or her neuromuscular physiology.

2.2 Application to Music and the Mirror Neuron System

DST can be applied to the operations of neurological networks including the MNS. In this view, the action-perception coupling mechanism of the MNS is a dynamic, iterative process modulated by a variety of influences.[57] How perceptions and actions are represented in the MNS may be shaped by other neurological processes such as attention, arousal, emotion and memory, and by external influences such as color and light contrast, volume and familiarity of music, and the presence of familiar or unfamiliar persons. In turn, the perceptions and actions within the MNS may also impact the same processes and external influences.

The dynamic interaction of music and the MNS has been empirically investigated as it relates to sensorimotor synchronization and neural entrainment. Sensorimotor synchronization refers to the ability to synchronize movements to an external input, such as tapping your fingers to a musical beat. Neural entrainment is the

phenomenon of neurons oscillating at the frequency of an external beat. Nozaradan et al.[58] used EEG to demonstrate emergent neural oscillations during hand tapping to an external auditory beat that corresponded to the beat frequency (2.4Hz), the movement frequency (1.2Hz), and the cross-modulation frequency (3.6Hz). The cross-modulation frequency is the sum of the beat and movement frequency. Nozaradan et al.[58] suggested that the steady-state evoked potential at this frequency represents a non-linear convergence of sensory and motor activities, providing support for the DST's application to the MNS. In addition to the emergence of a cross-modal neural oscillation, the magnitude of the beat frequency evoked potential was significantly increased during hand tapping conditions when compared to auditory-only conditions.[58] The enhancement was more significant over the contralateral hemisphere to the tapping hand. Nozaradan et al.[58] suggested that this is evidence of a top-down influence of movement on the processing of the auditory beat, in agreement with the non-linear structure of DST. Further support for placing music and the MNS within DST comes from research examining infants who were bounced to every second or third beat while listening to an unaccented musical pulse. Phillips-Silver and Trainor[33] found that infants later preferred listening to an auditory rhythm with the same accented beats to which they had been bounced. Infants that only observed an adult bouncing to a beat but did not experience movement themselves did not demonstrate a preference for either rhythmical pattern.[33] In later studies; Phillips-Silver and Trainor[59,60] demonstrated that adults are also subject to the influence of vestibular motion when perceiving the metrical structure of an ambiguous rhythm. They found that adults would perceive a musical

piece as either a march or a waltz depending on the timing of recently experienced body movements. Phillips-Silver and Trainor[33,59,60] concluded that body motion can modulate the perception of auditory rhythms. Their findings support the DST concept of bidirectional connections within a network of subsystems.

2.3 Dynamic Systems Theory: A Critical Reflection

A reflection of DST was conducted by asking the critical questions proposed by Chinn and Kramer:[61]

1. How clear is this theory?
2. How simple is this theory?
3. How general is this theory?
4. How accessible is this theory?
5. How important is this theory?

2.3.1 How Clear is this Theory?

Major concepts within DST are consistent across the literature, and include non-linearity, complexity, dynamic, continuous, rate-limiting, multi-level, and multi-factorial. Publications have defined these concepts to varying depths, but in general are uniform in their descriptions. The clarity of this theory could be improved by providing diagrams to demonstrate the interactions of the major concepts.

2.3.2 How Simple is this Theory?

The major concepts and relationships of DST are relatively simple and few. However, subsets of concepts can vary greatly according to the discipline to which DST is being applied. The impact of DST embracing all possible influences on an overall system is that specific terms and relationships are limitless. While researchers will often define such sub-concepts to ensure simplicity for a particular study, the potential interactions of DST are broad and complex.

2.3.3 How General is this Theory?

A strength of DST is the ability for it to be generalized to many fields of knowledge. DST has been applied to a broad range of phenomena across disciplines including the recovery of function following paediatric acquired brain injuries,[55] infant attachment,[62] the management of children with cerebral palsy,[56] the processing of taste stimuli,[63] treadmill stepping in infants,[64] and general motor development.[54,65] DST has also been used as a framework for human consciousness,[66] and the self-organizing processes of football players.[67] The purpose of DST is to provide a framework for all systems encountered in human experience and is not limited to specific areas of knowledge. Indeed, its multi-factorial nature embraces the complex links and interactions across all domains.

2.3.4 How Accessible is this Theory?

The complexity of DST limits its accessibility when designing empirical studies. Repp[2] discusses the ease with which experiments can be designed according to a

linear information-processing model (input-output) compared to the non-linear model of DST. However, advances in computer modelling and increased awareness of multi-factorial influences on outcomes are stimulating research of phenomena using a DST framework. For example, Romero et al.[51] used measures of inter- and intra-limb coordination and measures of spatial deviation to demonstrate the dynamic processes by which an individual's movements are responsive to environmental movements in both space and time, and are emergent properties of a complex system. Repp[2] used measures of variability to demonstrate the dynamic changes in sensorimotor synchronization throughout development. In this experiment, it was demonstrated that variability of sensorimotor synchronization decreases during childhood and adolescence, and then remains constant throughout adulthood and old age.[2] It was also demonstrated that there was increased variability of sensorimotor synchronization during exposure to visual stimuli compared to auditory stimuli.[2] In another experiment, Miura et al.[68] used phase transition (sudden and spontaneous shifts between two coordinated states) to examine the dynamic relationship between neural systems and perceptual information during whole-body rhythmic movements by dancers and non-dancers. They found significant differences between the groups, and identified contributing influences to coordination such as tempo of the beat, gravity, intention, and practice.[68] The accessibility of DST is shifting as researchers identify empirical designs and measures appropriate for this theoretical framework.

2.3.5 How Important is this Theory?

DST establishes important considerations for research in a variety of domains. Specific to action-perception coupling, DST highlights the influence of multiple factors and interactions during the response of the MNS to different stimuli and experiences. Compared to the traditional model of a single perceptual experience stimulating a particular action, DST allows for perception and action to be intertwined in an iterative process modulated by other neurological networks, tasks, and environmental factors. This perspective has advanced our understanding of the complex bi-directional nature of action-perception coupling in a variety of populations. Maes et al.[69] used the DST framework to explain how motor disorders can influence changes in perception including the ability to recognize auditory and musical features, and to describe the influence of introspection and social interaction on action-perception coupling. Schaefer et al.[70] used the framework to explain how different tasks and stimuli involved in action-perception coupling can modulate attention networks. These examples demonstrate the important shift in research to consider dynamic non-linear interactions in mechanistic and clinical studies.

An important property of a good theory is its usefulness in predicting phenomena.[61] A DST framework has been used to predict outcomes such as bifurcation frequencies of phase transition[68] and frequencies of neural oscillations during sensorimotor synchronization.[58] In the current study, DST predicts that modulation of the MNS (mu suppression) will differ significantly as a function of multiple influences including tempo, mode of stimulus (visual, auditory, multi-modal), congruency of multi-modal stimuli (equivalent, differing), age, sex, musical and dance experience.

2.4 Summary

DST views the perception of music and actions within the MNS as having non-linear, dynamic and continuous relationships with one another, and with other factors in a larger all-encompassing system. Changes in external influences such as the tempo of a regular pulse may exert a small or large change in the MNS and/or the overall system, subject to conditions of the remainder of the variables within the system (brain, body, task, environment). DST has influenced important advances in the empirical investigation of action-perception coupling, including the examination of MNS modulation in children following observation of varying stimuli.

3 Literature Review

A PICO (Population, Intervention, Comparison, Outcome) format was used to develop the question, concepts, and search strategy for this literature review.

3.1 Objective

The objective of this review was to complete an exhaustive search of peer-reviewed publications relevant to the question, “In children (P), what influence does the tempo of regular pulse (I) have on the mirror neuron system (C) as measured by mu suppression (O)?” Major search concepts included: (I) tempo, pulse, beat, music, rhythm; (C) mirror neurons, MNS, action perception, action observation; and (O) mu suppression, mu power, mu rhythm desynchronization.

3.2 Data Sources

The electronic databases MEDLINE (OvidSP), CINAHL, EMBASE (OvidSP), Music Index, and RILM Abstracts of Music Literature were searched from the earliest available date until December 17, 2014. MeSH terms included Music, Mirror Neurons, Motion Perception and Perception. Key words included tempo, rhythm, mirror neuron system, action observation system, action perception, and mu rhythm. Searches were limited to English publications. See Appendix B for detailed search strategies.

3.3 Study Selection

After removing 318 duplicates, 1323 records were screened for eligibility by one reviewer. Publications were included if they reported human research with a focus on tempo and the execution or perception of action. Papers were excluded if they were unrelated to the research question, or if they focused on only one aspect of the research question (e.g., rhythm but not how it relates to action perception). As the literature relating directly to tempo was thought to be scarce, all populations including both adults and children were included in this review. Following screening by title, 241 records remained. These were screened by abstract, leaving 72 publications for full text review. Of these, 8 articles and one conference abstract were identified to have investigated the influence of tempo on action or audio-visual perception. One article examined the influence of tempo in children; other publications examined the effects of tempo in adult populations. Figure 3.1 depicts a flow diagram of the study selection process.

3.4 Results

3.4.1 Critical Appraisal of Publications

Critical appraisal of the studies was conducted using criteria outlined by du Prel et al.[71] These criteria were modified to ensure maximal relevancy to this literature review. The critical appraisal asked the questions:

1. Does the study investigate the predefined study goals?
2. Are statements and numerical data supported by literature citations?
3. Are the study population and inclusion/exclusion criteria described in detail?

4. Is the study design apt to address the aims and/or hypotheses?
5. Are the methods of measurement suitable for determination of the target variable?
6. Have the correct statistical methods and analyses been selected, and are they clearly described?
7. Is there information regarding data loss (response rates, loss to follow-up, missing values)?
8. Are the important parameters (confounding variables) included in the analysis or at least discussed?
9. Do the data support the authors' conclusions?
10. Do the authors and/or the sponsor of the study have irreconcilable financial or ideological conflicts of interest?

All studies except for the abstract publication (Avanzino et al., 2014[72]) described and adhered to their predefined study goals throughout their experiments, and provided literature citations to support their statements and numerical data. While most papers attempted to describe their population, only two of the nine publications explicitly stated their inclusion and exclusion criteria (Pfordresher and Benitez, 2007[73]; Whitall et al., 2006[74]). Two studies introduced bias by having study authors act as participants in the experiment (Arrighi et al., 2006[75]; Su and Jonikaitis, 2011[76]). All studies except for the abstract publication (Avanzino et al., 2014[72]) reported adequate detail of appropriate study procedures and conditions in order for experiments to be replicated, and provided reasonable justification for the measures

used. A common limitation of the studies in this review was the absence of explicitly reporting attrition rates or methods of dealing with incomplete or unusable data. Watanabe[77], and Su and Jonikaitis[76] were the only authors to report this information. Statistical analyses were appropriate and detailed in their description for all studies except the Avanzino et al.[72] abstract. The identification and discussion of confounding variables within studies were mixed across publications. Pfordresher and Benitez,[73] Styns et al.,[78] Watanabe,[77] Whitall et al.,[74] and Petrini et al.[79] explicitly addressed concerns of confounding variables such as influences from other neurological networks,[79] gender,[78] and musical experience.[73] Avanzino et al.,[72] Ramos et al.,[80] Arrighi et al.,[75] and Su and Jonikaitis[76] did not discuss the impact of any confounding variables on their studies. All studies except the Avanzino et al.[72] abstract reported reasonable interpretations and conclusions for which their data were supportive. Two studies[72,78] did not report potential financial or other conflicts of interest; all other studies reported financial supports that were deemed to be not in conflict of interest of their research. Recognizing the limitations of word counts for publication, future research should strive to be more explicit in describing eligibility criteria and data inclusion/exclusion, and should include discussions of potential confounding variables. Table 3.1 summarizes the findings of the critical appraisal for each study.

3.4.2 Discussion of Related Research

This literature review did not identify any research examining the influence of tempo on the mu rhythm in the sensorimotor cortex (SMC). Studies examined behavioural and neurological outcomes following perception of varied visual and auditory stimuli.

3.4.2.1 Movement Execution: Tempo and Speed

Three studies investigated the ability to synchronize movements with external auditory stimuli at a variety of tempi.[73,74,78] Styns et al.[78] presented 20 healthy musicians with musical fragments and metronome beats with nominal tempi ranging from 50 – 160BPM, and asked them to walk or tap their fingers in synchrony with the perceived auditory tempo. They found 72.6% of participants were able to synchronize walking tempo to the nominal tempo (±1BPM), while 84.4% were able to synchronize tapping tempo to the nominal tempo. Some participants walked or tapped at half the nominal tempo (more frequently for faster tempi), or at double the nominal tempo (more frequently for slower tempi). 13.9% and 3.6% of participants did not synchronize to the nominal tempo at all, for walking and tapping respectively. Styns et al.[78] reported optimal synchronization of walking to an external beat occurred between 106 and 130BPM. Walking speed was also correlated with walking tempo: speed increased linearly with tempo from 50 – 114BPM and then stabilized between 118 and 190BPM. Maximum walking speed was reached between 126 and 142BPM. Additionally, walking speed was significantly faster when listening to musical stimuli compared to metronome stimuli. The authors concluded that musicians have the ability to synchronize walking to a wide range of tempi, but

this synchronization appears to be optimal around 120BPM, a tempo which is found often in musical pieces and also appears to be a comfortable walking pace for most individuals.[78] They proposed that further research be conducted to explore the finding that a musical stimulus promotes faster walking compared to a metronome even when the stimuli depicts the same tempo.[78]

Whitall et al.[74] also examined the influence of tempo on executed movements, but compared children with developmental coordination disorder (DCD) with typically developing (TD) children and healthy adults. In their study, 10 children with DCD, 8 TD children, and 10 adults were asked to synchronously clap (using small hand-held cymbals) and march on the spot to an external auditory beat at tempi of 0.8, 1.2, 1.6 and 2.0Hz. The researchers calculated a synchronization error (absolute deviation value – how closely participants timed their foot strike or clap to the metronome beat) for each participant under each tempo condition. Whitall et al.[74] found significant main effects for limb (clapping vs. marching), tempo and group. Overall, marching steps were more closely coupled to the metronome beat compared to the claps. However; less variability was seen in the clapping conditions. Performance at the 0.8Hz and 2.0Hz were more closely coupled to the metronome beat compared to the 1.2Hz and 1.6Hz conditions. Both groups of children (DCD and TD) demonstrated increased variability of synchrony with increasing tempi, whereas the adults demonstrated less variability of synchrony with increasing tempi. For all conditions, adults were significantly more closely coupled to the external beat compared to both groups of children; the two groups of children did not significantly

differ from each other. However, the children with DCD demonstrated significantly more variability than either the adults or the TD children. Whitall et al.[74] concluded that perception-action coupling and sensorimotor synchronization are influenced by both development and the condition of DCD.

Pfordresher and Benitez[73] further looked at the execution of movement as a function of tempo and auditory feedback timing. Twenty-five adults with a range of musical experience (0-14 years, M=3.96) were instructed to tap their fingers on a drum pad or play a short sequence of tones at three different tempi (330, 500, and 660ms). Following a period where the participants tapped or played the tone sequence with the external beat, auditory feedback was then provided at fixed (0, 330, 500 or 660ms) or adjusted (0%, 66%, 100% or 132% of actual taps or key strokes) delays during which the participants were required to maintain the original tempo. A produced inter-response interval (IRI, time between successive taps or key strokes) was calculated for each condition (with varying tempo and delay). Pfordresher and Benitez[73] found that mean IRIs during the synchronous conditions only differed from the expected IRI by 14ms on average, which they interpreted as an indication that participants were able to accurately synchronize with an auditory beat. With auditory feedback being provided at fixed delays, there was a significant main effect of delay magnitude and a significant interaction of delay and tempo for the sequence production IRIs, but not for the tapping IRIs. Disruption of the IRIs by auditory delays resulted in an increase of the IRI. This effect was reduced when the feedback delay timing matched the tempo – for example, when the delay was 500ms during

production of the 500ms tempo. With auditory feedback being provided at adjustable delays, there was a significant main effect of delay magnitude for both the sequence production IRIs and the tapping IRIs. Additionally, there was a significant interaction of delay and tempo for the tapping IRIs but not the sequence production IRIs. Pfordresher and Benitez[73] concluded that timing of executed movements is disrupted by asynchronous feedback due to relative timing relationships between perception and action.

Taken together, these three studies[73,74,78] support the hypothesis that tempo of external stimuli can influence the tempo and synchrony of executed movements.

3.4.2.2 Cortical Excitability: Congruent and Incongruent Tempi

One study investigated the influence of congruent and incongruent tempi on the cortical excitability of a hand muscle.[72] Avanzino et al.[72] first recorded the tempo of participants' spontaneous finger opposition movements. Participants then observed videos of a hand performing the same action at the same tempo, or a slower or faster tempo as their spontaneous movements while cortical excitability of the hand muscle was recorded using transcranial magnetic stimulation (TMS). Avanzino et al.[72] found significantly increased cortical excitability during observation of action at the same tempo compared to observation of action at slower or faster tempi. After completing the initial phase of the experiment, participants viewed a 10-minute training video of finger-opposition movements at a faster tempo compared to their previously demonstrated spontaneous movements. Avanzino et al.[72] reported an

increase in tempo of spontaneous finger-opposition movements in participants following observation of the training video. At the time of this literature search this study was available only in abstract form and thus, key details are missing in order to evaluate the rigour of the research. For example, it is unknown if authors addressed the potential confounding factor of task practice influencing the increased tempo of spontaneous movements in the second phase of their experiment. Caution should be taken when considering these results.

3.4.2.3 Perception of Emotion: Tempo and Mode

One study evaluated the effects of musical tempo and mode on the perception of emotion.[80] Ramos et al.[80] explored the interactions of these concepts in 24 musicians and 24 non-musicians (aged 17-25 years). Participants listened to three different Greek musical excerpts played in seven different modes and three different tempi for a total of 63 conditions. Musical modes included Ionian, Dorian, Phrygian, Lydian, Mixolydian, Aeolian, and Locrian. Tempi included 72, 114, and 184BPM. Participants were asked to make choices among four emotions in association with each condition. Emotions were labelled and coded as: Happiness (high arousal, positive valence); Sadness (low arousal, negative valence); Serenity (low arousal, positive valence) and Fear/Anger (high arousal, negative valence). It is important to note that participants were rating the emotion they perceived the music to be portraying and not the emotion they were feeling, as these may not be the same. For example, a sad piece of music may be pleasing to hear. Ramos et al.[80] found significant main effects of tempo on arousal and valence, with faster tempi

associated with higher arousal, and slower tempi associated with negative valence. Interestingly, musicians were significantly less sensitive to changes in arousal from slow to moderate tempi compared to the non-musicians, but the effect of tempo on valance was more pronounced in the musicians. For both groups, valence only evolved to positive values when tempi changed from moderate to fast. Ramos et al.[80] also reported significant main effects of mode on arousal and valance. The Ionian mode depicted the highest arousal for both musicians and non-musicians. Major modes (Ionian, Lydian, Mixolydian) were associated with positive valence for both groups, while the remaining minor modes were associated with negative valence. A significant interaction between mode and tempi was found for the arousal dimension but not for valence. Ramos et al.[80] concluded that mode and tempo each contribute to the perception of emotion in music by exerting influence on arousal and valence, and that musical training modulates this influence.

3.4.2.4 Behavioural Tempo Contagion

One study investigated the experience of behavioural tempo contagion – the phenomenon by which an individual's behaviour takes on the tempo or speed perceived by an external influence.[77] Watanabe[77] had 40 healthy participants observe point-light displays of biological motion, scrambled biological motion, and solid object motion at three different rates (half, normal, and double). Biological motion included displays of whole body movements including jumping, running, walking, kicking and throwing a ball. Following a variable blank period (300-2400ms), participants were required to perform an unrelated reaction-time task. For

each participant and condition, Watanabe[77] calculated the slope of reaction time (ms) as a function of motion speed (frame rate, Hz). The findings indicated reaction time significantly decreased as a function of speed with biological motion, but not with the object or scrambled motion displays. For biological motion, the faster tempo was correlated with faster reaction times. Importantly, this effect was observed only when the reaction time task was performed within one second of viewing the biological motion. Watanabe[77] suggested that this timing window indicates that behavioural tempo contagion is an automatic process rather than a deliberate conscious response. Acknowledging the need to explore other influencing factors (e.g., duration of stimulus presentation, partial body movements vs. whole body movements, laboratory vs. real-life scenarios) Watanabe[77] concluded that the tempo of others' movements may automatically impact the speed of execution of an observer's movements.

3.4.2.5 Perception of Auditory Tempo as a Function of Visual Condition

One study explored the influence of static and moving visual stimuli on the perception of auditory tempo.[76] Su and Jonikaitis[76] had 11 participants (and one author) listen to five tones in a standard sequence at either 100 or 150BPM while observing stationary or moving dots on a screen. The static dots changed luminescence in a constantly accelerating manner, while the moving dots traced a circle in an accelerating manner. The changes in visual stimuli did not have a discrete rhythm (beat). Following each standard sequence, participants listened to a comparison sequence of tones without the visual stimuli. The comparison

sequences were presented at ±4%, ±8%, or ±12% of the standard sequence tempo. Participants were required to choose if the comparison sequence was faster or slower than the standard sequence they had just perceived. Su and Jonikaitis[76] found significant main effects of both tempo and visual condition. In general, the 100BPM signal was perceived as faster than it actually was, whereas the 150BPM signal was perceived as slower than it actually was. In addition, the same auditory tempo was perceived as faster when accompanied by the moving visual stimuli compared to being accompanied by the static dots. Su and Jonikaitis[76] concluded that concurrent visual information interacts with perception of auditory tempo even when the visual information does not have a discrete rhythm or beat (by which the visual rhythm may be recoded into an audio-motor rhythm).

3.4.2.6 Tempo and the Perception of Synchronous Audio-Visual Stimuli

Two studies investigated the influence of tempo on the perceived synchronization of auditory and visual stimuli with varying onset delays.[75,79] Arrighi et al.[75] tested this ability in two study authors and one naïve participant (mean age=30 years). Participants observed videos of a drummer playing a congo drum at three different tempi (1, 2 and 4Hz) with auditory and visual stimuli in synchrony or varying presentations of asynchrony. Participants were required to choose if each presentation was synchronous or asynchronous. Arrighi et al.[75] found that for all drumming tempi, perceived synchrony occurred when the auditory stimulus was delayed compared to the visual stimulus. Tempo significantly influenced the

magnitude of auditory delay needed for perceived synchrony; larger delays were required for slower tempi (80ms for 1Hz, 60ms for 2Hz, and 40ms for 4Hz).

Petrini et al.[79] also demonstrated that perceived synchrony is achieved with delay of auditory stimuli in their study examining four expert jazz drummers and four novices with no musical experience. These participants observed point-light displays of drumming with three different tempi (60, 90, 120BPM), three different accented beats (first, second, third), and varying auditory or visual stimuli onset delays (0, ±66.67, ±133.33, ±200, ±266.67ms). Following each presentation, participants were required to choose if it was perceived as synchronous or asynchronous. Both drummers and non-musicians best perceived synchrony when the auditory stimulus was delayed compared to the visual stimulus. Drummers detected synchrony with a significantly smaller auditory delay compared to the novices. Tempo significantly affected non-musician's perception of synchrony; they perceived slower tempi as being more asynchronous compared to faster tempi. This effect of tempo was not present in the drummers. The position of the accented beat did not significantly affect synchrony perception for either group. Petrini et al.[79] concluded that musical experience influences the relationship between tempo and perceived audio-visual synchrony.

3.4.3 Summary of Related Research

Nine publications explored the influence of tempo on the perception and execution of action. Six areas of focus were identified within this literature.

Three studies[73,74,78] support the hypothesis that external tempi influences spontaneous movements by participants. Musical experience, task (e.g., walking, tapping, tone sequence production), type of stimuli (e.g., musical fragments, metronome beats), development, developmental coordination disorder and timing of auditory feedback are all factors which can modulate this influence.

One study[72] supports the hypothesis that congruent stimuli enhance activation of the motor cortex more than incongruent stimuli.

One study[80] supports the hypothesis that tempo and musical mode influence the perception of arousal and valence in music. Musical training is one factor that can modulate this influence.

One study[77] supports the hypothesis of behavioural tempo contagion, whereby the tempo of others' movements influences the tempo of an observer's executed movements. This contagion may be limited to a narrow time window.

One study[74] supports the hypothesis that concurrent visual stimuli influence the perception of auditory tempo.

Two studies[75,79] support the hypothesis that tempo influences the perception of synchrony in audio-visual stimuli. Stimulus onset-delay, the order of stimulus onset

(e.g. auditory before visual or visual before auditory) and musical experience are factors that can modulate this influence.

3.4 Limitations

This literature review was limited by having only one author screen and analyze the collected publications. Subjective bias may have impacted the articles chosen for full text screening and ultimate inclusion in the review. While multiple databases with a range of search terms were used, it is possible that articles were missed due to terminology differences. Additionally, any literature not translated into English was excluded from this review.

3.5 Conclusions

The literature examining the influence of tempo on the MNS and action-perception coupling is scarce. To date, no studies have directly examined the influence of tempo on mu rhythm in the SMC in adults or children. Studies with small sample sizes provide preliminary support for the significant influence of tempo on spontaneously executed movements, cortical excitability, the perception of emotion in music, and the perception of synchrony in audio-visual stimuli. Additionally there is support for the significant influence of concurrent visual information on the perception of auditory tempo. The literature endorses the presence of several modulating factors such as musical experience, timing of feedback, and developmental level. Overall, the complex, non-linear, and multi-level effects and

interactions of tempo identified in this literature review are well placed in the framework of DST.

Figure 3.1 Literature Review Study Selection Flow Diagram

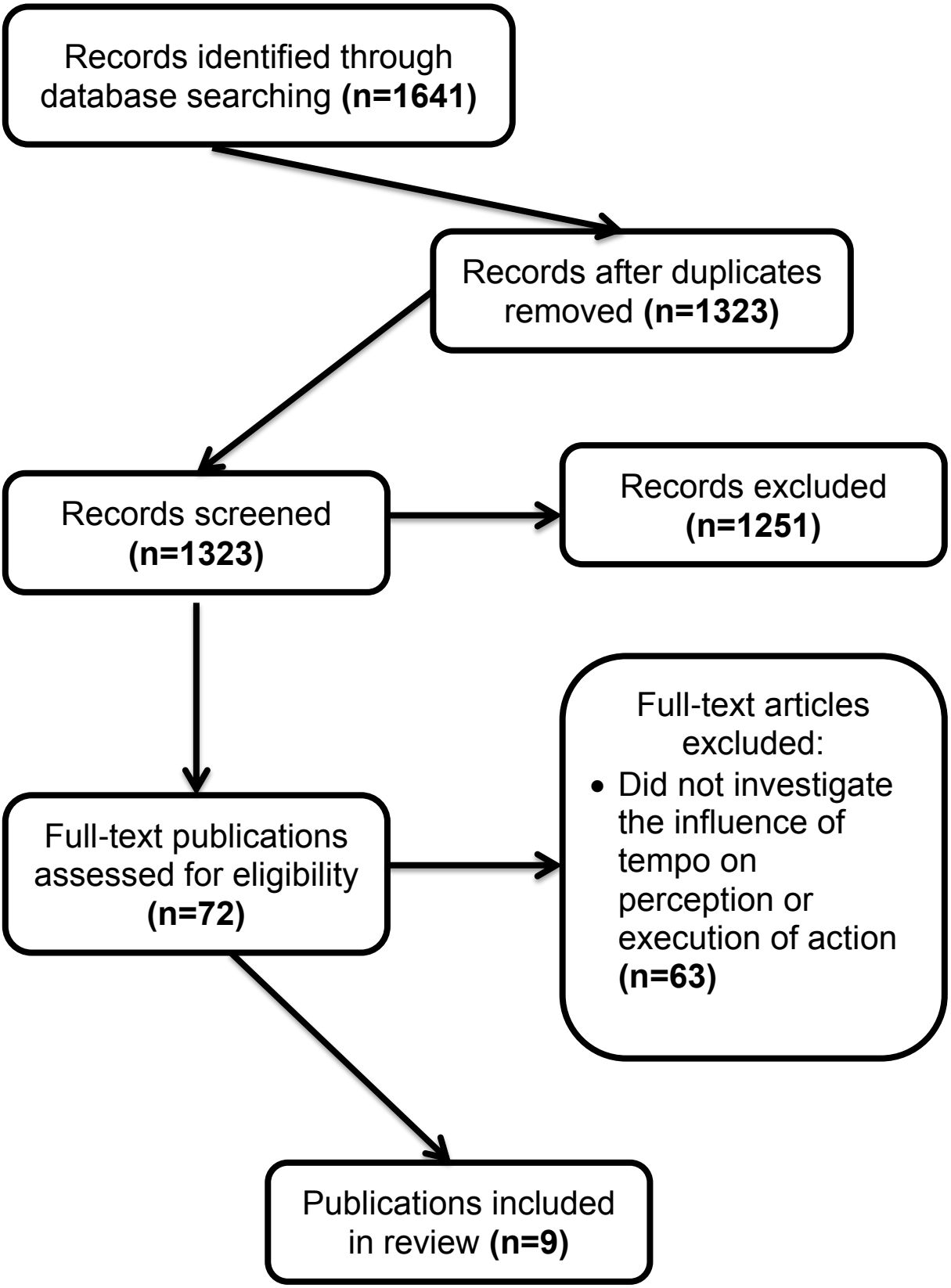


Table 3.1 Critical Appraisal of Review Studies. NR = Not Reported

	Styns et al., 2007[78]	Whitall et al., 2006[74]	Pfordresher and Benitez, 2007[73]	Avanzino et al., 2014 Abstract[72]	Ramos et al., 2011[80]	Watanabe, 2008[77]	Su and Jonikaitis, 2011[76]	Arrighi et al., 2006[75]	Petrini et al., 2009[79]
1. Predefined Study Goals	YES	YES	YES	NO	YES	YES	YES	YES	YES
2. Literature Citations	YES	YES	YES	NO	YES	YES	YES	YES	YES
3. Eligibility Criteria	NO	YES	YES	NO	NO	NO	NO	NO	NO
4. Study Design	YES	YES	YES	NO	YES	YES	YES	YES	YES
5. Measures	YES	YES	YES	NO	YES	YES	YES	YES	YES
6. Statistical Analyses	YES	YES	YES	NO	YES	YES	YES	YES	YES
7. Data Loss	NO	NO	NO	NO	NO	YES	YES	NO	NO
8. Confounding Variables	YES	YES	YES	NO	NO	YES	NO	NO	YES
9. Conclusions	YES	YES	YES	NO	YES	YES	YES	YES	YES
10. Conflict of Interest	NR	NO	NO	NR	NO	NO	NO	NO	NO

Table 3.2 Literature Review Summary of Data

	Sample	Methods	Measures	Results
Styns et al., 2007[78]	• 20 healthy adults aged 20-29 years (M=25) • 10 male, 10 female • All with significant musical experience (M=5.9hrs/wk)	Participants were instructed to walk at the perceived pulse tempo of 68 different musical fragments and 12 metronome stimuli ranging from 50BPM to 160BPM. On a subsequent day, participants were instructed to tap their fingers to the perceived pulse tempo of the same musical fragments but not the metronome stimuli.	• Walking/tapping tempo • Walking/tapping speed	• 72.6% of cases demonstrated walking tempo equal to the nominal tempo. Some participants stepped at half the tempo (more frequently for faster tempi) or double the tempo (more frequently for slow tempi). 13.9% of cases did not synchronize with the stimuli at all. Optimal synchronization occurred between 106 and 130BPM. • 84.4% of cases demonstrated tapping tempo equal to the nominal tempo. 3.6% of cases did not synchronize with the stimuli. • 80.7% of participants tapped at the same rate as they walked. • Walked speed increased linearly with walking tempo from 50-114BPM. Walking speed stabilized from 118-190BPM. Max walking speed occurred between 126 and 142BPM. • Walking speed was significantly slower with the metronome stimuli compared to the musical stimuli.
Whitall et al., 2006[74]	• 28 participants • 10 adults (18-30 years) • 10 children with DCD (7.09 ±0.48 years) • 8 typically developing children: age, gender and ethnically matched to the children with DCD.	Participants were asked to clap (using small hand-held cymbals) and march on the spot to external auditory beats (metronome) at 0.8, 1.2, 1.6, and 2.0 Hz. Participants completed four trials of each condition for a total of 16 trials. Each trial lasted 25 seconds (first 5 seconds was just listening to the beat).	• Synchronization error (absolute deviation value – how closely participants timed their foot strike or clap to the metronome beat).	• Significant main effect for limb (legs vs. arms), frequency, and group. • Steps were more closely coupled to the metronome compared to claps, however less variability was seen in the clapping conditions. • Performance at 0.8Hz and 2.0Hz were more closely coupled to the metronome beat. Both groups of children showed more variability with increasing frequency. Adults showed less variability with increasing frequency. • Overall, adults were significantly more closely coupled than both groups of children. The two groups of children did not significantly differ from each other. However the DCD group showed significantly more variability than the other two groups.

Table 3.2 Literature Review Summary of Data

	Sample	Methods	Measures	Results
Pfordresher and Benitez, 2007[73]	• 25 adults (mean age 19.6, range 17-30) • 15 female, 10 male • Mean years musical performance experience = 3.96, range = 0-14	Participants were instructed to tap their fingers or play a short sequence of tones at 3 tempi (330, 500 and 660 ms). Auditory feedback was provided at fixed (0, 330, 500 or 660 ms) or adjusted (0, 66%, 100% or 132% of actual key strokes) delays.	• Timing of produced inter-response intervals (IRIs)	• Mean IRIs during synchronous conditions only differed from the prescribed IRI by 14ms on average. • For fixed delays during sequence production only, there was a significant main effect of delay magnitude, and a significant delay x tempo interaction. Disruption was reduced when the delay matched the mean IRI (e.g., 500ms delay during 500ms tempi). • For adjustable delays, there was a main effect of delay magnitude for sequence production. There was a significant main effect of delay magnitude and a delay x tempo interaction for tapping.
Avanzino et al., 2014 [Abstract][72]	Not described	Participants performed spontaneous finger opposition movements for which the tempo was recorded. Participants then viewed videos of a hand performing finger opposition movements that were the same, slower, or faster than their spontaneous movements. Participants then watched a 10-min training video of movements faster than their initial spontaneous movements, before being asked to perform finger opposition movements again.	• Cortical excitability measured in the hand muscles by transcranial magnetic stimulation (TMS).	• Cortical excitability of the hand muscle was significantly enhanced during observation of finger opposition movements that were at the same speed of execution as the spontaneous movements compared to observing the slower or faster conditions. • Observational training induced a behavioural shift of the spontaneous execution rate.

Table 3.2 Literature Review Summary of Data

	Sample	Methods	Measures	Results
Ramos et al., 2011[80]	• 24 musicians (more than 6 years experience) aged 19-25 years (12 males, 12 females) • 24 non-musicians (no experience) aged 17-25 years (12 males, 12 females)	Participants listened to three different Greek musical excerpts played in: • 7 different modes (Ionian, Dorian, Phrygian, Lydian, Mixolydian, Aeolian, Locrian) at: • 3 different tempi (72BPM, 114BPM, 184BPM) for a total of 63 conditions	Forced choice emotions associated with each of the 63 conditions: • Happiness (high arousal, positive valence) • Sadness (low arousal, negative valence) • Serenity (low arousal, positive valence) • Fear/Anger (high arousal, negative valence)	• A significant main effect of tempo was found for arousal, with faster tempi associated with higher arousal. Musicians were significantly less sensitive to changes in arousal from slow to moderate tempi compared to non-musicians. • A significant main effect of mode was found for arousal with the Ionian mode depicting the highest arousal for both musicians and non-musicians. • There was a significant interaction between mode and tempi for arousal. • A significant main effect of tempo was found for valence, with negative valence associated with slower tempi. Valence only evolved to positive values when tempi changed from moderate to fast. The effect of tempo on valence was more pronounced in musicians. • A significant main effect of mode was found for valance, which was also modulated by musical training. Major modes (Ionian, Lydian, Mixolydian) were associated with positive valence for both groups. The four remaining minor modes were associated with negative valence. • Differences in both arousal and valence were found between all major and minor modes.

Table 3.2 Literature Review Summary of Data

	Sample	Methods	Measures	Results
Watanabe, 2008[77]	• 40 participants (not described) • All had normal or corrected to normal vision, and normal motor function	Participants viewed point-light displays of biological motion (whole body – jumping, running, walking, kicking, throwing a ball, etc.), scrambled biological motion or solid object motion at three rates (half, normal, and double). Following a 300-2400ms blank period, observers performed an un-related simple choice reaction-time task.	• Slope of reaction time (ms) as a function of motion speed (frame rate; Hz)	• Reaction time decreased as a function of speed with biological motion, but not with object or scrambled motions. (Faster speed observed correlated with faster reaction times). • This phenomenon was only observed when reaction time task was performed within 1 second of viewing biological motion.
Su and Jonikaitis, 2011[76]	• 11 adults (mean age 25 years, SD 3.1) and one study author • Musical training ranged from 0-8 years	Participants listened to five tones in a standard sequence (either 100 or 150BPM) while observing dots on a screen that either remained in a static position but changed luminescence, or moved around a circle. The visual stimuli were presented in a constantly accelerating manner and did not have a discrete rhythm. Participants then listened to a comparison sequence without concurrent visual stimuli (presented at ±4%, ±8%, or ±12% of the standard sequence tempo).	Forced choice: • Was the tempo of the comparison sequence faster or slower than the standard sequence?	• Significant main effects of tempo and visual condition were found. • In general, the 100BPM auditory signal was perceived as faster than it was, and the 150BPM signal was perceived as slower than it was. • The same auditory tempo was perceived as faster when accompanied with the moving visual stimuli compared to the static dots.

Table 3.2 Literature Review Summary of Data

	Sample	Methods	Measures	Results
Arrighi et al., 2006[75]	• Two authors and one naïve participant (mean age 30 years)	Participants observed videos with sound of a drummer playing a congo drum at 3 different tempi (1, 2 and 4 Hz). Audio-visual stimuli were either synchronous or asynchronous (delayed auditory or delayed visual).	Forced choice: • Synchronous vs. Asynchronous.	• For all drumming tempi, perceived synchrony occurred when the auditory stimulus was delayed compared to the visual stimulus. Magnitude of auditory delay for perceived synchrony significantly varied with drumming tempo – larger delays were required for slower tempi (1Hz – 80ms delay, 2Hz – 60ms delay, 4Hz – 40ms delay).
Petrini et al., 2009[79]	• 4 expert jazz drummers (mean age=20.5 years) • 4 novices with no musical experience (mean age=19.5 years) • All had normal hearing and normal or corrected-to-normal vision	Participants observed point-light display videos with sounds of drumming with the following variable conditions: Tempo: 60, 90, or 120BPM Accents: first, second or third beat Audio-visual onset delay: 0, ±66.67, ±133.33, ±200, or ±266.67 ms Each of the 81 movies were presented 21 times for a total of 1701 presentations (presented over 3 days)	Forced choice: • Synchronous vs. Asynchronous	• Synchrony best detected when auditory stimulus was delayed compared to visual stimulus for both groups. • Experts detected synchrony with a smaller auditory delay compared to novices • Tempo significantly affected novices' perception of synchrony (less synchrony with slower tempi), while there was no significant effect for experts. • Accent did not significantly affect synchrony perception

4 Methodology

4.1 Participants

A sample of convenience was recruited from the greater Vancouver community via distributed flyers (community centres, after-school care programs, local sports facilities) (see Appendix C), social media invitations (Facebook, Craigslist), and word-of-mouth (snowball sampling). Participants were eligible for inclusion in this pilot study if they met all of the following criteria:

1. Aged 10-12 years
2. History of typical development (motor, language, cognitive, social)
3. Parent willing to give informed consent and child willing to give informed assent

Interested individuals were excluded from participating in the study if they met any of the following criteria:

1. Any known neurological deficit (e.g., cerebral palsy, autism spectrum disorder, learning disabilities)
2. Any known vision or hearing impairment (uncorrected)

Descriptive measures of participant characteristics were investigated through a questionnaire (see Appendix D) and included sex, age, ethnicity, hours spent in music or dance training, and experience with treadmills (observation of, use) and drums (type, observation of, use). These participant characteristics were collected because they may influence how children perceive the presented stimuli (e.g.,

children with more experience using drums may demonstrate a greater response than children with no experience).[16,17,28-30,44-46,48]

4.2 Study Protocol

Figure 4.1 depicts a schematic of the study protocol. This pilot study employed a single group pre-post repeated measures design. Participants were screened for inclusion and exclusion criteria via phone or email communication following their response to the recruitment material. Participants that were deemed eligible were invited to come to the Perception-Action Lab at UBC. A request was made for the children to refrain from using hair products (e.g., gels, hairspray) prior to coming into the lab. Once at the Perception-Action Lab, children and their parent(s) or guardian(s) reviewed written assent and consent forms respectively (see Appendix E), and were invited to discuss any questions. Participants that were willing to sign these forms were then asked to fill out a questionnaire to obtain demographic information. Next, the child's head circumference was measured to determine which size of 64-channel HydroCel Geodesic EEG Sensor Net (EGI, Eugene, OR) he or she would wear. The appropriate net was then placed on the child's head, with the vertex (Cz) electrode placed midway between the ears, and midway between the nasion and inion. The child sat in front of a 60cm desktop monitor at a distance of approximately 60cm with feet flat on the ground. The child was also fitted with noise isolating earphones (Etymotic Research, Inc., Elk Grove Village, IL). EEG data were recorded with a Net Amps 300 amplifier at a sampling rate of 250 Hz, and referenced to Cz. The scalp electrode impedance threshold was set at 50 kΩ.

Participants were requested to sit quietly without moving, and to focus on the monitor and the sounds for the duration of the experiment. Stimuli files were randomly displayed using the software Presentation®.[81] Participants viewed the randomized rest and uni-modal conditions (14.5 minutes), received a short break while the impedance levels of the EEG sensor net were re-checked, and finally viewed the multi-modal stimuli (12.5 minutes). Figure 4.2 depicts the experimental set-up for participants.

4.3 Experimental Conditions

4.3.1 Uni-Modal Stimuli

Each condition was presented to the participant 25 times. Trials lasted five seconds, separated by 2-second wash out periods. The uni-modal stimuli conditions consisted of:

1. Rest/Baseline: A – silence; V – cross-hair fixation
2. A40: A – sampled drum beat at 40 BPM; V – cross-hair fixation
3. A173: A – sampled drum beat at 173 BPM; V – cross-hair fixation
4. V40: A – silence; V – video clip depicting the lower half of an adult walking on a treadmill at 40 BPM
5. V173: A – silence; V – video clip depicting the lower half of an adult walking on a treadmill at 173 BPM

4.3.2 Multi-Modal Stimuli

Each condition was presented to the participant 25 times. Trials lasted five seconds, separated by 2-second wash out periods. The multi-modal stimuli conditions consisted of:

1. Equivalent Conditions

   a) A40 – V40: A – sampled drum beat at 40 BPM; V – video clip depicting the lower half of an adult walking on a treadmill at 40 BPM

   b) A173 – V173: A – sampled drum beat at 173 BPM; V – video clip depicting the lower half of an adult walking on a treadmill at 173 BPM

2. Differing Conditions

   c) A40 – V173: A – sampled drum beat at 40 BPM; V – video clip depicting the lower half of an adult walking on a treadmill at 173 BPM

   d) A173 – V40: A – sampled drum beat at 173 BPM; V – video clip depicting the lower half of an adult walking on a treadmill at 40 BPM

4.4 Outcome Measure: Mu Suppression Index

In general, EEG measures of band power demonstrate wide variability among individuals, and *relative* power values are more stable than *absolute* power values within individuals.[82] For this reason, mean *relative* power is used in EEG studies to compare activity across participants and conditions. Relative mu rhythm, or the Mu Suppression Index (MSI), has been utilized as a measure of motor activity and reflection of the mirror neuron system in healthy adults,[25,26] healthy children,[83,84] healthy infants,[39,85,86] children with autism spectrum disorder,[83] and children with

cerebral palsy.[84] The test-retest reliability of the MSI has been investigated in healthy children and children with cerebral palsy, with resulting intra-class coefficients of 0.93 – 0.99.[84]

The MSI is a change score of absolute mu band power (8-13Hz) between a baseline and experimental condition that has been normalized by performing a log function of the ratio in order to be able to run parametric analyses. The MSI is therefore expressed by the function:

$$Mu \text{ Suppression Index} = LOG\left(\frac{Experimental}{Baseline}\right)$$

In this study, EEG data collected from each participant were processed and analyzed using the software, Brain Electrical Source Analysis® Research.[87] Trials from each condition were averaged using 5-second epochs (-500ms – 5000ms). Fast Fourier transforms were performed for each condition to calculate power in the 8-13Hz-frequency band. An MSI was then calculated for each condition (using rest as baseline) for the electrode placements of C3 and C4 according to the international 10-10 system montage (Figure 4.3). C3 correlates with the left SMC, and C4 correlates with the right SMC.

4.5 Data Synthesis and Analysis

4.5.1 Descriptive Measures

Sex is presented as a count (male/female). Age and number of hours spent in music/dance training per week are described using means and standard deviations.

Participant experiences with treadmills and drums are presented as counts (yes/no) and narrative description.

4.5.2 Experimental Outcome Measure

The dependent variable in this study is mean Mu Suppression Index. SPSS software,[88] was used to conduct statistical analyses of the data. A statistician was consulted to ensure appropriate analyses were performed. The following *a priori* analyses were run to test each of the reported hypotheses:

4.5.2.1 Mu Desynchronization

One sample t-tests were calculated for each condition at C3 and C4 to determine if the mean MSI was significant from zero. Alpha level was set at .05.

4.5.2.2 Auditory vs. Visual MSI

Participants contributed an average value of their MSI for A40 and A173 to the auditory condition. Participants contributed an average value of their MSI for V40 and V173 to the visual condition.

C3: Data were found to be normally distributed (Shapiro-Wilk Test of Normality (SW): A, p=.917; V, p=.472); therefore an analysis of covariance (ANCOVA) for repeated measures (RM) comparing auditory and visual conditions and including sex, age, dance, and music as covariates was performed.

C4: Data were found to be normally distributed (SW: A, p=.763; V, p=.861); therefore an RM-ANCOVA comparing auditory and visual conditions and including sex, age, dance, and music as covariates was performed.

4.5.2.3 Uni-Modal vs. Multi-Modal MSI

Participants contributed an average value of their MSI for A40, A173, V40, and V173 to the uni-modal (UM) condition. Participants contributed an average value of their MSI for AV40, AV173, A40V173 and A173V40 to the multi-modal (MM) condition.

C3: Data were found to be normally distributed (SW: UM, p=.109; MM, p=.658); therefore an RM-ANCOVA comparing uni-modal and multi-modal conditions and including sex, age, dance, and music as covariates was performed.

C4: Data were found to be normally distributed (SW: UM, p=.399; MM, p=.641); therefore an RM-ANCOVA comparing uni-modal and multi-modal conditions and including sex, age, dance, and music as covariates was performed.

4.5.2.4 Equivalent vs. Differing MSI

Participants contributed an average value of their MSI for AV40 and AV173 to the equivalent condition. Participants contributed an average value of their MSI for A40V173 and A173V40 to the differing condition.

C3: Data were found to be normally distributed (SW: E, p=.777; D, p=.454); therefore an RM-ANCOVA comparing equivalent and differing conditions and including sex, age, dance, and music as covariates was performed.

C4: Data were found to be normally distributed (SW: E, p=.226; D, p=.668); therefore an RM-ANCOVA comparing equivalent and differing conditions and including sex, age, dance, and music as covariates was performed.

4.5.2.5 Effect of Stimulus and Tempo on MSI

C3: Data did not meet the assumption of normality for all conditions (SW: A40, p=.025; V40, p=.027); therefore a related-samples Friedman's two-way analysis of variance (ANOVA) comparing all conditions was performed.

C4: Data were found to be normally distributed (SW: p=.099-.898); therefore an RM-ANCOVA comparing all conditions and including sex, age, dance, and music as covariates was performed. Pairwise comparisons were run using a Bonferroni correction for multiple comparisons (p=.05).

Figure 4.1 Schematic Representation of Study Protocol

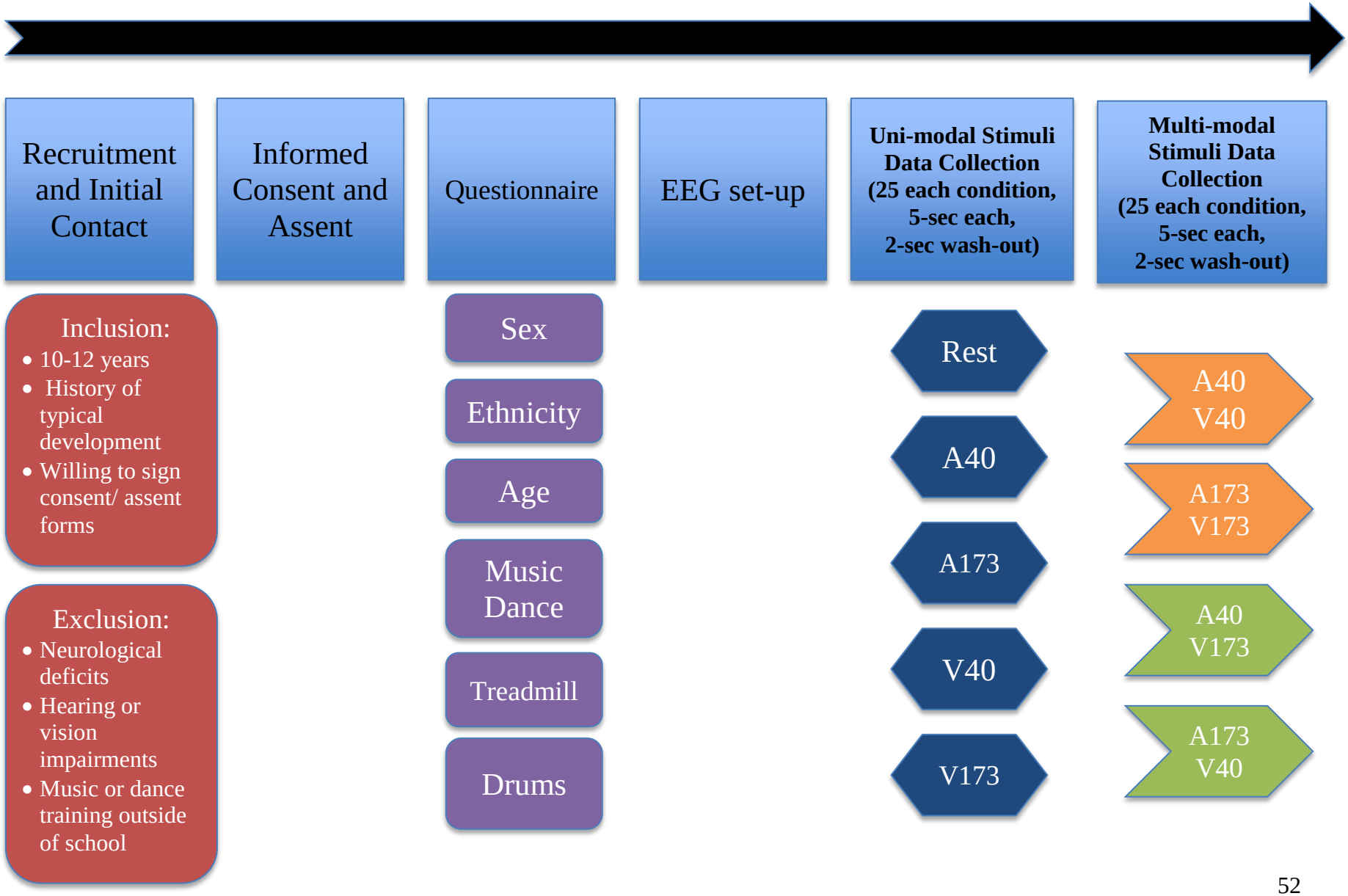


Figure 4.2 Experimental Set-Up for Participants. Pictures used with permission.

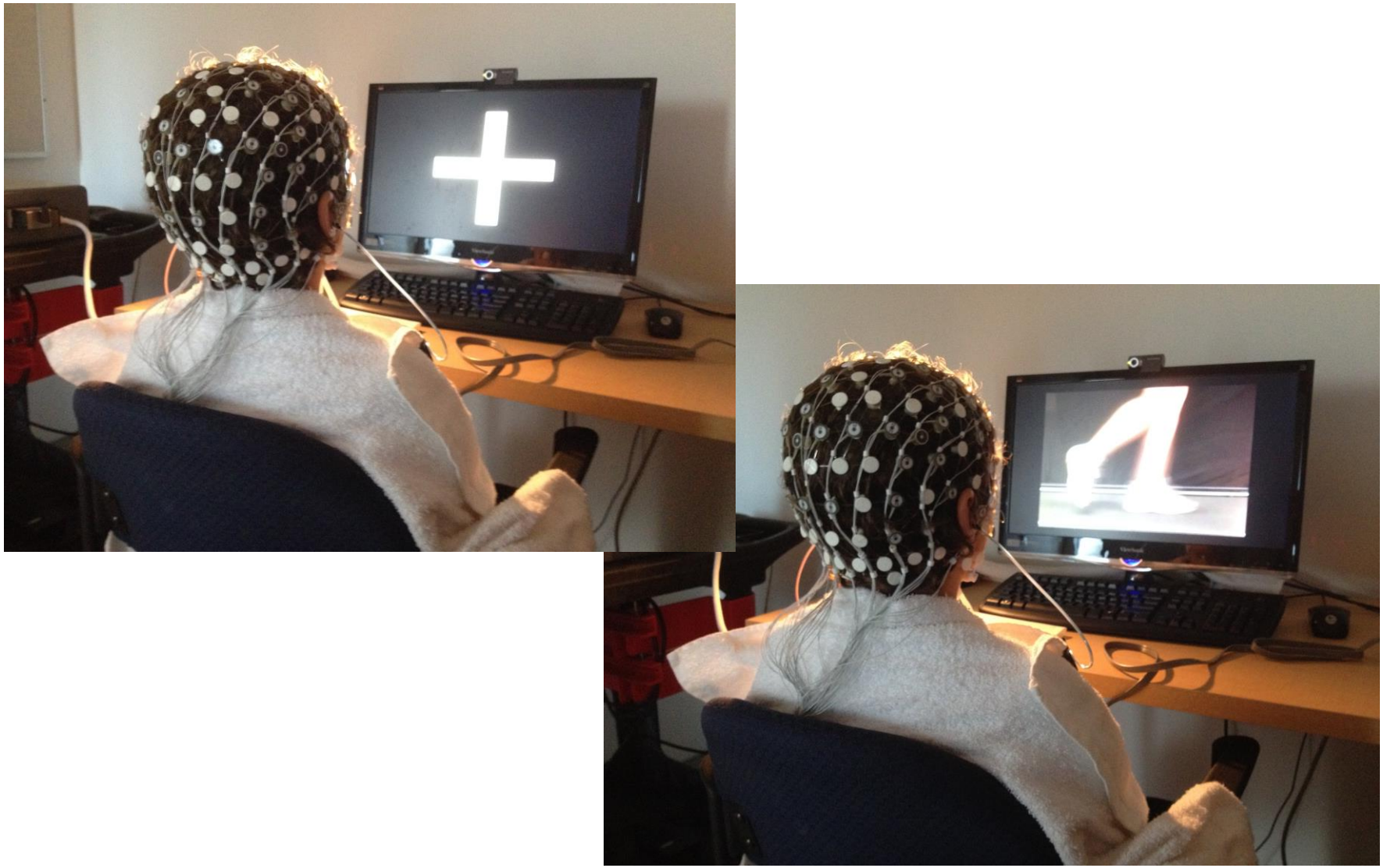
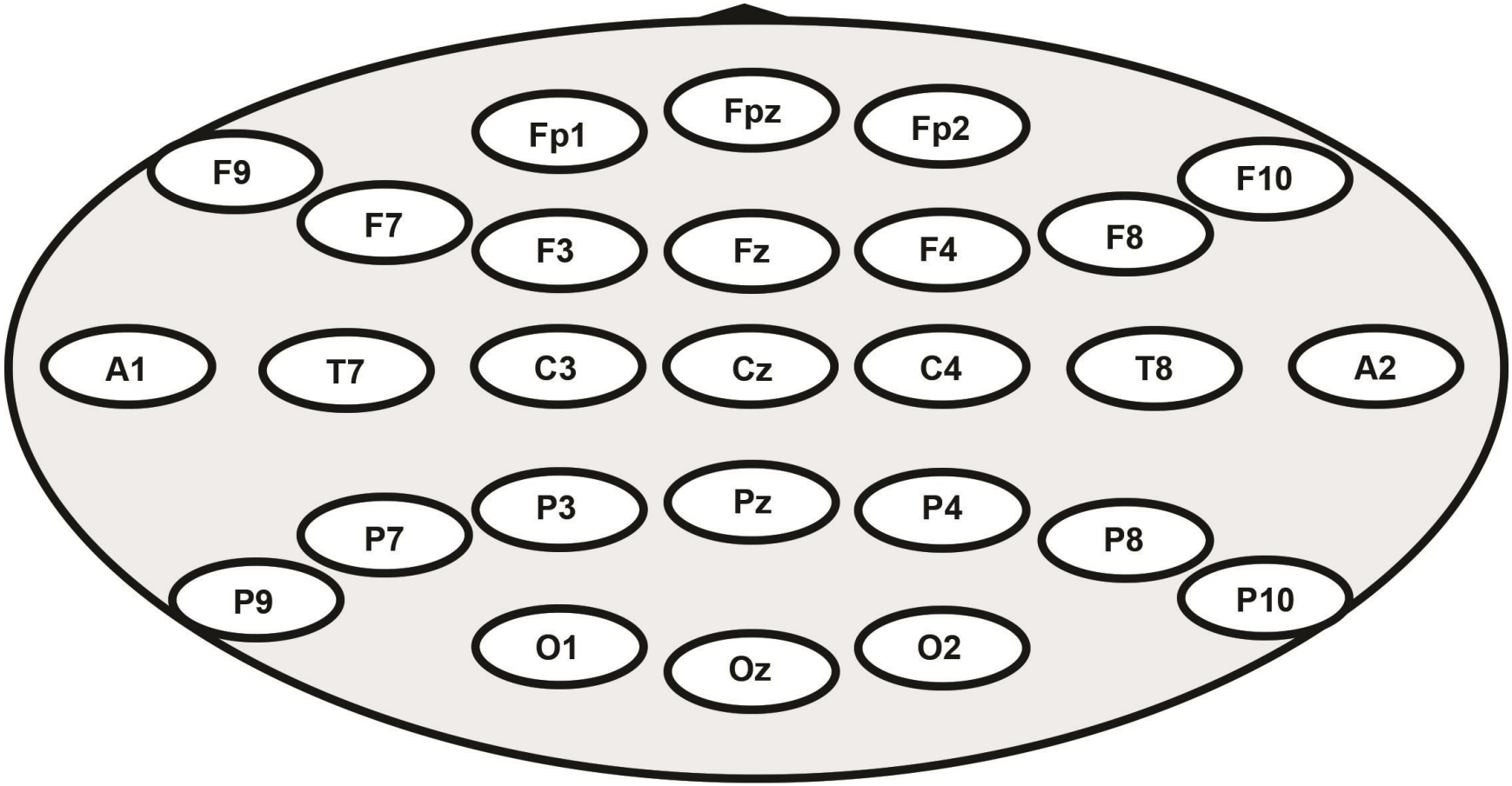


Figure 4.3 International 10 – 10 System Montage for EEG Electrode Placement



5 Research Findings

5.1 Participant Characteristics

Twelve participants were recruited and met eligibility criteria for this study. Unfortunately technical difficulties arose with the collection of EEG data of participants S04 and S05, and therefore these participants were excluded from all data synthesis and analysis. This left 10 participants for evaluation. Table 4.1 summarizes the participant characteristics. Six females and four males with an average age of 132.9 months (SD 10.82 months) formed the sample of this study. Participants identified with a variety of ethnicities including Caucasian, Canadian, Canadian-Czech, Scottish-English-Irish, Chinese, Jewish, Brazilian, and Asian-Italian. Nine participants reported currently taking music classes (mean hours 3.33, SD 2.5) and all 10 participants reported past experience with music classes. Four participants reported currently taking dance classes (mean hours 5.63, SD 3.68) and seven participants reported past experience with dance classes. Nine participants reported experience with watching someone else use a treadmill, and seven participants reported experience with using a treadmill. Nine participants reported having watched someone else play the drums, and seven participants reported having used drums themselves.

5.2 Experimental Measure: MSI

5.2.1 Mu Desynchronization

<u>C3:</u> Mean MSI was significantly different from zero for the V40 ($t(9)=-2.982$, $p=.015$), V173 ($t(9)=-4.757$, $p=.001$), Visual ($t(9)=-4.194$, $p=.002$) and Uni-modal

(t(9)= -3.233, p=.010) conditions. Mean MSI was not significantly different from zero for the A40 (t(9)=-1.386, p=.199), A173 (t(9)=-1.174, p=.271), AV40 (t(9)=-.699, p=.520), AV173 (t(9)=-1.034, p=.328), A40V173 (t(9)=-2.036, p=.072), A173V40 (t(9)=-1.748, p=.114), Auditory (t(9)=-1.599, p=.144), Multi-modal (t(9)=-1.415, p=.191), Equivalent (t(9)=-.875, p=.404), or Differing (t(9)=-1.898, p=.090) conditions. Figures 5.1 – 5.4 note the significant differences from zero with asterisks.

C4: Mean MSI was significantly different from zero for the A173 (t(9)=-4.145, p=.003), V40 (t(9)=-4.536, p=.001), V173 (t(9)=-6.270, p<.001), AV40 (t(9)=-2.968, p=0.16), AV173 (t(9)=-2.283, p=.048), A40V173 (t(9)=-2.793, p=.021), A173V40 (t(9)=-2.619, p=.028), Auditory (t(9)=-2.970, p=.016), Visual (t(9)=-6.915, p<.001), Uni-modal (t(9)=-5.345, p<.001), Multi-modal (t(9)=-3.481, p=.007), Equivalent (t(9)=-3.090, p=.013) and Differing (t(9)=-2.982, p=.015) conditions. Mean MSI was not significantly different from zero for the A40 (t(9)=-1.639, p=.136) condition. Figures 5.1 – 5.4 note the significant differences from zero with asterisks.

5.2.2 Hypotheses Outcomes

Analyses of all hypotheses were conducted using alpha = .05, the Bonferroni adjustment for multiple comparisons, and the covariate values: Age=132.90 months, Music=3.00 hours per week, Dance=2.25 hours per week.

5.2.2.1 Hypothesis #1: Auditory vs. Visual

C3: The RM-ANCOVA did not identify a significant within-subjects effect of Condition (F(1,5)=3.096, p=.139) or significant within-subjects interactions for Condition*Sex (F(1,5)=1.426, p=.286), Condition*Age (F(1,5)=4.302, p=.093), Condition*Music (F(1,5)=.019, p=.896), or Condition*Dance (F(1,5)=.626, p=.465). However; the pairwise comparison of Auditory (M=-.077, 95%CI [-.234, .080]) and Visual (M=-.206, 95%CI [-.314, -.098]) estimated marginal means was statistically significant (p=.005) (See Figure 5.1). The visual condition demonstrated significantly greater mu suppression compared to the auditory condition.

C4: The RM-ANCOVA did not identify a significant within-subjects effect of Condition (F(1,5)=.018, p=.899) or significant within-subjects interactions for Condition*Sex (F(1,5)=0.157, p=.708), Condition*Age (F(1,5)=0.081, p=.787), Condition*Music (F(1,5)=0.80, p=.789), or Condition*Dance (F(1,5)=0.337, p=.587). The pairwise comparison of Auditory (M=-.125, 95%CI [-.245, -.005]) and Visual (M=-.247, 95%CI [-.364, -.129]) estimated marginal means was not statistically significant (p=.053) (See Figure 5.1).

5.2.2.2 Hypothesis #2: Uni-Modal vs. Multi-Modal

C3: The RM-ANCOVA identified a significant within-subjects main effect of Condition (F(1,5)=12.416, p=.017), and significant within-subjects interactions of Condition*Age (F(1,5)=16.666, p=.010) and Condition*Music (F(1,5)=13.158, p=.015). The within-subjects interactions of Condition*Dance (F(1,5)=0.727, p=.433)

and Condition*Sex (F(1,5)=3.585, p=.117) were not significant. The pairwise comparison of Uni-modal (M=-.141, 95%CI [-.271, -.012]) and Multi-modal (M=-.078, 95%CI [-.148, -.009]) estimated marginal means was not statistically significant (p=.231) (See Figure 5.2).

C4: The RM-ANCOVA identified a significant within-subjects interaction of Condition*Dance (F(1,5)=9.421, p=.028). There were no significant within-subjects interactions of Condition*Sex (F(1,5)=.009, p=.929), Condition*Age (F(1,5)=6.522, p=.051), or Condition*Music (F(1,5)=2.799, p=.155) and no significant within-subjects effect of Condition (F(1,5)=5.953, p=.059). The pairwise comparison of Uni-modal (M=-.186, 95%CI [-.287, -.084]) and Multi-modal (M=-.166, 95%CI [-.267, -.065]) estimated marginal means was not statistically significant (p=.440) (See Figure 5.2).

5.2.2.3 Hypothesis #3: Equivalent vs. Differing

C3: The RM-ANCOVA did not identify a significant effect of Condition (F(1,5)=.518, p=.504) or significant within-subject interactions for Condition*Sex (F(1,5)=.016, p=.905), Condition*Age (F(1,5)=.507, p=.508), Condition*Music (F(1,5)=.001, p=.979) or Condition*Dance (F(1,5)=.459, p=.528). The pairwise comparison of Equivalent (M=-.055, 95%CI [-.224, .114]) and Differing (M=-.101, 95%CI [-.177, -.025]) estimated marginal means was not statistically significant (p=.617) (See Figure 5.3).

C4: The RM-ANCOVA did not identify a significant effect of Condition ($F(1,5)=.304$, $p=.605$) or significant within-subject interactions for Condition*Sex ($F(1,5)=.021$, $p=.890$), Condition*Age ($F(1,5)=.298$, $p=.608$), Condition*Music ($F(1,5)=.127$, $p=.736$) or Condition*Dance ($F(1,5)=.042$, $p=.846$). The pairwise comparison of Equivalent ($M=-.139$, 95%CI [-.264, -.014]) and Differing ($M=-.194$, 95%CI [-.366, -.021]) estimated marginal means was not statistically significant ($p=.557$) (See Figure 5.3).

5.2.2.4 Hypothesis #4: Effect of Stimulus and Tempo

C3: The related-samples Friedman's two-way ANOVA by ranks did not find a significant effect of Condition at the C3 electrode location (Test Statistic 5.547, $p=.594$); therefore, the null hypothesis is retained (See Figure 5.4).

C4: The RM-ANCOVA did not identify a significant within-subjects effect for Condition ($F(7,35)=.798$, $p=.594$), or significant within-subjects interactions for Condition*Sex ($F(7,35)=.121$, $p=.996$), Condition*Age ($F(7,35)=.774$, $p=.613$), Condition*Music ($F(7,35)=.817$, $p=.580$) or Condition*Dance ($F(7,35)=.895$, $p=.521$). However; pairwise comparisons identified a significant difference of means between the conditions of A40 ($M=-.071$, 95%CI [-.197, .055]) and V173 ($M=-.312$, 95%CI [-.453, -.170]) ($p=.033$). The V173 condition demonstrated significantly greater mu suppression compared to the A40 condition. All other pairwise comparisons were non-significant ($p>.05$) (See Figure 5.4).

5.3 Summary

Six female and four male typically developing children with a range of music and dance experience comprised the sample for this study. Figure 5.5 summarizes the conditions and differences that demonstrated significance.

Auditory vs. Visual

Left SMC: Significant mu suppression was found for the visual condition only. Mean mu suppression was significantly greater in the visual condition compared to the auditory condition.

Right SMC: Significant mu suppression was found for both visual and auditory conditions. Mean mu suppression was not significantly different between the conditions.

Uni-Modal vs. Multi-Modal

Left SMC: Significant mu suppression was found for the uni-modal condition only. While a significant effect of condition was identified, mean mu suppression was not significantly different in a pairwise comparison of uni-modal and multi-modal conditions. Age and musical experience demonstrated significant interactions with condition.

Right SMC: Significant mu suppression was found for both conditions. Mean mu suppression was not significantly different between the conditions. Dance experience demonstrated a significant interaction with condition.

Equivalent vs. Differing

Left SMC: Neither condition demonstrated significant mu suppression. Mean mu suppression was not significantly different between the conditions.

Right SMC: Significant mu suppression was found for both conditions. Mean mu suppression was not significantly different between conditions.

Stimulus and Tempo

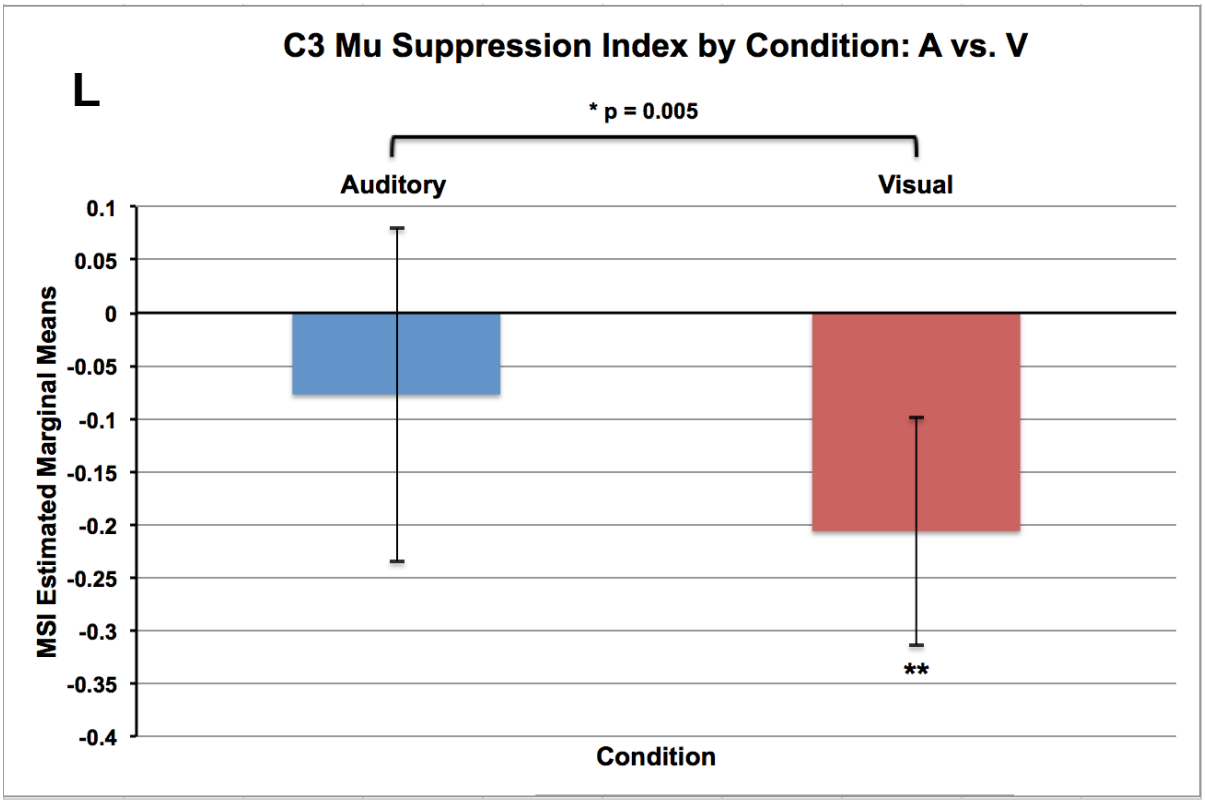
Left SMC: Mu suppression was significant for the V40 and V173 conditions. There was no significant effect of condition.

Right SMC: Mu suppression was significant for the A173, V40, V173, AV40, AV173, A40V173 and A173V40 conditions. The V173 condition demonstrated significantly greater mu suppression compared to the A40 condition.

Table 5.1: Participant Characteristics

	Sex	Age (Months)	Music (Experience, Hours/week)	Dance (Experience, Hours/week)	Treadmill (Experience)	Drums (Experience)
Count	4 M 6 F		Current 9 YES 1 NO Past 10 YES	Current 4 YES 6 NO Past 7 YES 3 NO	Watched 9 YES 1 NO Used 7 YES 3 NO	Watched 9 YES 1 NO Used 7 YES 3 NO
Mean (SD)		132.9 (10.82)	3.33 (2.5)	5.63 (3.68)		
Ethnicity						
2 Caucasian 1 Canadian 1 Canadian/Czech 2 Scottish/English/Irish 1 Chinese 1 Jewish 1 Brazilian 1 Asian/Italian		**Description**	S01: school, choir, recorder S02: piano 3 years S03: piano 5 years S06: music classes 8 years, in Gr 10 piano S07: violin lessons, school strings program S08: piano S09: piano classes S10: guitar, piano S12: choir 2 years	S02: hip hop, ballet S07: ballet, jazz, modern S08: Dance Co for ballet, jazz 2 years S09: rhythmic gymnastics S10: ballet, hip hop S11: tap, jazz, musical theatre, ballet, lyrical jazz S12: ballet, hip hop, contemporary	S01: watched mom, used self S06: only tried a couple times S08: used one at hotel gym S09: watched dad and tried for fun S10: at the gym S11: for fun S12: used just once	S01: just for fun, bongos and drum kit S02: drum kit S03: used friend's drum kit S06: played drum kit a couple of times. S07: big bongo drums, cymbals S08: marching band, bongo drums S10: rock band S11: for fun, bongo, snare S12: Brazilian drums, drum kit, pandeiro, agogo

Figure 5.1. Estimated Marginal Means of Mu Suppression Index by Condition: Auditory vs. Visual. Evaluated with the covariate values: Age = 132.90; Music = 3.00; Dance = 2.25. Error bars represent 95% CIs. * p≤.05, ** p≤.01, *** p≤.001



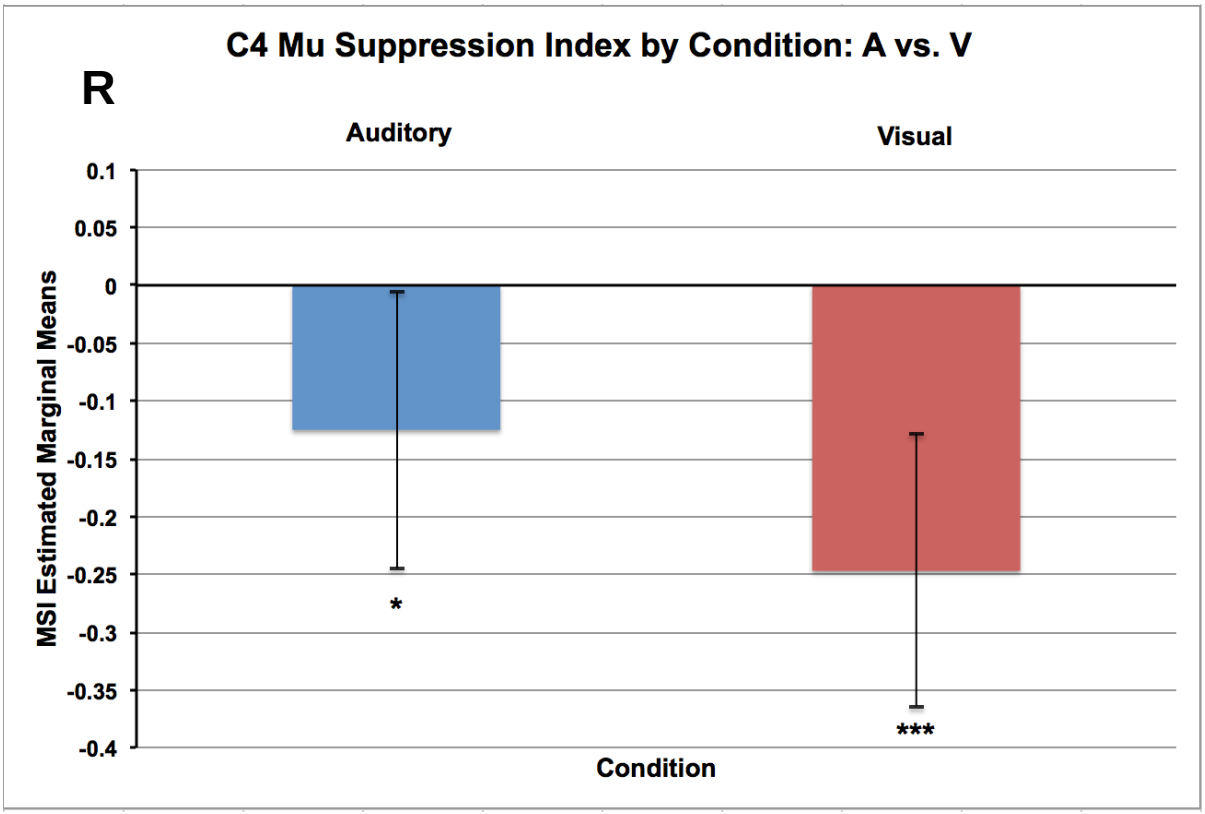
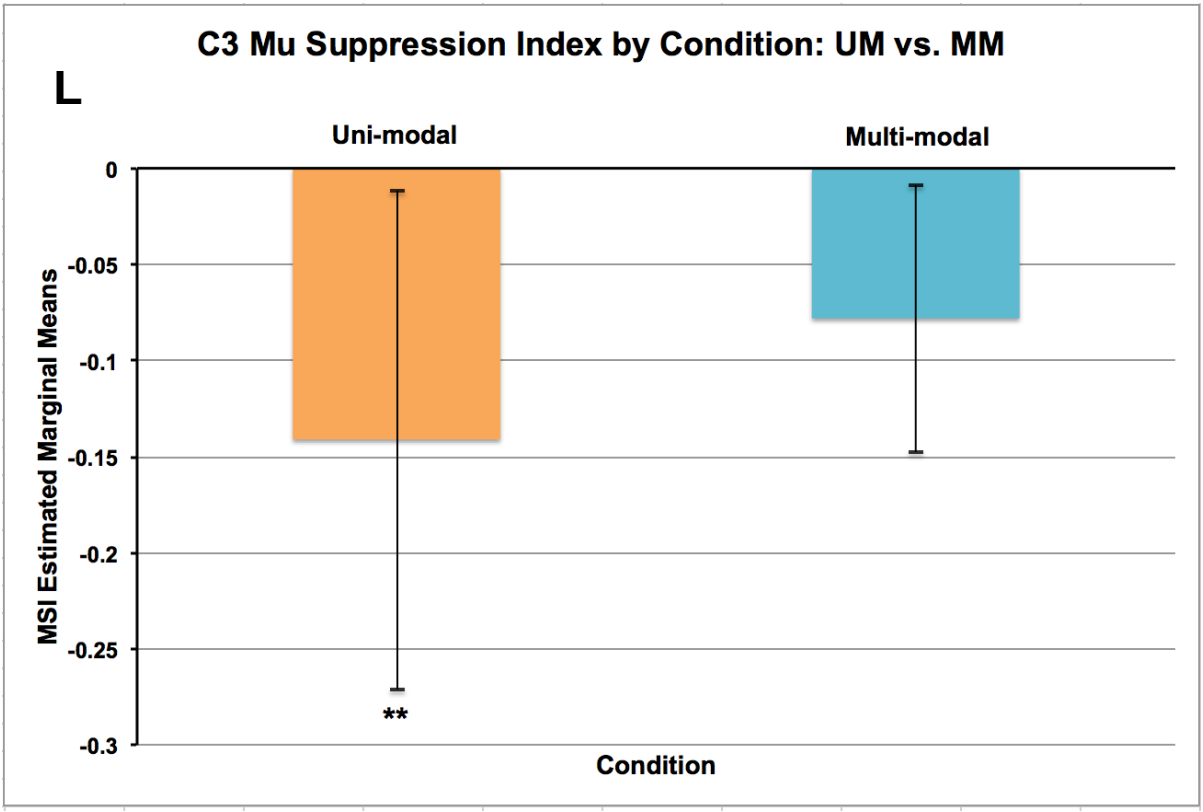


Figure 5.2. Estimated Marginal Means of Mu Suppression Index by Condition: Uni-Modal vs. Multi-Modal. Evaluated with the covariate values: Age = 132.90; Music = 3.00; Dance = 2.25. Error bars represent 95% CIs. * p≤.05, ** p≤.01, *** p≤.001



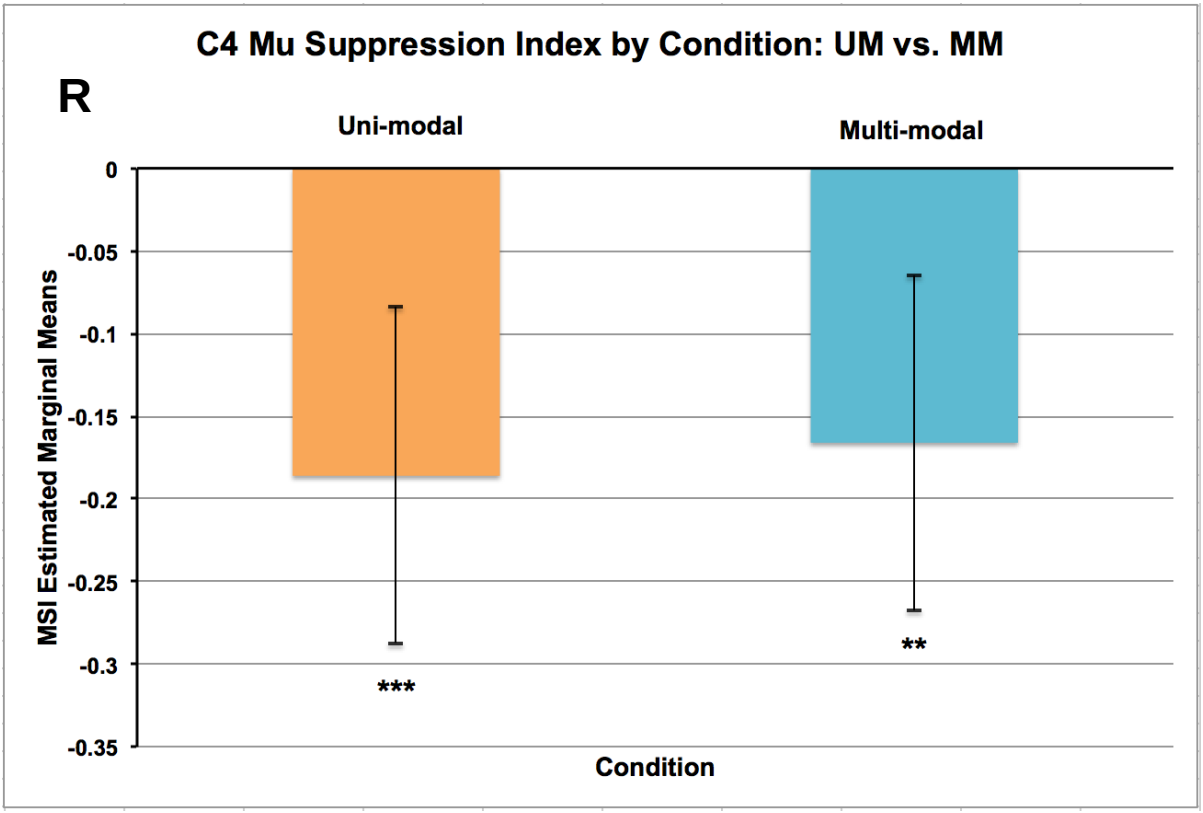
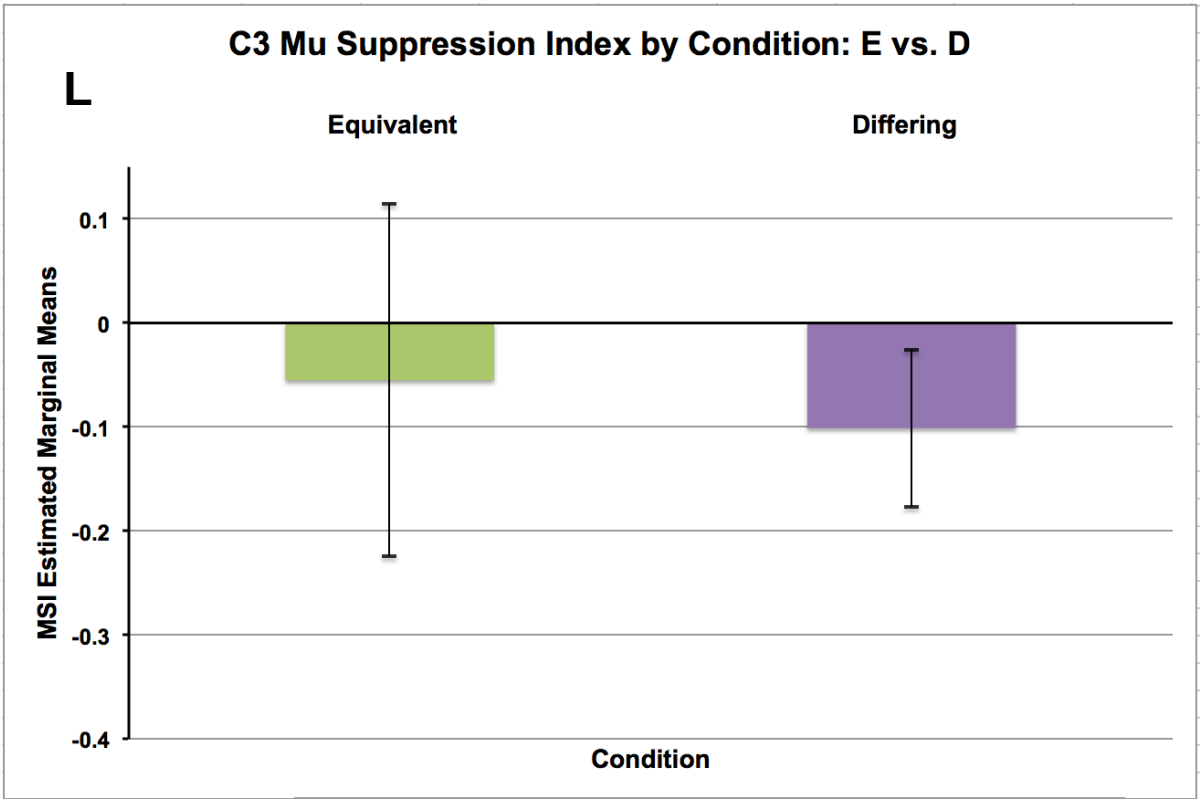


Figure 5.3. Estimated Marginal Means of Mu Suppression Index by Condition: Equivalent vs. Differing. Evaluated with the covariate values: Age = 132.90; Music = 3.00; Dance = 2.25. Error bars represent 95% CIs. * p≤.05, ** p≤.01, *** p≤.001



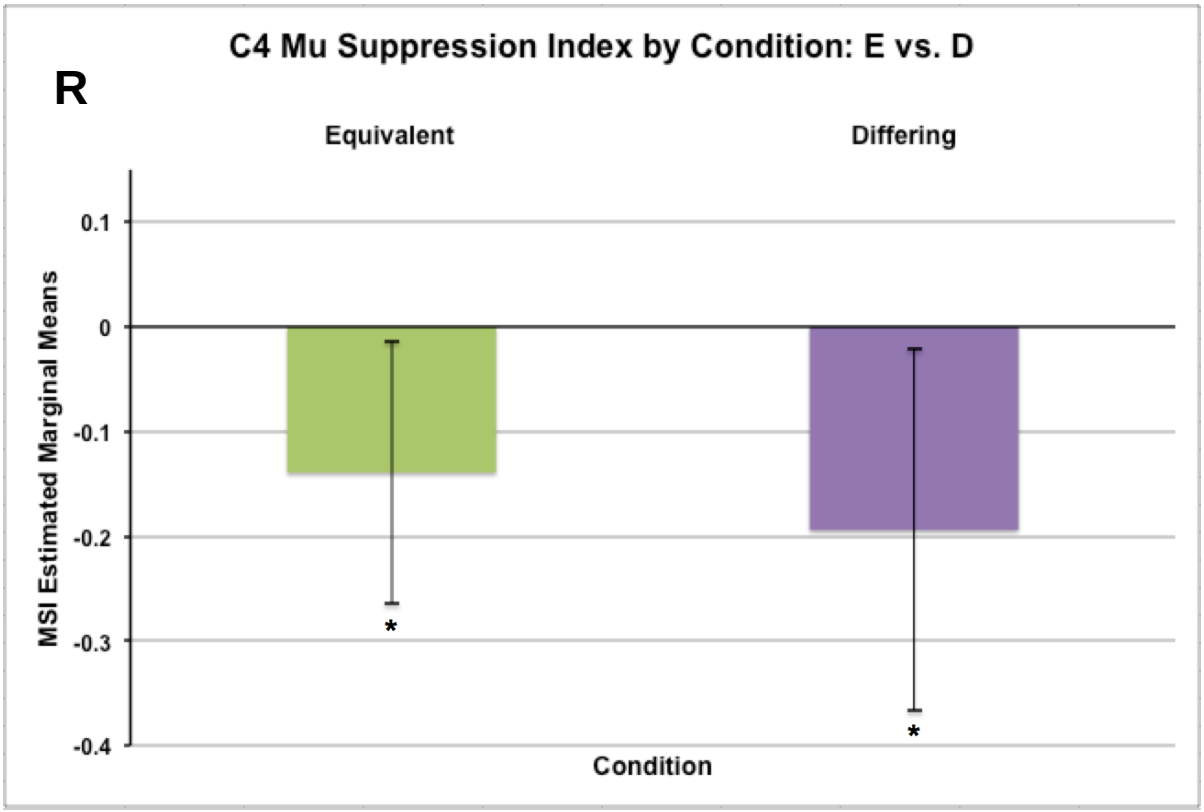
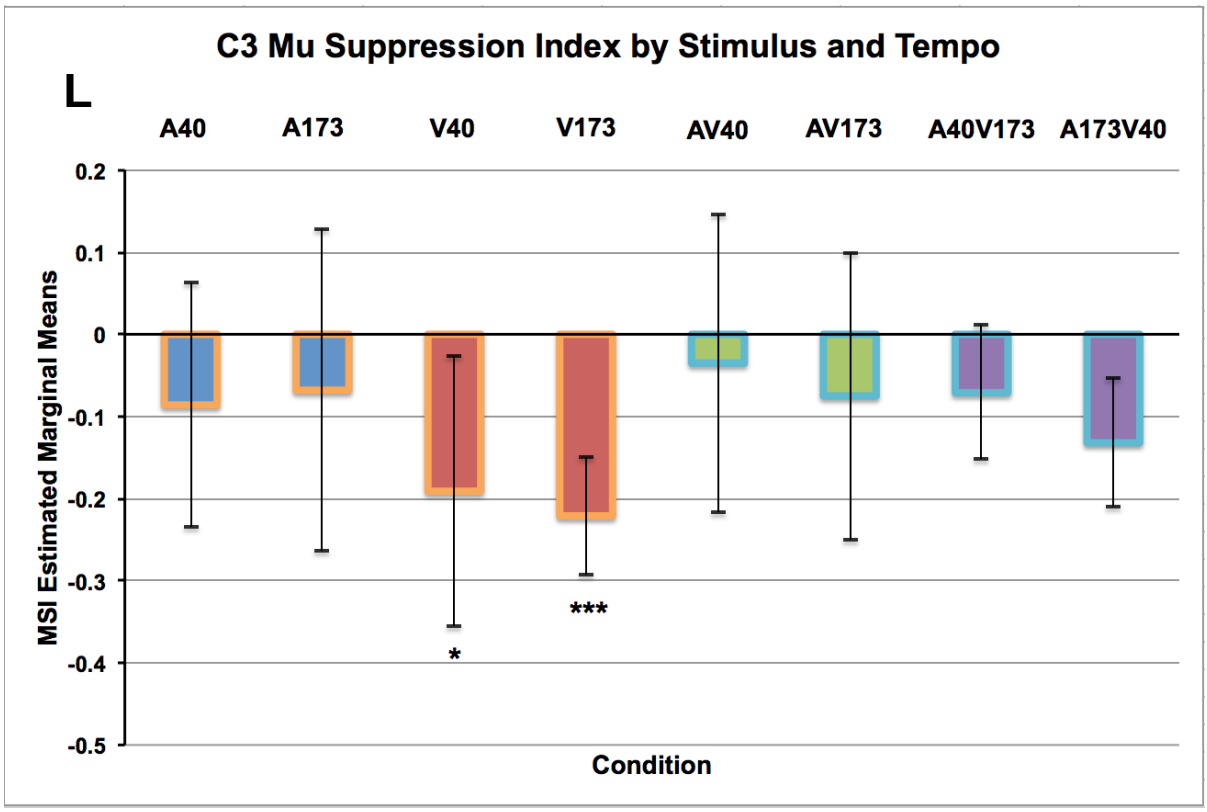


Figure 5.4. Estimated Marginal Means of Mu Suppression Index by Stimulus and Tempo. Evaluated with the covariate values: Age = 132.90; Music = 3.00; Dance = 2.25. Error bars represent 95% CIs. * p≤.05, ** p≤.01, *** p≤.001



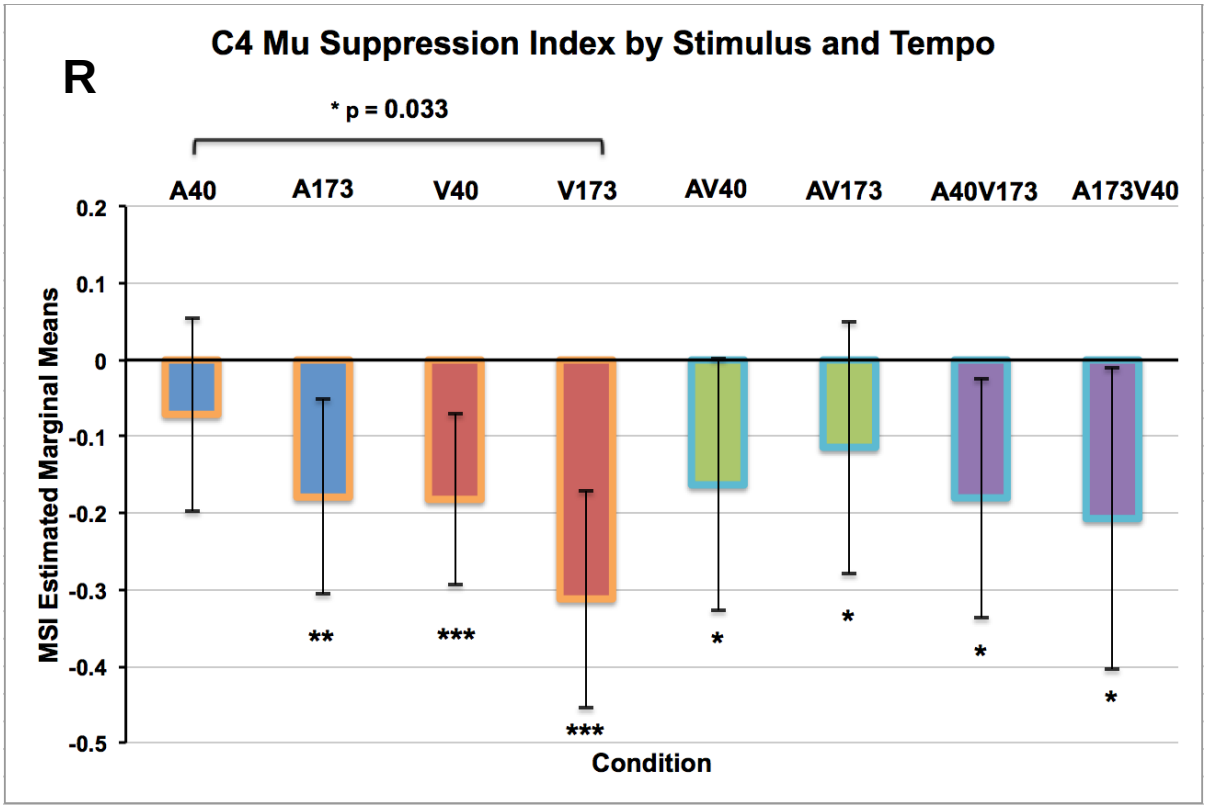
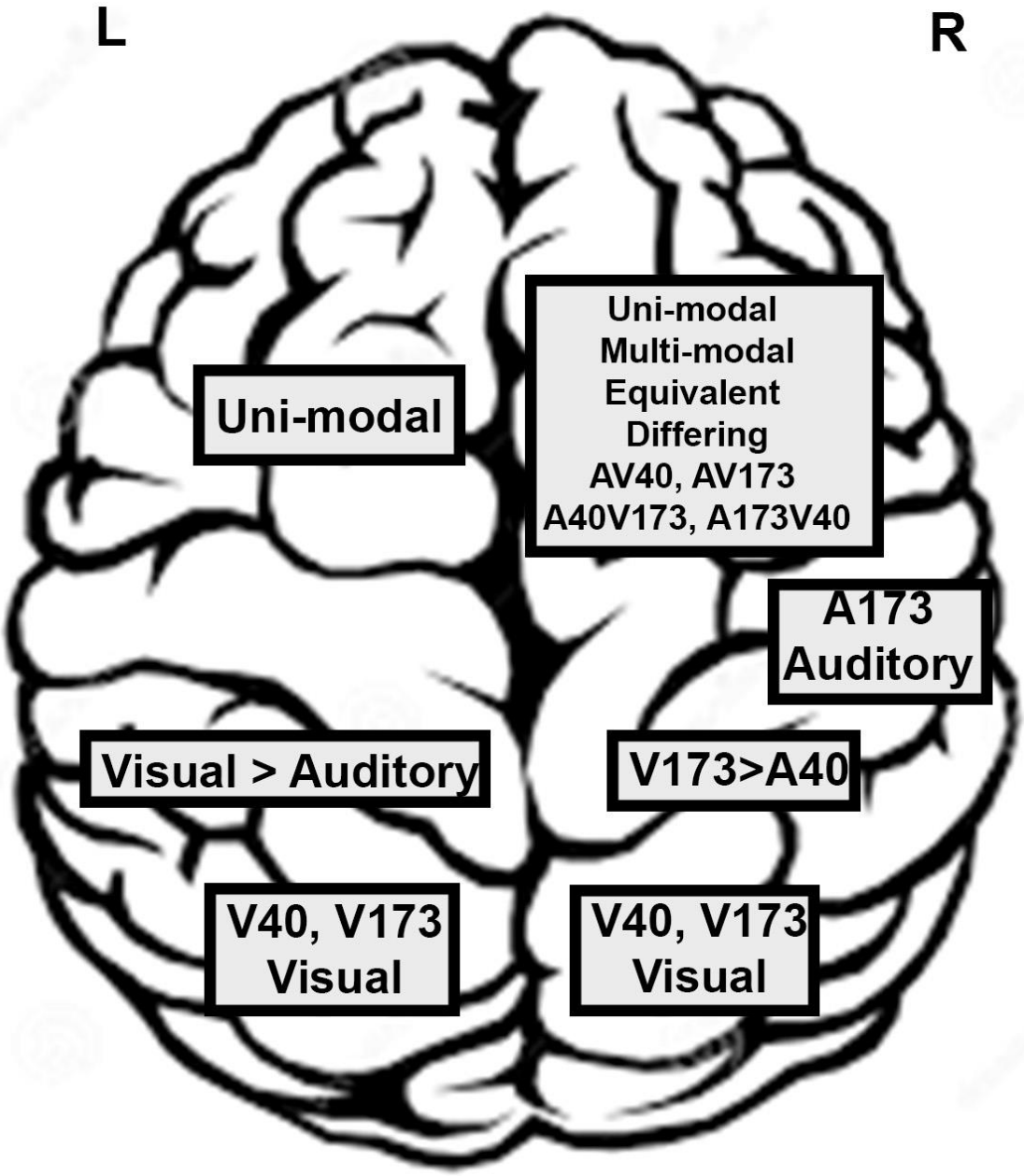


Figure 5.5. Summary of Significant Conditions and Differences



6 Discussion and Conclusions

6.1 Hemisphere Differences

In this sample of 10 typically developing children, perception of stimuli modulated the MNS differently in the left and right sensorimotor cortices. The left SMC responded to visual stimuli only, while the right SMC responded to both auditory and visual stimuli whether they were presented uni-modally or multi-modally. This finding is consistent with other literature that has demonstrated hemispherical differences in action-perception coupling involving audition. Pineda et al.[42] demonstrated that action sounds were primarily processed in the left hemisphere while non-action sounds were primarily processed in the right hemisphere. Marinoni et al.[47] and Ohnishi et al.[48] demonstrated that musicians process music in the left hemisphere while non-musicians activate the right hemisphere during exposure to music. In this study of children with limited drum-playing experience, the stimulus of a regular drum pulse may have been perceived as a non-action sound and thus processed in the right hemisphere. Musical experience (not limited to drums) demonstrated a significant interaction with uni-modal and multi-modal conditions in the left hemisphere, whereas dance experience demonstrated a significant interaction for the same conditions in the right hemisphere. This finding contributes support to the varying patterns of action-perception coupling as a function of previous experiences.

6.2 Auditory vs. Visual Stimuli

Consistent with previous literature, this study provided further verification that visual stimuli induce stronger mu suppression compared to auditory stimuli. In the left

hemisphere, the visual condition demonstrated significantly greater mu suppression compared to the auditory condition. In the right hemisphere, although significance was not reached (p=.053), the visual condition showed a trend towards greater mu suppression compared to the auditory condition as well. The participants of this study participated in a mean of 5.63 hours of dance per week (SD 3.68); however, dance experience was not a significant factor in the comparison between auditory and visual information. This finding corroborates previous reports that although dancers demonstrate greater mu suppression during observation of dance movements, no significant differences between dancers and non-dancers are found during observation of everyday movements such as walking.[44] This suggests that specific previous experience does in fact influence the response of the MNS.

6.3 Uni-Modal vs. Multi-Modal Stimuli

Contrary to previous findings that demonstrated greater mu suppression in both hemispheres following exposure to multi-modal stimuli,[49] this study did not demonstrate significant differences between uni-modal and multi-modal stimuli in either hemisphere. One possible explanation for this could be related to the design of this study. Participants viewed all uni-modal stimuli during the first phase of the experiment and all multi-modal stimuli during the second phase. Participants consistently reported feeling bored following the first phase, and this may have influenced the response in the MNS during the second phase via attention networks. Further research could investigate the validity of this explanation in three ways. First, the experimental set-up could include the addition of an eye tracker. This current

experiment did include time-locked video recordings of the participants to ensure they were looking at the screen; however, an eye tracker would provide additional information as to the exact gaze of the participants – are they looking at the human movement? The background? The treadmill belt? While this adaptation would provide insight into the participant's external attention, it would be unable to discern the individual's internal attention, which may be more relevant. Woodruff and Klein[89] have demonstrated that simply fixating eye gaze on an action without actually focusing attention is insufficient to induce mu suppression. Another experimental modification would be to analyze the neurological attention networks following display of the stimuli. Attention networks include the dorsolateral prefrontal cortex, which corresponds to the F3 and F4 electrodes in the international 10-10 system. Analysis of the activation at these sites may give clues to the influence of attention on the response of the MNS. Finally, the experiment could be re-designed to randomly present all the stimuli together rather than uni-modal and multi-modal separately. This adaptation would eliminate the order bias present in the current experiment.

While significant differences were not identified in pairwise comparisons of uni-modal and multi-modal conditions, significant interactions between condition and age (C3), condition and music experience (C3), and condition and dance experience (C4) were found. These interactions suggest that previous experience with perceiving multi-modal stimuli influences the response in the MNS, which is consistent with existing literature.[46]

6.4 Equivalent vs. Differing Stimuli

This study did not find any significant differences between stimuli with equivalent tempi and stimuli with differing tempi. However, conclusions cannot be made at this time as the current study was underpowered to identify significant differences between these conditions (Observed power: C3=.091; C4=.074). Calculations using G*Power 3 software[90] indicate a sample size of at least 24 participants to identify significant differences between equivalent and differing conditions. A consideration for further research in this area is the relative timing of audio-visual stimuli. In this study, the differing conditions were both presented with auditory information being delayed compared to the visual stimulus. Previous research has demonstrated that individuals will perceive synchrony when auditory stimuli are delayed compared to visual stimuli.[75,79] The participants in this study may therefore be perceiving the differing stimuli as synchronous. Further research with a larger sample should investigate varying relative timing of audio-visual stimuli to explore the influence of equivalent and differing tempi.

6.5 The Influence of Tempo: A Dynamic Interaction

In this pilot study, tempo was perceived primarily in the right hemisphere. A faster tempo perceived in uni-modal stimuli (173BPM) was associated with greater mu suppression compared to a slower tempo (40BPM). There was a significant difference between the V173 condition and the A40 condition. While other pairwise comparisons did not meet significance, visual inspection of the graphs suggests a trend supporting greater mu suppression during perception of a faster tempo in uni-

modal stimuli. The analysis of the influence of tempo was limited by low statistical power (Observed power: C4=.291). Calculations with G*Power 3 software[90] indicate a minimum sample size of 33 participants to identify significant differences between all eight conditions taking into consideration the covariates. The fact that a significant difference was found despite this low power warrants further investigation of the influence of tempo on the MNS in children.

The findings of the current study and the research identified in the literature review support the multi-dimensional interactions of tempo with other factors to influence the MNS. In this study, tempo had a relatively small effect on the MNS response in children compared to the mode of stimuli (auditory, visual, multi-modal). The response was also influenced by age, musical experience and dance experience, consistent with a DST framework of a non-linear complex system for action-perception coupling.

6.6 Limitations

Several limitations were present in this pilot study examining the influence of tempo on the perception of action in children. As noted in the previous sections, low statistical power limited the analyses of some comparisons; larger sample sizes in follow-up studies are needed. While music and dance experience were considered as covariates in this study, the significant interactions they demonstrated also warrant investigating experts and non-experts separately.

The design of this study focusing on the tempo of regular pulse without a broader musical context could also be considered a limitation. By reducing music to single attributes, real-world experiences of perception are missed. In his book, *This is Your Brain on Music*,[91] Daniel Levitin cautions that deconstructing sound into its components removes the influence of properties of music that emerge from relationships among the components. In this study, the tempo of regular pulse had a relatively small effect on the response of the MNS in children. It is possible that the tempo of a complete musical composition would have a larger effect on this response compared to the tempo of a regular drumbeat. Further research could explore this possibility by substituting a musical piece for the regular pulse in the current experimental design.

Another limitation of this study relates to the properties of EEG data collection. EEG has relatively poor spatial resolution, restricting the ability to attribute neurological activity to broad areas. EEG is only able to detect activity in the cortex; activation of deeper structures that have been associated with musical processing and the interactions between music, action and emotion are unable to be analyzed in this paradigm. Further research could use alternative methods such as fMRI to investigate other areas involved in the MNS network.

6.7 Implications

This pilot study provides a foundation for further investigation of the influence of tempo on the MNS in children. To the author's knowledge, this was the first study to

explore the interactions of tempo and mu suppression in children within the framework of DST. Further research should consider larger sample sizes, separation of experts and non-experts, investigation of clinical populations (e.g., children with DCD, children with cerebral palsy, etc.), relative onsets of auditory and visual stimuli, isolated musical attributes vs. complete musical compositions, and examination of other neurological areas associated with the MNS.

6.8 Conclusions

This research examined the influence of tempo of regular pulse on the MNS in children. A literature review found preliminary support for the significant influence of tempo on spontaneously executed movements in adults and children, and the significant influence of tempo on cortical excitability, the perception of emotion in music, and the perception of synchrony in audio-visual stimuli in adults. The conducted pilot study provided support for the greater influence of visual stimuli compared to auditory stimuli on the MNS, hemispheric differences in the processing of stimuli, and a relatively small effect of the tempo of regular pulse on the perception of action in children. Overall, the findings of this research are consistent with a DST lens of action-perception coupling in that multiple factors including previous experience exert varying non-linear influences on the overall MNS network.

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Appendices

Appendix A: Literature Review Search Strategies

1. *MEDLINE (OvidSP)*

Searches	*Results*
1) Music/	10,863
2) Tempo.mp.	5,125
3) Rhythm.mp.	118,104
4) 1 or 2 or 3	133,254
5) mirror neuron system.mp.	570
6) Mirror Neurons/	249
7) action observation system.mp.	8
8) mu rhythm.mp.	276
9) Motion Perception/ or action perception.mp. or Perception/	37,774
10) 5 or 6 or 7 or 8 or 9	38,658
11) 4 and 10	**652**

2. *CINAHL*

Searches	*Results*
S1) (MH"Music")	4,230
S2) "tempo"	217
S3) "rhythm"	7237
S4) S1 OR S2 OR S3	11,574
S5) "mirror neuron system"	40

S6) “mirror neurons”	52
S7) “action observation system”	0
S8) “mu rhythm”	9
S9) “action perception”	11
S10) S5 OR S6 OR S7 OR S8 OR S9	101
S11) S4 and S10	**11**

3. *EMBASE (OvidSP)*

Searches	*Results*
1) music/	12,083
2) Tempo.mp.	5,817
3) Rhythm.mp.	166,427
4) 1 or 2 or 3	183,177
5) mirror neuron system.mp.	733
6) mirror neuron/	477
7) action observation system.mp.	9
8) mu rhythm.mp. or mu rhythm/	419
9) movement perception/ or action perception.mp	12,196
10) 5 or 6 or 7 or 8 or 9	13,499
11) 4 and 10	**605**

4) *Music Index*

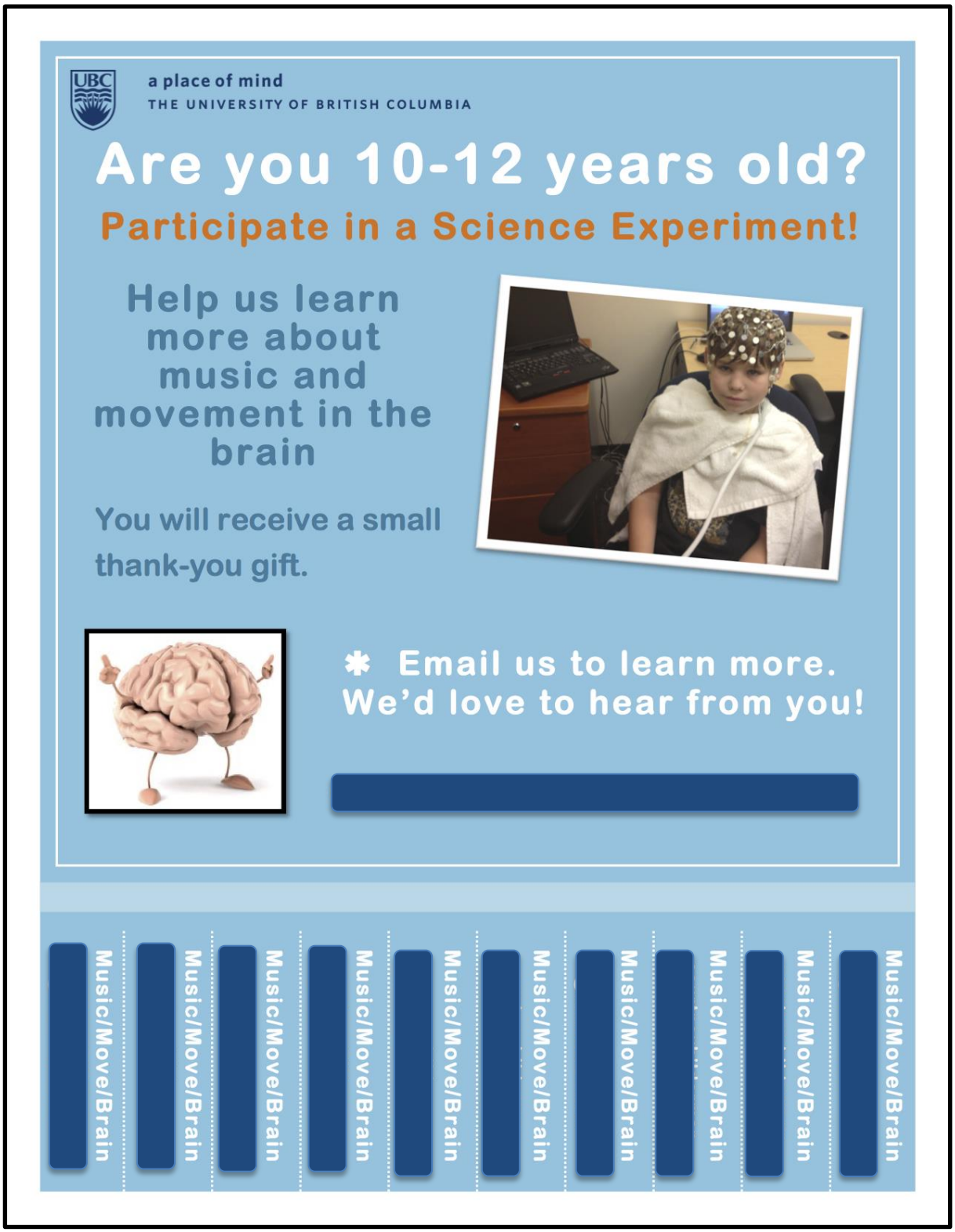
Searches	*Results*
S1) music	1,641,878
S2) tempo	7962
S3) rhythm	35,347
S4) S1 OR S2 OR S3	1,647,120
S5) mirror neuron system	12
S6) mirror neurons	18
S7) action observation system	0
S8) action observation system (SmartTextSearching mode)	83
S9) mu rhythm	3
S10) action perception	43
S11) S5 OR S6 OR S7 OR S8 OR S9 OR S10	139
S12) S4 and S11	**96**

5) *RILM Abstracts of Music Literature*

Searches	*Results*
S1) music	714,459
S2) tempo	11,643
S3) rhythm	18,781
S4) S1 OR S2 OR S3	716,076
S5) mirror neuron system	12
S6) mirror neurons	32

S7) action observation system	0
S8) action observation system (SmartTextSearching)	193
S9) mu rhythm	2
S10) action perception	63
S11) S5 OR S6 OR S7 OR S8 OR S9 OR S10	283
S12) S4 and S11	**277**
Total	**1641**

Appendix B: Recruitment Flyer



Appendix C: Study Questionnaire

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Questionnaire for Parents and Children

Music and Movement:
The Influence of Tempo on the Mirror Neuron System in Children

_____ _____
Participant # **Date**

Are you a boy or a girl?

☐ Boy ☐ Girl

What is your age (years and months)? _____

What is your ethnicity? _____

Do you **currently** take music classes?

☐ Yes ☐ No

If yes, how many hours per week? _____

Have you **ever** taken music classes?

☐ Yes ☐ No

If yes, please describe:

_____
_____
_____

Do you **currently** take dance classes?

☐ Yes ☐ No

If yes, how many hours per week? _____

Have you **ever** taken dance classes?

☐ Yes ☐ No

If yes, please describe:

_____
_____
_____

Have you ever watched someone on a treadmill, or used a treadmill yourself?

Watched: ☐ Yes ☐ No Used: ☐ Yes ☐ No

Please describe.

_____

_____

_____

Have you ever watched someone play the drums, or used drums yourself?

Watched: ☐ Yes ☐ No Used: ☐ Yes ☐ No

Please describe (including type of drums).

_____

_____

_____

Thank you!

Appendix D: Consent and Assent Forms

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Consent Form for Parents

Music and Movement:
The Influence of Tempo on the Mirror Neuron System in Children

Who is conducting this study?

Student Investigator:
Courtney Hilderman, Master's of Science in Rehabilitation Sciences Student, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.
[redacted]

Principal Investigator:
Dr. Naznin Virji-Babul, Assistant Professor, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.
[redacted]

Co-Investigators:
Dr. Susan Harris, Professor Emerita, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.

Dr. Liisa Holsti, Associate Professor, Department of Occupational Sciences and Occupational Therapy, Faculty of Medicine, University of British Columbia.

Dr. Robert Pritchard, Assistant Professor, School of Music, Faculty of Arts, University of British Columbia.

Why are we doing this study?

The purpose of this study is to investigate how music influences the way children observe movement. This study will help us learn more about how children process sensory information (what they see and hear) in their brains. This study will form the basis of Courtney Hilderman's MSc. thesis. You are being invited to take part in this research study because your child is between 10-12 years old.

What happens if you say, "Yes, I want my child to be in the study"?

If you say 'Yes', here is how we will do the study:

- We will ask you to fill out a short questionnaire about your child.
- Your child will wear an EEG cap and earphones. They will be asked to sit quietly for 20 minutes while watching video clips of a person walking on a treadmill, and listening to drum beats.

- We will analyze the data collected from 25 children, including your child, to see how their brains respond to the images and sounds presented to them.

What will happen with the study results?

The study findings will be published in a thesis paper and academic journal articles, and presented at academic conferences.

Is there any way being in this study could be bad for you or your child?

EEG (Electroencephalography) is very safe and cannot harm your child. The sensors on the cap are only reading signals from your child's brain – they do not emit any radiation.

How will your child's identity be protected?

Your child's confidentiality and privacy will be respected. Data that are collected will be identified only by a code number and will be kept in a locked filing cabinet. Participants will not be identified by name in any reports of the completed study.

Will you be paid for taking part in this study?

Your child will receive a gift card for one 'RedBox' movie rental. You will receive $10 for transportation costs.

Who can you contact if you have questions about the study?

If you have questions or concerns about the study, please contact:

Courtney Hilderman, PT
[redacted]

Who can you contact if you have complaints or concerns about this study?

If you have any concerns about your or your child's rights as a research subject and/or your experiences while participating in this study, you may contact the Research Subject Information Line in the UBC Office of Research Services at 604-822-8598 or if long distance e-mail RSIL@ors.ubc.ca or call toll free 1-877-822-8598.

Please keep these first two pages for your own records.

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Music and Movement:
The Influence of Tempo on the Mirror Neuron System in Children

CONSENT AND SIGNATURE PAGE

Taking part in this study is entirely up to you. You have the right to refuse to participate in this study. If you decide to take part, you may choose to pull out of the study at any time without giving a reason. You will still receive your transportation compensation.

- Your signature below indicates that you have received a copy of this consent form for your own records.
- Your signature indicates that you consent to participate in this study.

I consent/I do not consent (circle one) to my child's participation in the study.

_____
Parent or Guardian Signature Date

_____
Printed Name of Parent or Guardian

_____
Witness Signature Date

_____
Printed Name of Witness

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Assent Form for Children

Music and Movement:
The Influence of Tempo on the Mirror Neuron System in Children

Who is conducting this study?

Student Investigator:
Courtney Hilderman, Master's of Science in Rehabilitation Sciences Student, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.
[redacted]

Principal Investigator:
Dr. Naznin Virji-Babul, Assistant Professor, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.
[redacted]

Co-Investigators:
Dr. Susan Harris, Professor Emerita, Department of Physical Therapy, Faculty of Medicine, University of British Columbia.

Dr. Liisa Holsti, Associate Professor, Department of Occupational Sciences and Occupational Therapy, Faculty of Medicine, University of British Columbia.

Dr. Robert Pritchard, Assistant Professor, School of Music, Faculty of Arts, University of British Columbia.

Why are we doing this study?

We want to learn more about how children's brains work while they are watching somebody move and are listening to music at the same time.

What happens if you say, "Yes, I want to be in the study"?

If you say 'Yes', this is what will happen:

- We will ask you some questions.
- You will wear an EEG cap and earphones.
- You will sit quietly for 20 minutes. You will watch short videos and listen to drum beats.

What happens if you say, "No, I don't want to be in the study"?

If you say 'No', no one will be mad at you. You do not have to be in the study if you don't want to.

Is there any way being in this study could be bad for you?

EEG (Electroencephalography) is very safe and cannot harm you. It reads signals from your brain. It does not put anything into your brain.

How will your identity be protected?

The information that we get from you is kept private and locked in a filing cabinet. We do not use your name in any reports that we write about the study.

Will you be paid for taking part in this study?

You will receive a gift card for one 'RedBox' movie rental.

Who can you contact if you have questions about the study?

If you have questions about the study, please contact:

Courtney Hilderman, PT
[redacted]

Who can you contact if you have complaints or concerns about this study?

If you have any concerns about your rights as a research subject and/or your experiences while participating in this study, you may contact the Research Subject Information Line in the UBC Office of Research Services at 604-822-8598 or if long distance e-mail RSIL@ors.ubc.ca or call toll free 1-877-822-8598.

Please keep these first two pages for your own records.

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Music and Movement:
The Influence of Tempo on the Mirror Neuron System in Children

ASSENT AND SIGNATURE PAGE

You do not have to be in this study if you don't want to. You can start the study and say, "stop" at any time, and no one will be mad at you. You will still receive your gift card.

- Your signature below means that you have a copy of this form to keep.
- Your signature means that you want to be in this study.

_____
Participant Signature Date

_____
Printed Name of Participant

_____
Witness Signature Date

_____
Printed Name of Witness