

Performance Analysis of Rhythmic Unimanual and Bimanual Wrist Coordination

Tasks

by

Troy Wilson

Bachelor of Science in Kinesiology Honours, University of New Brunswick, 2016

A Thesis in Partial Fulfillment
of the Requirements for the Degree of

Master of Science in Kinesiology

in the Graduate Academic Unit of Kinesiology

Co-Supervisors: Tim McGarry, Ph.D., Faculty of Kinesiology
Jeremy Noble, Ph.D., Faculty of Kinesiology

Examining Board: Jonathon Edwards, Ph.D., Faculty of Kinesiology, Chair
Jon Sensinger, Ph.D., Institute of Biomedical Engineering
Samuel Howarth, Ph.D., Canadian Memorial Chiropractic College

This thesis is accepted by the
Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

November 2020

©Troy Wilson, 2021

ABSTRACT

This research sought to provide a more in-depth understanding of the coordination of rhythmic actions resulting from self-organizing behaviours through the Haken-Kelso-Bunz model (HKB model) and how the central nervous system affects the resulting behaviour of rhythmic tasks. Four hypotheses tested the aspects of the HKB model. The first addresses the differences between the dominant and nondominant limb's ability to maintain a rhythm task. The second and third hypotheses focused on how the contralateral limb affected task performance. Fourth, couplings between limbs and the metronome were assessed to determine which one is dominant. Twenty participants between the ages of 19-30 (17 Right-handed, 3 Left-handed) were asked to complete six different rhythmic wrist coordination tasks (4 single-limb and two double-limb), each increasing step-wise in frequency with a metronome. Relative phase variance was used to compare each task's performance, with low variance indicating increased performance. We were unable to discriminate between the presence of either one or two oscillators at the spinal level from the results. This is in part due to a two-oscillator being unable to describe the results solely. This research implies that the differences between one and two-oscillators at the behaviour level are not as evident as initially hypothesized. Therefore, more sophisticated measurement techniques should be implemented when analyzing the central nervous system's oscillator layout.

Table of Contents

ABSTRACT	ii
Table of Contents.....	iii
List of Tables.....	v
List of Figures.....	vii
List of Symbols, Nomenclature or Abbreviations	x
Introduction	1
Background and Significance.....	3
Conducting the Research and Boundaries.....	4
Literature Review	5
Central Pattern Generator.....	5
Background.....	5
Locomotion/Lower Limb	6
Upper Limb.....	7
The Haken-Kelso-Bunz Model.....	9
Coordination Dynamics.....	15
Two/Multi-tiered Model and Amplitude.....	17
Gaps in Literature	22
Hypotheses and Statistical Procedure	23
Instructions for Participants.....	29
Experimental Set-up and Tasks	36
Recording and Measurement Devices.....	36
Equipment Set-up.....	36
Tasks	38

Results	39
Hypothesis 1 – Handedness (UDM < UNM)	40
Hypothesis 2 & 3– Hands (Dominant/Nondominant) (BDM ≠ UDM, BNM < UNM)	
.....	42
Hypothesis 4 – Coupling (BDN = BDM < BNM).....	45
Discussion	47
Handedness (UDM < UNM)	48
Hands (BDM ≠ UDM, BNM < UNM).....	50
Coupling (BDN = BDM < BNM).....	52
Limitations	65
Statistical Methodology.....	65
Performance Metrics	65
Summary	66
Conclusion.....	67
Bibliography	68
Appendix	78
Curriculum Vitae	

List of Tables

Table 1 - Summary of handedness data for hypothesis 1. RPV – Mean Relative Phase Variability, Dom - Dominant Hand, Non - Nondominant Hand, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.	40
Table 2 - Results of the robust repeated measures ANOVA for hypothesis 1.....	41
Table 3 - Results of yuen’s trimmed mean t-test post hoc analysis for hypothesis 1. UDM - Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling, ψ_{hat} – the difference between test means.	41
Table 4 - Summary data of the dominant limb hypothesis 2. RPV - Relative Phase Variance, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.....	42
Table 5 - Results of the robust repeated measures ANOVA for hypothesis 2.....	43
Table 6 - Results of the yuen’s trimmed mean t-test post hoc analysis for hypothesis 2. UDM - Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling. ψ_{hat} – the difference between test means.	43
Table 7 - Summary of data used for hypothesis 3. RPV – Relative Phase Variability, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.	44
Table 8 - Results of the robust repeated measures ANOVA for hypothesis 3.....	45
Table 9 - Results of the yuen’s trimmed mean t-test post hoc analysis for hypothesis 3. UDM - Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling. ψ_{hat} – the difference between test means.	45

Table 10 - Summary of the data used for hypothesis 4. Both – Dominant and Nondominant coupling, Dom – Dominant limb, Non – Nondominant limb, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval. 46

Table 11 - Results of robust repeated measures for hypothesis 4. 46

Table 12 - Results of the yuen’s trimmed mean t-test post hoc analysis for hypothesis 4. Dom – Bimanual Dominant Metronome coupling, Non – Bimanual Nondominant Metronome coupling, Both – Bimanual Dominant Nondominant coupling. ψ_hat – the difference between test means. 47

List of Figures

Figure 1 - HKB Potential. k indicates the ratio of the constants b/a . Minimums indicate a stable phase relation, and maximums indicate unstable phase relations. 11

Figure 2 - HKB Phase portrait (Equation 1). k indicates the ratio of the constants b/a . A zero-crossing with a negative slope indicates an attractor, and zero-crossing with a positive slope indicates a repeller. 12

Figure 3 - HKB phase portrait with an additional constant for differing intrinsic frequencies between component oscillators (Equation 3). w represents the differing intrinsic frequencies ($\Delta\omega$). 14

Figure 4 - Phase portrait of the HKB model with the addition of both the different intrinsic frequencies constant ($\Delta\omega$) and noise terms ($\sqrt{Q}\xi$) (Equation 4). 15

Figure 5 - Diagram of the proposed level of organization for this experiment. The two-level model with the middle level representing the ‘neural’ components located in the spine (CPGs) and the bottom (black) represents the limbs’ ‘effector’ components. Arrows represent the information coupling between the components..... 18

Figure 6 - Two-tiered model. Bolded direction arrow refers to coupling strength from the dominant limb (Dom) to nondominant limb (Non) direction..... 25

Figure 7 - Two-tiered model. Bolded direction arrow refers to coupling strength from the nondominant limb (Non) to the dominant limb (Dom) direction..... 26

Figure 8 - Two-tiered model. Solid rectangles indicate BDN and BNM couplings. The dotted rectangle indicates BNM coupling. 27

Figure 9 - Raw data from a bimanual in-phase task. The joint angle is measured in degrees, with a decrease in angle representing wrist flexion. 32

Figure 10 - Centred data from a bimanual in-phase task. The joint angle is measured in degrees, with a decrease in angle representing wrist flexion. The centring method is detailed in Equation 6. 33

Figure 11 - Analytic signal from a bimanual in-phase task. The method of transformation is detailed in Equation 7. 34

Figure 12 - Imaginary portion of the analytic signal from a bimanual in-phase task. The method of transformation is detailed in Equation 7..... 34

Figure 13 - Phase angle from a bimanual in-phase task. The method of transformation is detailed in Equation 8. The phase angle is measured in radians and is bound between $\pm\pi$ 35

Figure 14 - Continuous relative phase (CRP) of a bimanual in-phase task. The method of transformation is detailed in Equation 9. CRP is measured in Radians and is bound between $\pm\pi$ 35

Figure 15 - Photos of electric goniometer placement on participant's wrists. 37

Figure 16 - Photo of the participant's arm and wrist position during the experiment. The foam block is placed under the forearm to allow for unhindered wrist flexion and extension..... 38

Figure 17 - Plot of mean relative phase variance from Table 1. Error bars are standard deviation from Table 1..... 41

Figure 18 - Plot of mean relative phase variance from Table 4. Error bars are standard deviation from Table 4..... 43

Figure 19 - Plot of mean relative phase variance for hypothesis 3 from Table 7. Error bars are standard deviation from Table 7.....	44
Figure 20 - Plot of mean relative phase variance for hypothesis 4 from Table 10. Error bars are standard deviation from Table 10.....	46
Figure 21 - Phase distribution plot of the in-phase BDN coupling.	54
Figure 22 - Phase distribution plots of in-phase BDM coupling.....	55
Figure 23 - Phase distribution plots of in-phase BNM coupling.....	55
Figure 24 - Group steps phase distribution plot of the in-phase BDN coupling.	57
Figure 25 - Group steps phase distribution plot of in-phase BDM coupling.	57
Figure 26 - Group steps phase distribution plot of in-phase BNM coupling.	58
Figure 27 - Phase distribution plot of the anti-phase BDN coupling.....	59
Figure 28 - Phase distribution plots of anti-phase BDM coupling. Note – For the anti-phase tasks, the dominant limb moved in-phase (0°).	59
Figure 29 - Phase distribution plots of anti-phase BNM coupling. Note – For the anti-phase tasks, the nondominant limb moved anti-phase (180°).	60
Figure 30 - Group steps phase distribution plot of the anti-phase BDN coupling.	61
Figure 31 - Group steps phase distribution plot of the anti-phase BDM coupling.....	62
Figure 32 - Group steps phase distribution plot of the anti-phase BNM coupling.....	62

List of Symbols, Nomenclature or Abbreviations

Anti-phase – Achieving maximum wrist extension on the metronome beat. *Note:

During the bimanual anti-phase task, the dominant limb achieves maximum wrist flexion.

Attractor – Describes a point in state space that causes trajectories to be drawn towards it.

Component – A part of a(n) organism/system which possesses unique characteristics that differentiates itself from other parts of the organism/system.

CPG – Central Pattern Generator

CRP – Continuous Relative Phase

Dominant Limb – The Modified Edinburgh Handedness Inventory determined the participant's preferred limb (Vlade et al., 2016).

HKB model – An abbreviation referring to the Haken-Kelso-Bunz model of limb coordination.

In-phase – Achieving maximum wrist flexion on the metronome beat.

Linear System – A system with an output that is linearly proportional to its input.

Neural Level – Term used to refer to the couplings occurring at the spinal cord level.

Non-dominant Limb - The participant's non-preferred limb as determined by the Modified Edinburgh Handedness Inventory (Vlade et al. 2016).

Nonlinear System – A system with an output that is nonlinearly proportional to its input.

Repeller – A point in state space that pushes trajectories away from it.

RPV – Relative Phase Variance.

Introduction

Thought and action are fundamental to human life. Without either, we would be unable to function, adapt and survive as species. A fundamental question about movement production is how coordination is derived from the interactions of the many independent parts that comprise the system. This issue for motor control is known as the degrees of freedom problem (Bernstein, 1967). This problem was posed to address the issue of motor equivalence in which the same task can be accomplished by coordinating different components. Following Bernstein, a possible answer for the movement control centres on how these many degrees of freedom might be managed through reduction, thereby simplifying the control problem's complexity. In dual-limb or multi-limb rhythmic actions, for example, it is hypothesized that central pattern generators (CPGs) at the spinal level assist in reducing the number of controlled degrees of freedom (Haken et al. (1985), Berkowitz (2019), Guertin (2013), Arya and Pandain (2014)). In this view, a single CPG is responsible for the rhythmic outputs of a single limb. During dual-limb rhythmic actions, the spinal level interactions of two separate CPGs – one for each limb – help produce the rhythmic outputs observed at the behavioural level. The same account likewise extends to multi-limb rhythmic actions requiring multi-limb CPGs (Berkowitz, 2019; Arya and Pandain, 2014). Specifically, CPGs are hypothesized to be assemblies (networks) of neurons that underpin rhythmic motor tasks by reducing the control problem from a lower dimension of individual neurons to a higher one. Therefore, CPGs are an essential assumption for this research as they provide a possible explanation for reducing the number of controlled degrees of freedom.

Another valuable tool for understanding how movement can be controlled is complex systems theory. In the context of human movement, a complex system is a system composed of few or many independent components whose interactions allow for the emergence of self-organizing behaviours (Kelso, 1995). Thus, system control stems from within the system itself instead of being prescribed outside by some external control agent. For examples of complex systems demonstrating self-organizing behaviours resulting from interactions among a system's components, see Haken's synergetics (1975, 1978). Akin with synergetics, coordination dynamics can describe and explain complex changing systems' behaviour: how the system trajectories change in time regarding human rhythmic actions (Haken, Kelso, and Bunz, 1985; Kelso, 1995). Several mathematical models have been proposed that describe these rhythmic actions' behaviour, most notably the Haken-Kelso-Bunz (HKB) model, which describes the systematic switching of rhythmic finger movements from less stable to more stable coordination states under certain system constraints (Haken et al., 1985). The HKB model provides an approach to investigating and understanding human movement control complexities for dual- and multi-limb rhythmic actions.

Understanding system control using coordination dynamics theory has several promising related applications to the study of human movement. In particular, the nervous system and motor control.

Background and Significance

The purpose of this research is to investigate the control of human rhythmic motor tasks using coordination dynamics. This approach uses a two-tiered model proposed by Treffner and Turvey (1995, 1996) with further expansion by Beek, Peper, and Daffershofer (2000, 2002). This model extends the HKB model by including a ‘neural level’ of coupling (i.e., the CPG couplings). This addition is held as necessary as the interplay between components (CPGs) dictates what behaviours a system displays. The difference between the HKB and the two-tiered extension is what interactions are being addressed; the HKB model focus is explaining the coordinative behaviour occurring between the limbs (specifically the index fingers) while the two-tiered extension builds upon it by focusing on the possible interactions between CPGs at the spinal level that cause behaviour anomalies at the limb level. Having these additional components increases behavioural flexibility and allows for additional system behaviours to be explained using coordination dynamics theory. The ‘neural level’ coupling accounts for the consistency issues of the extended HKB model (Beek et al., 2002; Peper, Ridderikhoff, Daffertshofer, and Beek, 2004). Literature to date has focused mostly on the brain and still relies on the single-tiered extended HKB model (Tognoli and Kelso, 2009, 2014a, b; Kelso, Dumas, and Tognoli, 2013; Fink, Kelso, and Jirsa, 2009; Meyer-Lindenberg, Ziemann, Hajak, Cohen, and Berman, 2002), a reliance that leads to the second aspect of this research focus: movement synchronization.

Past research focused on movement synchrony (Shirakawa, Honma, & Honma, 2001; Schneider, Askew, Abel, & Strüder 2010; Pollok, Müller, Aschersleben, & Schnitzler, 2005; Nobili, 2009) has understandably led to less focus on movement asynchrony and metastability (see Tognoli & Kelso, 2014b, for further detail). Moreover, data involving metastable characteristics of movement coordination has mainly been overlooked as it was considered unimportant. Metastability encompasses component interactions that are neither fully cooperative nor competitive. Thus, research is limited in that it explains a fraction of what is occurring during movement (Kelso, Dumas, & Tognoli, 2013; Bressler, & Kelso, 2016; Kelso & Tognoli, 2007). To this end, the research herein will consider movement stability and instability together and not merely through the lens of movement synchrony.

Conducting the Research and Boundaries

This research aims to investigate at the level of system behaviour how CPG interactions may explain system behaviour. Noted previously, the presence of CPGs is an assumption for this research regarding how the nervous system organizes, coordinates and produces bi- and multi-limb rhythmic movements. In keeping with coordination dynamics theory, CPGs can simplify the control problem by reducing the controlled degrees of freedom. This research seeks to build on previous work by examining how human rhythmic movement tasks' behavioural performance differs under different system constraints through the lens of coordination dynamics.

Literature Review

Central Pattern Generator

Background

A central pattern generator (CPG) is a series of neural connections that produces a patterned output without sensory input (Berkowitz, 2019). This definition has changed over the past century since Brown's (1911) seminal work and shifted from prior models in which reflexes were assumed to produce all vertebrates' rhythmic actions. In Brown's experiment, cats were able to perform treadmill locomotion while having both the spinal cord and the afferent nerves from the hind-limbs transected. As reflexes are a closed-loop system, they require feedback to function; however, they would not produce continuous action with no sensory feedback. Therefore, an open-loop system – in this case, a CPG – would need to be present to create the movement. This is not to downplay the importance of sensory feedback or descending neural drive, as it is required to produce smooth and accurate movement; it is only to demonstrate that it is not necessarily required to move.

Brown's work led others to investigate how rhythmic outputs are produced without feedback and the CPG hypothesis's eventual creation. In particular, von Holts (1937, 1973), Hughes and Wiersma (1960), and Wilson (1961) followed suit by demonstrating that fish, crayfish and locus were able to generate movement without the presence of sensory feedback. In combination, the CPG was hypothesized but was not restricted to its application to rhythmic movements. Recently, research has shown that CPGs may be

used in complex movement sequences that are learned; specifically, Brainard and Doupe (2013) and Mooney (2009) have demonstrated that CPGs may be responsible for singing learned mating calls in some bird species.

As the CPG hypothesis relates to human movement, two focus areas will be discussed: locomotion and the upper limb.

Locomotion/Lower Limb

Locomotion is a heavily researched topic in the field of CPG research in humans (Berkowitz, 2019; MacKay-Lyons, 2002; Arya and Pandian, 2014; Kay, Saltzman, and Kelso, 1991; Guertin, 2013; Golowasch, 2019; Russell et al., 2010; Arshavsky, Deliagina, and Orlovsky, 2016; and Meyns, Bruijn, and Duysens, 2013). A variety of participants were used in these studies encompassing both abled bodied and those with spinal cord injuries. Specifically, individuals with spinal cord injuries (SCI) are typical as the absence/limited (in the case of incomplete SCIs) presence of descending information from higher brain centres.

The first work of interest is Bussel et al. (1988), during which they analyzed the development of rhythmic myoclonic movements of the trunk and legs in an SCI participant. Following a 15 months post of a spinal lesion at C7, a rhythmic extension of the trunk and legs began to occur. Electromyography (EMG) found that all muscles involved were moving in-phase at a rate of 0.3-0.6 Hz. Moreover, extension movements

of the hips, knees, ankles, and toes would occur for extended periods at a rate of 0.6 Hz. From their analysis, the rhythmic movement mechanism was attributed to a CPG after ruling out the possibility of flexor reflex afferents (FRA). A subsequent follow-up study by Roby-Brami and Bussel (1992) further strengthen the findings by demonstrating that if FRA were part of the movement mechanism, it would still be related to the spinal CPG.

More recent research by Calancie (2006) further documented six individuals with either complete or incomplete quadriplegia producing stepping like patterns and rhythmic abdominal contractions. It was found that the movements were not attributed to spinal reflexes and were induced only when the hips and knees were extended. For the complete quadriplegia participants, activity co-occurred in both legs (agonist and antagonist muscles). The incomplete quadriplegia participants demonstrated activity alternating between agonist and antagonist muscle groups within a limb and alternating across limbs. It was concluded that the characteristics of the muscle activity had elements of a CPG for stepping tasks.

Upper Limb

Unlike its lower limb counterpart, research regarding solely upper limb CPGs is sparse. However, the research's central theme is that they are not as well documented as for locomotion. As the upper limb has evolved to perform various tasks, supraspinal

influences have played a large role in task-specific control. Specifically, that descending drive is proposed to have more control over the CPGs of the upper limb, allowing for a more generous array of tasks able to be performed (Rossignol Dubuc, and Gassrd, 2006; Zher and Duysens, 2004; Zher, 2004, Arshavsky, Deliagina, and Orlovsky, 2016).

As for upper limb CPG use in locomotion, the research base is more available. Dietz et al. (2001, 2002) sought to study the upper and lower limb's neural coordination during gait. They did so by driving a split-belt treadmill at varying speeds between the belts. In particular, the activity of the arms and legs were measured bilaterally. The EMG responses were most significant during gait, with small to almost no response in restricted and standing/sitting. The results found a strong task-related dependency on the EMG responses of the upper and lower limbs. It was found that a bilateral arm response was related to a coupling between the limbs via CPGs. Zehr and Duysens (2004) and Zehr (2004) further supported these results; specifically, the cutaneous and H-reflexes' behaviour in the upper limb greatly depends on the movement's timing the arm is completing; this behaviour mirror that of the lower limb. Lastly, Meyns, Bruijn, and Duysens (2013) summarized the use of upper limb movement during gait. From their analyses, they conclude three significant findings. First, the arms swing is crucial to locomotion and is controlled by passive means, but the movement's stability arises from CPGs. Second, that arm swing is a significant factor in reducing energy expenditure during gait. Finally, the arm swing could be of benefit in gait rehabilitation.

The Haken-Kelso-Bunz Model

Haken et al. (1985) were the first to propose a model that described the coordination dynamics between two limbs (fingers): the HKB model. Two variables were used to set the necessary foundation for the model: the system's order and control parameters. From Haken's synergetics theory (1978), the order parameter is the measure of order between points over a phase transition; for example, the difference in the relative phase between alternating tapping of the fingers (anti-phase) and tapping the fingers together (in-phase). In this case, the relative phase quantifies the movement relationship of two limbs (two fingers) in a bimanual (two-handed) rhythmic task; while both fingers are moving, their relative movement can be quantified from 0 and $\pm\pi$. Between these values, all possible movement relations are possible. For rhythmic movements, relative phase is the proposed order parameter as it describes the cooperation among the components of the system (the tapping fingers); moreover, the different coordination styles (in-phase and anti-phase) remain constant across different motor tasks and effector pairings (Haken et al., 1985). In-phase and anti-phase are also easily defined among other joints; in-phase occurs when both joints achieve max flexion, and anti-phase is when one joint reaches max flexion while the other reaches max extension.

The control parameter, also from Haken's synergetics (1978), is the driving force that causes the system to move from one state to another. An imperative characteristic of the control parameter is that it only drives the system to change and does not dictate its state. In finger tapping tasks, movement frequency is the proposed control parameter

based on Kelso's observations (1981a and, 1984). It was found that increasing movement frequency would eventually lead to changes in coordination states, specifically, from anti-phase to in-phase with increasing frequency, but not the inverse. The resulting function that describes this behaviour is the HKB model:

$$\dot{\phi} = -a * \sin (\phi) - 2b * \sin (2\phi) \text{ (Equation 1)}$$

The relative phase, order parameter, is represented by ϕ . Variables a and b represent the coupling coefficients between the two oscillators.

When HKB potential is plotted (*Figure 1*), it produces two cosine waves moving at different frequencies that have local minima at $\pm\pi$ (anti-phase) and $0\pm 2\pi$ (in-phase). One of the main features of this model is the relation between the coefficients a and b . The coefficients represent dampening terms that affect the amplitude of movement as the movement frequency increases. When the ratio of b/a - represented by k - is greater than 0.25, the anti-phase pattern is still observed, but when k achieves the critical value ($k = 0.25$), the anti-phase pattern destabilizes, and the in-phase pattern becomes the only

stable phase. In other words, k decreases with increasing movement frequency.

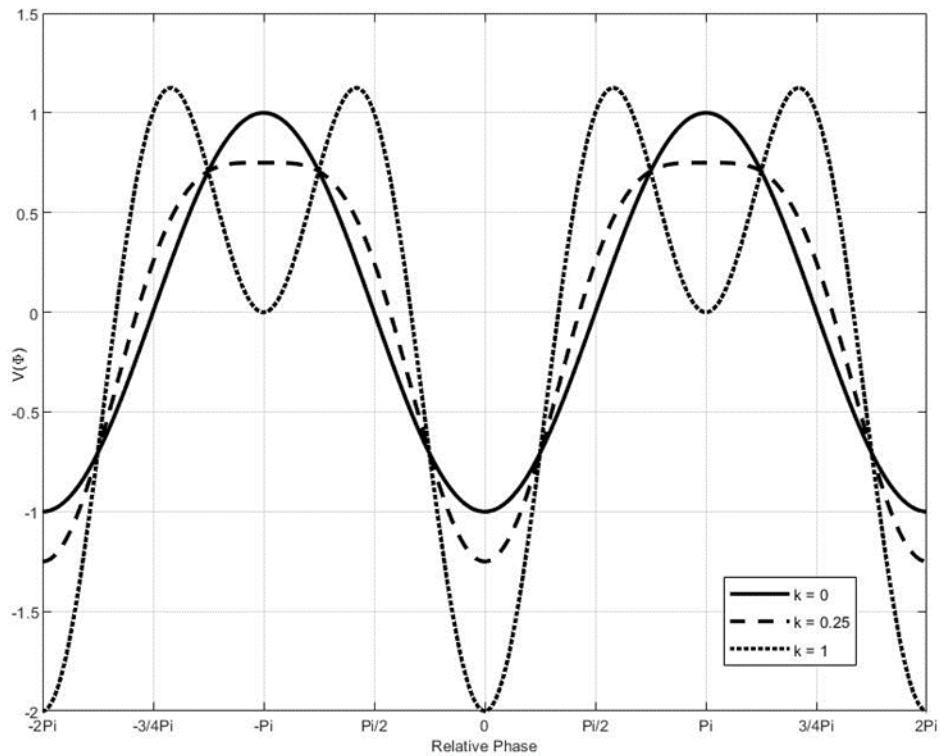


Figure 1 - HKB Potential. k indicates the ratio of the constants b/a . Minima indicate a stable phase relation, and maxima indicate unstable phase relations.

When *Equation 1* is plotted (*Figure 2*), it demonstrates how the stable points change as k is manipulated. Attractor points are represented by zero-crossing with a negative slope and repellers points by zero-crossings with positive slopes. When k reaches the critical value ($k = 0.25$), the attractor points at $\pm\pi$ disappear and are replaced with unstable phase relations; at this point, the phase relation is neither an attractor nor a repeller point. As k continues to decrease ($k < 0.25$), the phase relation becomes a repeller and will ‘push’ trajectories away from it. In summary, this is the HKB model in

its most basic form and only considers the differences in coupling strengths between the components (the variable k). However, this model is not without its limitations, specifically, those that pertain to the characteristics of biological systems.

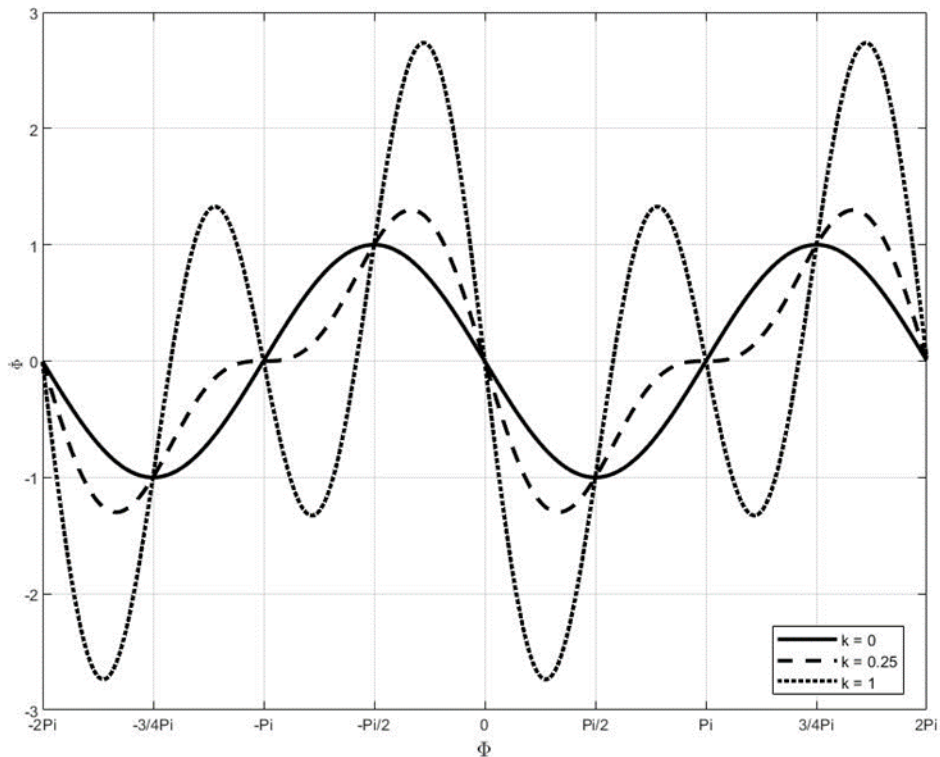


Figure 2 - HKB Phase portrait (Equation 1). k indicates the ratio of the constants b/a . A zero-crossing with a negative slope indicates an attractor, and zero-crossing with a positive slope indicates a repeller.

One of the characteristics of biological systems is that paired oscillators may have different eigenfrequencies. The eigenfrequency is influenced by the oscillator's unique tissue dynamics, which may vary in – but are not limited to – mechanical (muscle insertions, moment of inertia), neurological (limb dominance,

descending neural drive, feedback), and metabolic (muscle fibre distribution, blood flow, buffering capacity) characteristics (Kelso, 1995). As these differences increase, synchronization between components becomes more challenging and ‘running solutions’ may begin to dominate a system’s trajectory. Running solutions occur when some phase relations are favoured briefly but continue to move through all possible relations. To account for this new behaviour, Kelso, DelColle, and Schöner (1990) analyzed the effect of synchronization of finger tapping to a metronome that progressively increases in frequency. It was found that participants would reach a movement speed where synchronization with the metronome was lost and running solutions dominated. To accommodate running solutions, $\Delta\omega$ was introduced into the HKB model to account for these differences in eigenfrequencies between paired oscillators (*Equation 3 and Figure 3*).

$$\dot{\phi} = \Delta\omega - a * \sin\phi - 2b * \sin2\phi \text{ (Equation 3)}$$

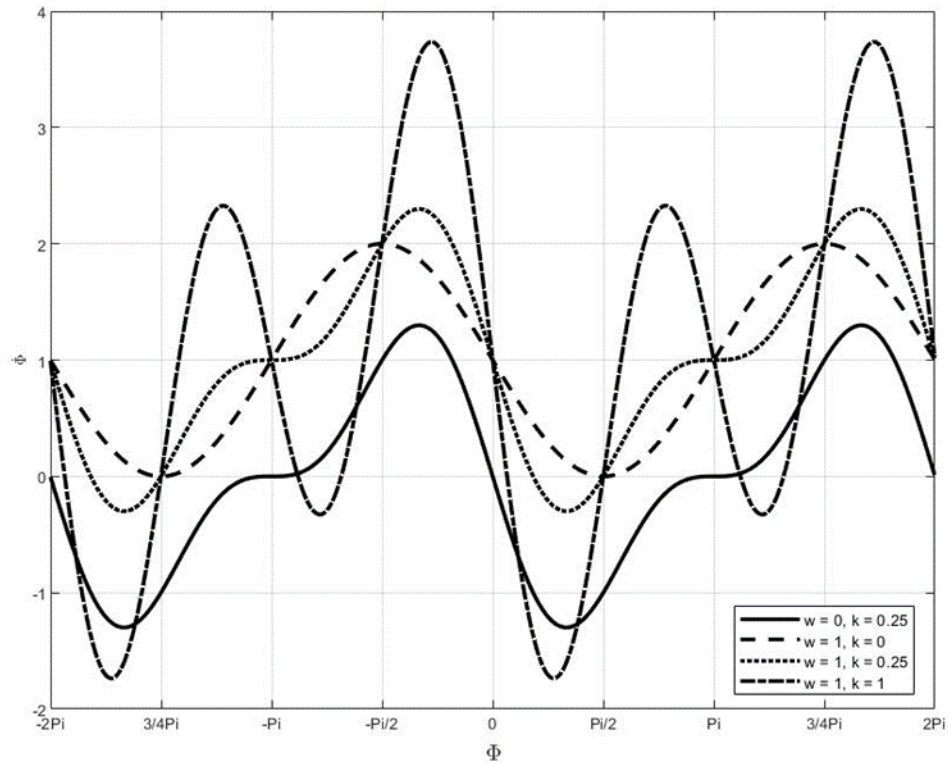


Figure 3 - HKB phase portrait with an additional constant for differing intrinsic frequencies between component oscillators (Equation 3). w represents the differing intrinsic frequencies ($\Delta\omega$).

As $\Delta\omega$ increases, all phase relations' relative stability - excluding the running solution - decreases until they are destabilized; this is evident by fewer zero-crossings in *figure 3* with larger $\Delta\omega$ values. With the addition of the noise term ($\sqrt{Q}\xi$) (Schöner, Haken, and Kelso, 1986), *Equation 4* is the currently accepted form of the HKB model as it is generalizable to most biological systems (Tognoli and Kelso, 2014; *figure 4*). In particular, this formulation provided a basis for analyzing an essential characteristic of coordination: metastability.

$$\dot{\phi} = \Delta\omega - a * \sin\phi - 2b * \sin2\phi + \sqrt{Q}\xi \text{ (Equation 4)}$$

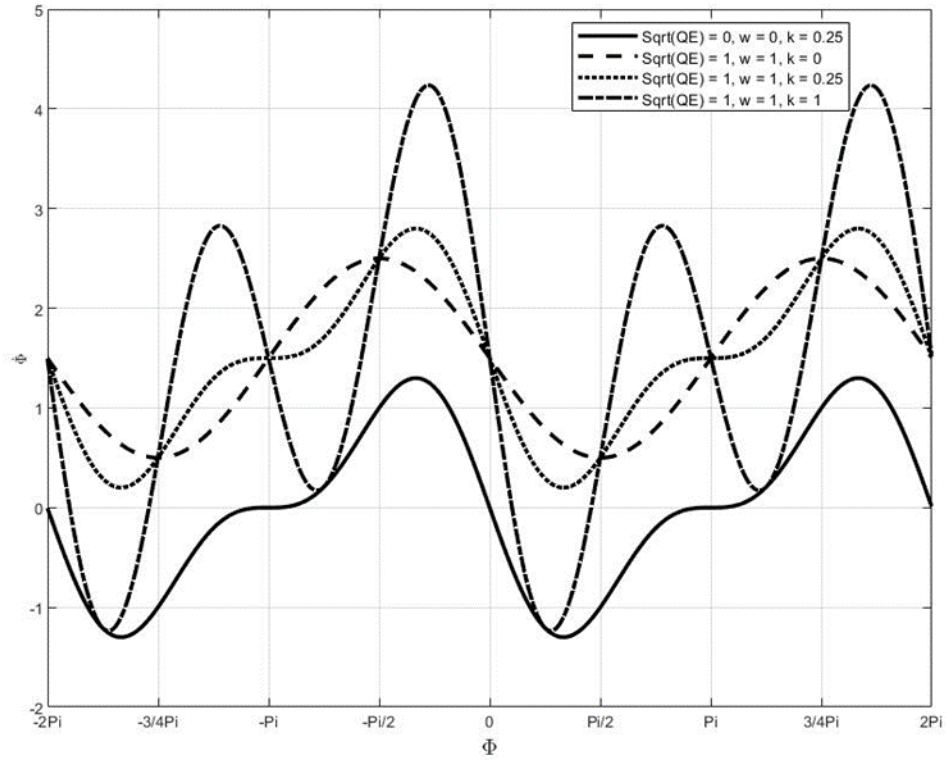


Figure 4 - Phase portrait of the HKB model with the addition of both the different intrinsic frequencies constant ($\Delta\omega$) and noise terms ($\sqrt{Q}\xi$) (Equation 4).

Coordination Dynamics

As Tognoli and Kelso (2014) described, coordination dynamics explain the temporal evolution of coordination and the system's emergent qualities. It does this by addressing the three characteristics of coordination: synchronization, segregation, and metastability.

Synchronization occurs when two components of a system share similar intrinsic characteristics and behave similarly. However, because the components are continuously exchanging information, they may become trapped in a trajectory and unable to produce other coordinative behaviours. In other words, the components reach a state of stability such that all other trajectories become repellers. Though preventing undesirable behaviours may sometimes be beneficial, it may also be detrimental to living systems with limited resources, requiring the flexibility of behaviour. Furthermore, preventing components from participating in other trajectories limits system behaviour.

The segregation characteristics prevent information exchange and allow components to work independently. Having components segregated is essential for complex systems to operate; for example, it would be impossible to play multiple parts to a piano piece if a pianist's hands could not play different keys or use the pedals with their feet independently. Indeed, it would be inefficient to have one component partake in only one task as such redundancy would limit system behaviour; however, segregation is still essential for system flexibility.

Metastability has features similar to the previous two characteristics but is more than a combination of them. Components experience metastability when their integration and segregation tendencies allow trajectories to converge or diverge depending on task constraints; metastability, therefore, allows systems to operate in a variety of states (phase relations). For a mathematical definition of metastability, it is a stable state that is not the most stable state of a system; as such, a system that is in a metastable state can

be described as being Lyapunov stable as it will stay within a given bound about an attractor but will not necessarily converge to it (Tognoli and Kelso, 2014). In general, metastability assists in explaining how paired oscillators behave and adapt to changes in task conditions (Bressler and Kelso, 2016; Shirakawa, Honma, and Honma, 2001; Jantzen, Steinberg, and Kelso, 2009; Daun-Gruhn and Büschges, 2011; Meyer-Lindenberg, Ziemann, Hajak, Cohen, and Berman, 2002, Chen et al., 2010). However, the HKB model is limited by its inability to account for metastability, thus hindering its analytic power. Fortunately, extensions to the HKB model, such as the Two-tiered model, have been developed to increase its robustness.

Two/Multi-tiered Model and Amplitude

Although the HKB model is currently being used for describing changes in motor behaviour (Tognoli and Kelso, 2014), inconsistencies within the model still exist (Peper & Beek, 1999). These issues were formalized by Peper, Beek, and Daffertshofer (2000) and expanded upon by Beek, Peper, and Daffertshofer (2002), and Peper, Ridderikhoff, Daffertshofer, and Beek (2004). The major shortcoming of the HKB model (specifically the extensions provided by Kelso et al., 1990; Treffner and Turvey, 1995, 1996) is only a description of the underlying dynamics at play. In other words, although the HKB model has been tested, it still reduces the control mechanism for dual-limb rhythmic behaviour to a single set of coupled oscillators. Besides, it does not account for a set of paired CPGs at the spinal level. Thus, another extension was

proposed in the form of additional oscillators at the ‘neural level’ (*Equation 5 and Figure 5*) (Treffner and Turvey 1995, 1996):

$$V(\phi) = -\Delta\omega - a * \cos\phi - b * \cos2\phi + c * \sin\phi + d * \sin2\phi \text{ (Equation 5)}$$

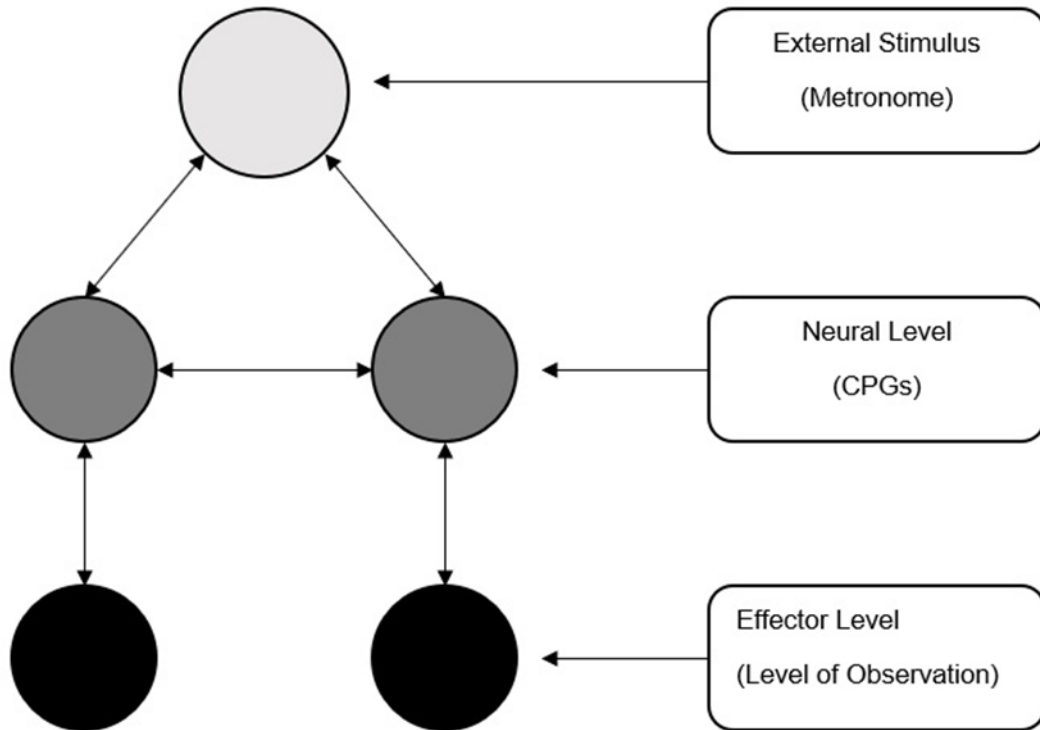


Figure 5 - Diagram of the proposed level of organization for this experiment. The two-level model with the middle level representing the ‘neural’ components located in the spine (CPGs) and the bottom (black) represents the limbs’ ‘effector’ components. Arrows represent the information coupling between the components.

The addition of two sinusoidal components allows for coupling asymmetries to exist between the oscillators. The work by Beek et al. (2002) extrapolates why individual limb movements cannot be modelled as single-level through four arguments.

The first of these arguments is that inconsistencies exist with the amplitude-frequency relationship. Specifically, the HKB model predicts that as movement speed increases, the amplitude of movement will decrease and lead to a non-equilibrium phase transition (Haken et al., 1985; Kelso, 1995). Although this was found to occur in the original work, it was inconsistent in subsequent studies (Beek, Rikkert, and Van Wieringen, 1996; Peper and Beek, 1999; Beek, Peper, and Daffertshofer, 2002). However, one problem with this argument is that when Beek et al. (2002) tested this assumption, the movement speed may not have been fast enough to elicit instability and amplitude changes. If the external stimulus used was driven at a higher frequency, more instability may have been introduced into the system, possibly decreasing amplitude. However, these results reconfirmed Peper and Beek's (1999) results by demonstrating inconsistencies with the HKB model.

The second argument made against the single level of the HKB model is that a “phase-dependent phase shift” occurred during follow-up work by Kay, Saltzman, and Kelso (1991). Following a perturbation to the fingers in layman's terms, an increase in movement speed occurred to accommodate the perturbation during a rhythmic motor task. This change in speed was attributed to an increase in the oscillators' ‘stiffness’ via feedback to the CPGs. This increase in stiffness is attributed to increased muscular

tension about the joint, limiting the amount of movement amplitude possible.

Furthermore, this finding indicates that additional coupling levels at the spinal level are needed to explain the results.

The third argument against the single level of coupling was made in part by confirming previous results theorizing how a two-tiered system would behave (Wing and Kristofferson, 1973; Daffertshoffer, 1998). In Beek and Peper (2002), participants were asked to perform continuous wrist flexion and extensions in time with a metronome and following a set number of tones the metronome was removed. Participants were asked to maintain the set tempo. The results showed that as time progressed, participants corrected errors in movement following the removal of the metronome; more specifically, a negative serial correlation was found, which is predictive of a two-tiered system (Wing and Kristofferson, 1973). Moreover, their results confirmed Daffertshofer's (1998) findings that a single oscillator would be unable to produce the same chaotic properties found in their data when exposed to a single noise source. From both of these comparisons, it was concluded that a single level model of coupling would be unable to satisfy both the stability and stochastic characteristics displayed in their experiment.

The final argument given by Beek and Peper (2002) is that a single level model would be unable to describe the stochastic characteristics of oscillatory limb movements. Though sounding similar to the third argument, this takes a different approach to describe a chaotic nature. Specifically, the authors stated that using a nonlinear time-

series analysis - which would be ideal for analyzing such a system - proves to be unreliable due to the “nonstationarity and brevity of biological data sets.” Although not much detail was given, the authors attributed the variability in biological data sets to low-dimensional chaotic motion caused by components containing three or more state variables instead of two. In other words, because human movement is unable to be accurately analyzed using nonlinear time-series analysis, it must contain components with more than two state variables and, therefore, more organization levels. Thus, further demonstrating support for the presence of multiple levels of organization involved in rhythmic movement control.

From these arguments and the qualitative analysis provided by Peper et al. (2000), a two-level, four-oscillator model is theorized (Beek et al. 2002) to better account for the arguments noted previously (*Figure 5*). The model states that the neural components are bilaterally coupled with their effector components unilaterally; this allows for a flow of information between the CPGs and the limbs. The ‘neural level’ is proposed to be a pair of CPGs located in the spinal cord (Beek et al., 2002). Though this modelling level provides more explanatory power than the single-level HKB model, it is limited in that these additional levels are unable to be measured without invasive protocols. This might be rectified by better spinal activity measures, perhaps in a clinical setting where invasive protocols are more appropriate (e.g., spinal cord and lower brain stem injuries). In short, more research needs to be completed to determine the presence and effects that CPGs may have on voluntary movement coordination.

Gaps in Literature

Though the HKB model is an accepted tool for describing the human body's coordination dynamics (Tognoli and Kelso, 2014), subsequent work exploring the two/multi-tiered approach is limited. Not only can it provide a more realistic representation of the coupling occurring at the neural level (Beek et al., 2002), it also provides solutions to the inconsistencies within the current HKB model (Beek et al., 2002; Peper et al., 2004; de Poel, Peper, and Beek, 2007; Treffner and Turvey 1995, 1996). Additional research is needed to understand how asymmetries in paired CPGs may influence motor behaviours to achieve a robust model.

Coupling strength asymmetries between dominant and non-dominant limbs are still unclear how these asymmetries affect motor tasks' stability, given higher movement rates. Although de Pole et al. (2007) demonstrated dominant limb entrainment of the non-dominant limb following a perturbation at 1, 1.25, and 1.5 Hz, it remains unknown if this coupling strength asymmetry stays constant if the movement frequency increased and if the limbs' eigenfrequency was not manipulated (no manipulandum). If changes in coupling strength were to occur, this could be due to changes in the two/multi-tiered HKB model (a , b , c , and d in Equation 5). Moreover, the dominant limb may begin to rely on the non-dominant limb as task constraints become increasingly difficult. In other words, the dominant limb could utilize the feedback from the non-dominant limb to maintain its task performance. On another note, it is also unclear which coupling is the strongest: limb-to-limb or limb(s)-to-stimulus, or would movement frequency increases

lead to coupling asymmetry changes to the limb-to-limb or limb(s)-to-stimulus couplings? This literature gap is further compounded by the limited understanding of how a component's addition affects a motor task's performance.

The last gap to be addressed is how the contralateral limb affects the other limb's performance in a rhythmic task. With a limb's addition, the number of possible couplings increases from one (limb-stimulus) to three (two limb-stimulus and one limb-limb). However, the introduction of a limb to the system brings additional noise sources. Although access to more information through additional couplings may benefit task performance, it may be detrimental instead. It is currently unclear if the addition of a contralateral limb will provide increased performance to rhythmic tasks. With these gaps in mind, four hypotheses are proposed to address these concerns.

Hypotheses and Statistical Procedure

The first hypothesis proposed was that the unimanual (U), dominant limb (D), metronome (M) couplings (UDM) would have a significantly less relative phase variability (RPV see later) compared to the unimanual non-dominant limb (N) metronome couplings (UNM) for both phase relations (In-phase and anti-phase): $UDM < UNM$. This directionality was expected to occur as the increased motor control refinement of the dominant limb allows for an increased nervous system's ability to fine-tune the model's performance variables (*Equation 5* variables *a*, *b*, *c*, and *d*). Moreover,

with increased use, the dominant limb's neural pathway increases signal sensitivity, possibly changing the limb's neural characteristics and eigenfrequency. As a result, these changes to both performance variables (variables *a*, *b*, *c*, and *d*, *see above*) and eigenfrequency would result in decreased RPV with the metronome during the unimanual tasks (Treffner and Turvey 1995, 1996; Peper et al. 2002; Peper et al. 2004; Ridderikoff et al., 2004; and de Poel, Peper, & Beek, 2007).

The second hypothesis tested was to determine if a difference in RPV existed between the bimanual (B), dominant limb, metronome coupling (BDM) and the unimanual, dominant limb, metronome (UDM) coupling for both phase relations: BDM \neq UDM. This hypothesis's lack of directionality stems from inconsistencies in pilot data and three potential outcomes' plausibility. The first possibility is that the non-dominant limb would have little effect on the BDM's RPV, indicating low coupling strength in the dominant to non-dominant limb direction (see *Figure 6*). The second possibility is that the BDM will have a higher RPV than the UDM; thus, the non-dominant limb would negatively impact the BDM's relative phase variance. The precedence would shift from the dominant to the non-dominant limb's performance. The third possibility is that the BDM coupling RPV is less than the UDM coupling; this would be an exciting result. This indicates that the non-dominant limb's additional information benefits the dominant

limb's ability to accurately complete the task.

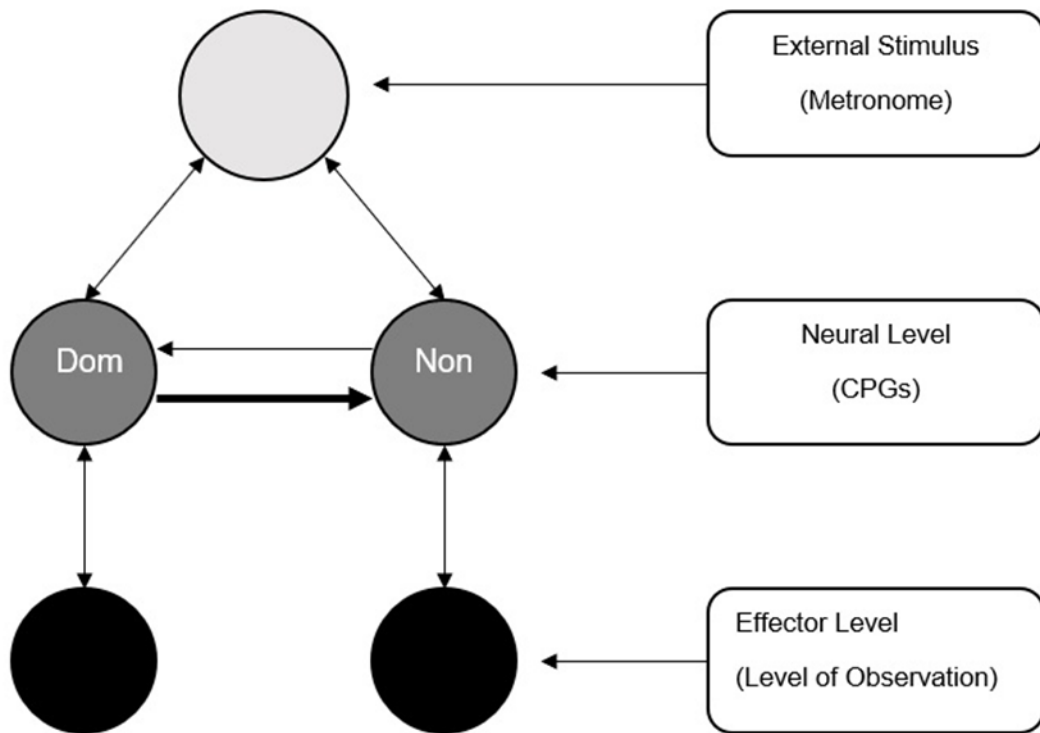


Figure 6 - Two-tiered model. Bolded direction arrow refers to coupling strength from the dominant limb (Dom) to nondominant limb (Non) direction.

The third hypothesis is that the bimanual, non-dominant limb, metronome (BNM) coupling RPV would be less than the unimanual, non-dominant limb, metronome (UNM) coupling for both phase relations: $BNM < UNM$. In opposition to the second hypothesis, directionality was expected given that previous research (Peper et al. 2002, Peper et al. 2004, and Ridderikoff et al. 2004) has illustrated entrainment effects involving the non-dominant limb. This entrainment effect, provided by the dominant limb, creates a more suitable environment for the non-dominant limb by

improving task stability and, thus, motor performance with the metronome (see *Figure 7*). This outcome would also suggest that coupling with the dominant limb could alter the performance variables (in particular the b/a ratio) of the non-dominant limb

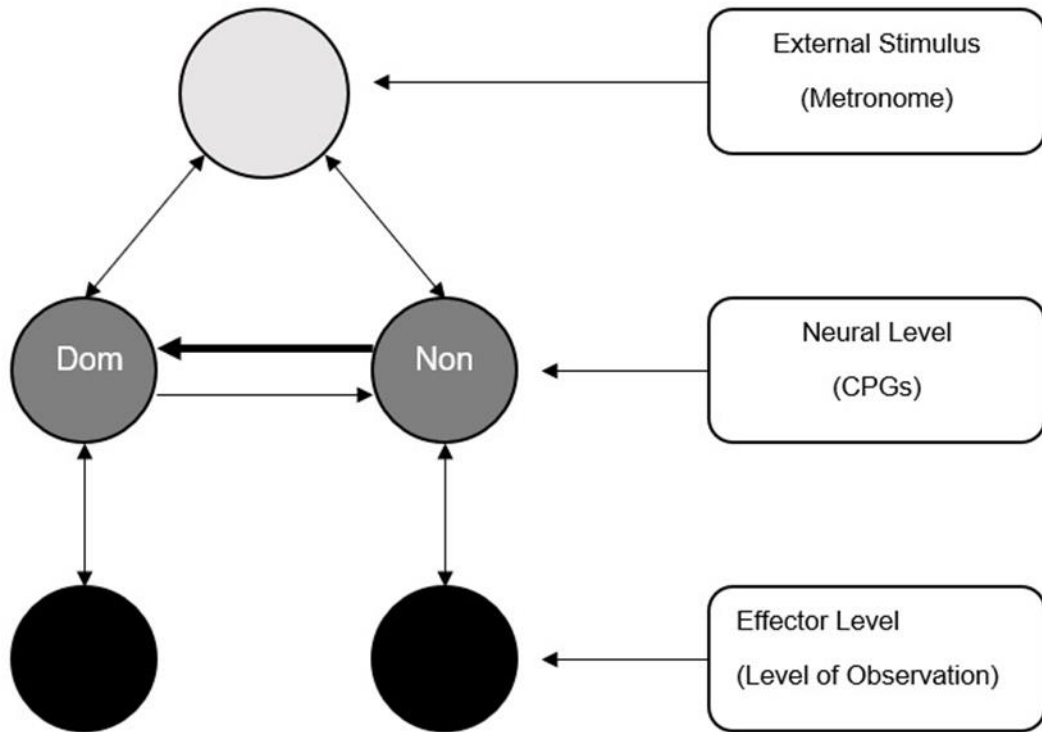


Figure 7 - Two-tiered model. Bolded direction arrow refers to coupling strength from the nondominant limb (Non) to the dominant limb (Dom) direction.

The fourth hypothesis addressed was that bimanual, dominant, non-dominant coupling (BDN) RPV would not significantly differ from the bimanual, dominant, metronome coupling (BDM) RPV, but will be greater than the bimanual, non-dominant, metronome coupling (BNM) RPV for both phase relations: $BDN = BDM < BNM$ (*Figure 8*). This outcome was expected as the dominant limb's refined motor control allows for finer tuning of the performance variables (a , b , c , and d in Equation 5, see

above) and thus minimizes the influence of the nondominant limb on RPV. In turn, this minimizes any increase in RPV to either BDN or BDM couplings. Although the nondominant limb metronome coupling (BNM) is hypothesized to have a decrease in RPV due to entrainment (Hypothesis 3), it is thought that the additional information available to the BNM will be insufficient to produce an RPV equal to that of the other two couplings.

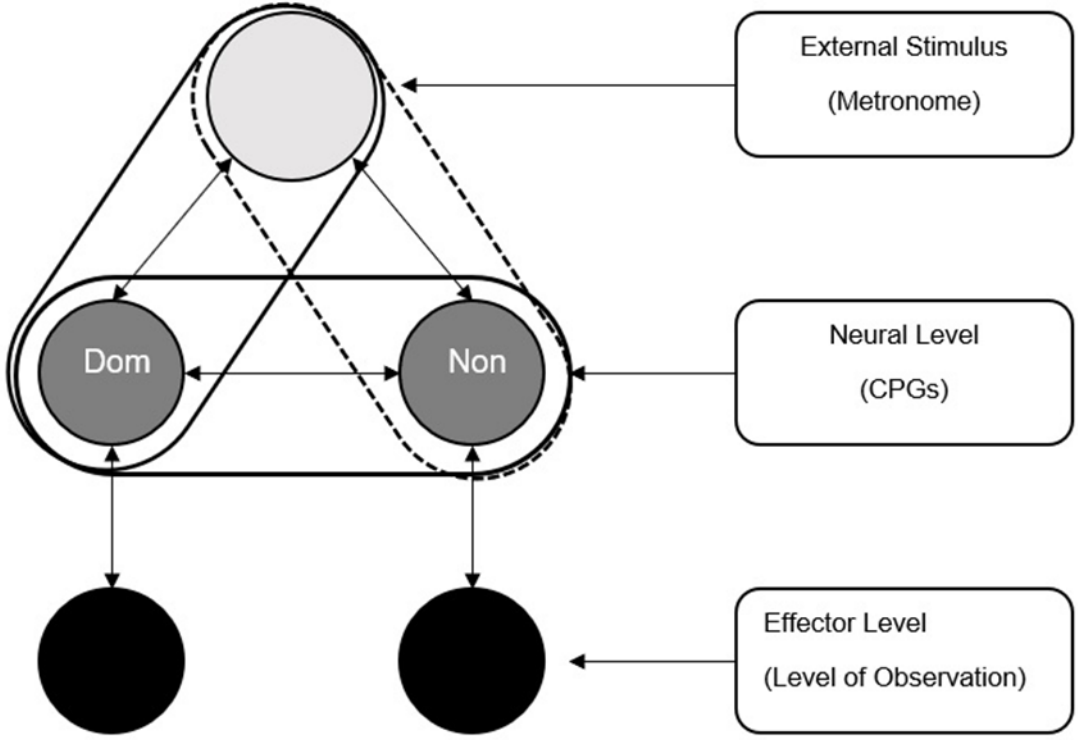


Figure 8 - Two-tiered model. Solid rectangles indicate BDN and BNM couplings. The dotted rectangle indicates BNM coupling.

Four robust repeated measures ANOVAs were used with nine yuen's trimmed mean t-test for the post hoc analyses for the statistical analysis. Moreover, to adjust for

the family-wise error, the Bonferroni correction was implemented for the primary analyses ($\alpha = 0.013$) and the post hoc analyses ($\alpha = 3.33e-3$). All the statistical analyses were completed using RStudio (Version 1.1.463).

Experimental Design, Sample, and Randomization

Experimental Design

Participants completed six rhythmic wrist coordination tasks. The tasks themselves are differentiated by three independent variables: Handedness (dominant or non-dominant), Hands (unimanual or bimanual), and Phase relation (in-phase or anti-phase). One dependent variable was used to determine the tasks' performance: Relative Phase Variance (RPV). Briefly, RPV is the variance of continuous relative phase (CRP) between two components of the system (either limb to limb or limb to a metronome). Participants' eyes remained closed for the movement tasks' duration to ensure that only haptic feedback from the limbs is used.

Sample

The sample was 20 individuals (17 right-handed and three left-handed) between the ages of 19 and 35 with no history of neurological disorders that would affect motor control. Moreover, following Serrien (2008) methodology, individuals who are avid musicians were excluded from this experiment as having additional rhythm training may affect the ability to perform the tasks. As for determining hand dominance, the Modified

Edinburg Handedness Index (Vlade et al. 2016) was used to identify the participants' dominant and non-dominant limbs.

Randomization

As the order of tasks may affect subsequent tasks' performance, the order was randomized for each participant. First, for each subject, the tasks were entered into the first column of an Excel spreadsheet: UD In-phase, UN In-phase, UD Anti-phase, UN Anti-phase, B In-phase, B Anti-phase. Second, each task was given a random number between 0-1 using the RAND function in a neighbouring column. Finally, both columns were sorted from smallest to largest concerning the randomly generated numbers. This method provided a proper randomized order for the trials.

Instructions for Participants

To ensure tasks were completed uniformly across participants, the following script was read to and by the participants.

- You will complete each of the trails in a predetermined random order.
 - Right hand with the metronome on the beat
 - Left hand with the metronome on the beat
 - Right hand with metronome offbeat
 - Left hand with metronome offbeat
 - Both hands with the metronome on the beat

- Both hands with one hand on the metronome on the beat and the other on metronome offbeat

- For the single hand trails, you will need to move the selected hand with the metronome on the beat (reaching maximum wrist flexion on the downbeat of the metronome) or on the metronome offbeat (reaching maximum wrist extension on the off-beat).

- For both hands conditions, you will need to move both hands with the metronome on the beat (both hands reaching maximum flexion to the beat of the metronome) or with one hand moving with the metronome on the beat and the other hand moving to the metronome offbeat (your dominant hand reaching maximum flexion and your non-dominant hand reaching maximum extension to the beat of the metronome).

- You must try to maintain the tasks (on the beat or offbeat) for as long as possible.
 - If coordination is lost, continue the task to the best of your ability.

- You will be given 2 minutes break to prevent fatigue from affecting the next trial between each trial.
 - If you still feel fatigued by the end of the 2 minutes, another 2 minutes will be provided.

Data Transformations

Continuous Relative Phase

The method proposed by Lamb and Stöckl (2014) was used for calculating the continuous relative phase (CRP) of the different component couplings: limb to limb and limb to the metronome. The method for calculating CRP is as follows:

1. Centring the amplitude of the data about zero

- $x_{centered}(t_i) = x(t_i) - \min(x(t)) - \frac{(\max(x(t)) - \min(x(t)))}{2}$ (Equation 6)

2. Transforming each signal into an analytic signal using the Hilbert transform.

- $\zeta(t) = x(t) + iH(t)$ (Equation 7)

3. Calculating the phase angle for each signal

- $\Phi(t_i) = \arctan\left(\frac{H(t_i)}{x(t_i)}\right)$ (Equation 8)

4. Calculating the continuous relative phase.

- $crp(t_i) = \Phi_1(t_i) - \Phi_2(t_i) = \arctan2\left(\frac{H_1(t_i)x_2(t_i) - H_2(t_i)x_1(t_i)}{x_1(t_i)x_2(t_i) + H_1(t_i)H_2(t_i)}\right)$ (Equation 9)

Performance Metrics

Relative Phase Variation

RPV is utilized to determine how similar a limb's movement is to another component: either the opposing limb or metronome. RPV is calculated by taking the variance of the CRP (Lamb and Stöckl, 2014). We infer stability through this procedure through the RPV change: a larger RPV would indicate that the participant could not

maintain the task condition than a smaller RPV. All RPV calculations were completed using Matlab 2019A.

Data Processing

The raw data (*Figure 9*) was first cropped between the initial and final metronome beeps. It was then smoothed via a low-pass second-order Butterworth filter at 0.2 Hz (*Figure 10*). Finally, the CRP (*Figures 11-14*) and RPV of the task were calculated for the entire task. For couplings involving the metronome, a cosine wave driven at the various movement frequencies was used.

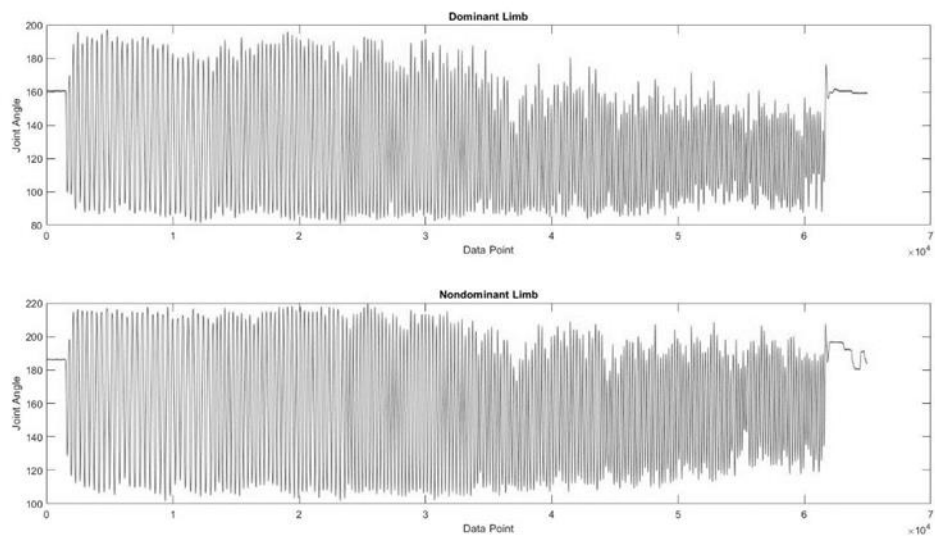


Figure 9 - Raw data from a bimanual in-phase task. The joint angle is measured in degrees, with a decrease in angle representing wrist flexion.

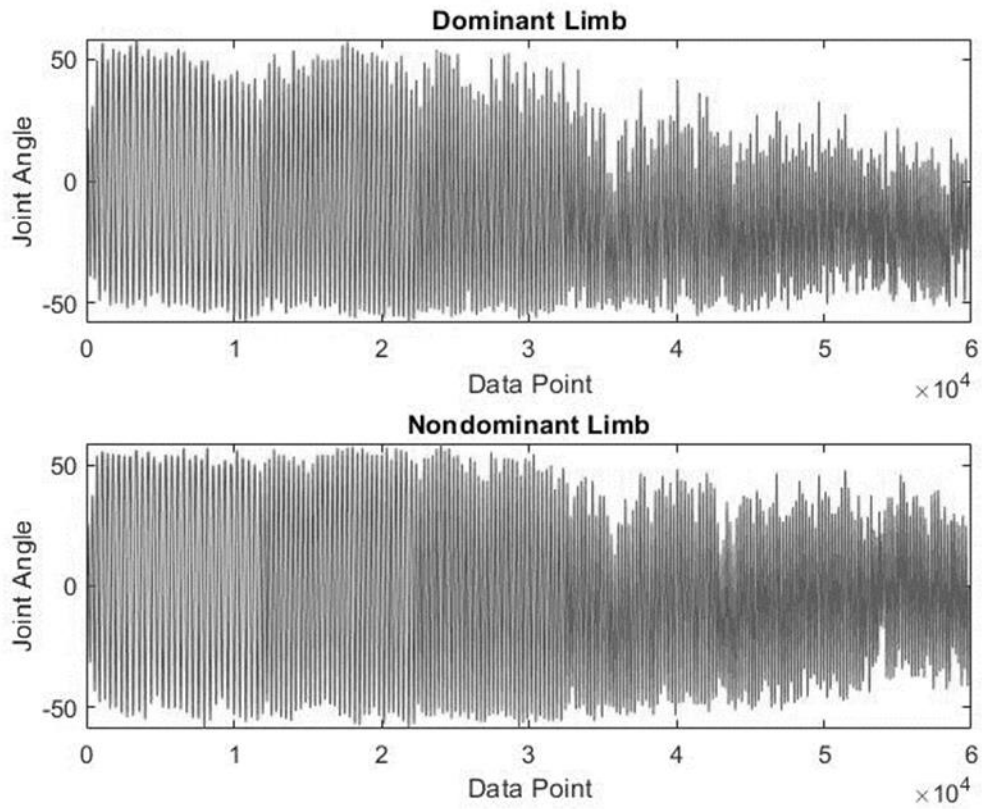


Figure 10 - Centred data from a bimanual in-phase task. The joint angle is measured in degrees, with a decrease in angle representing wrist flexion. The centring method is detailed in Equation 6.

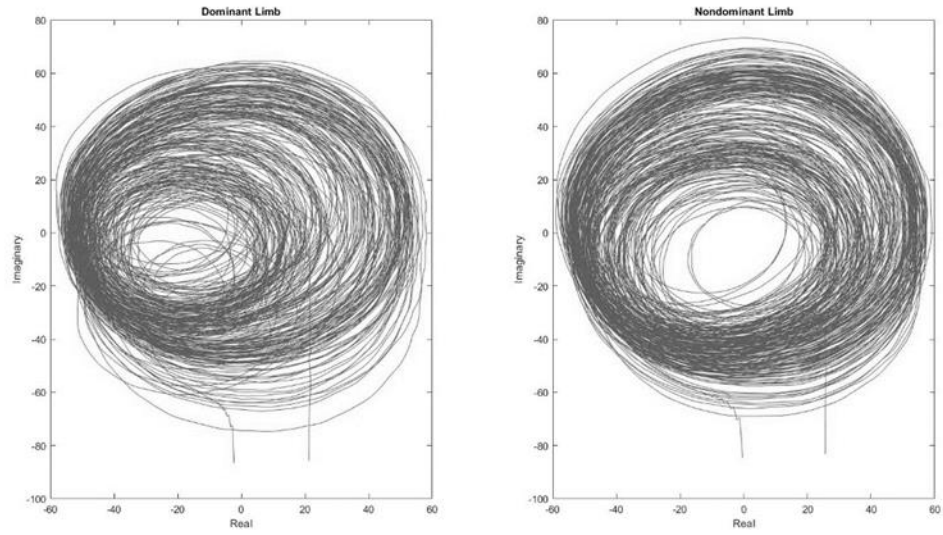


Figure 11 - Analytic signal from a bimanual in-phase task. The method of transformation is detailed in Equation 7.

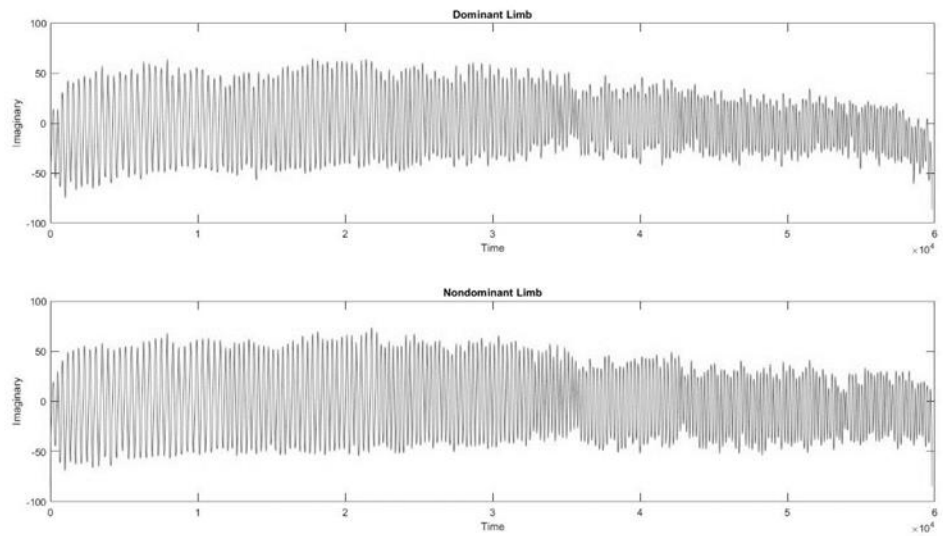


Figure 12 - Imaginary portion of the analytic signal from a bimanual in-phase task. The method of transformation is detailed in Equation 7.

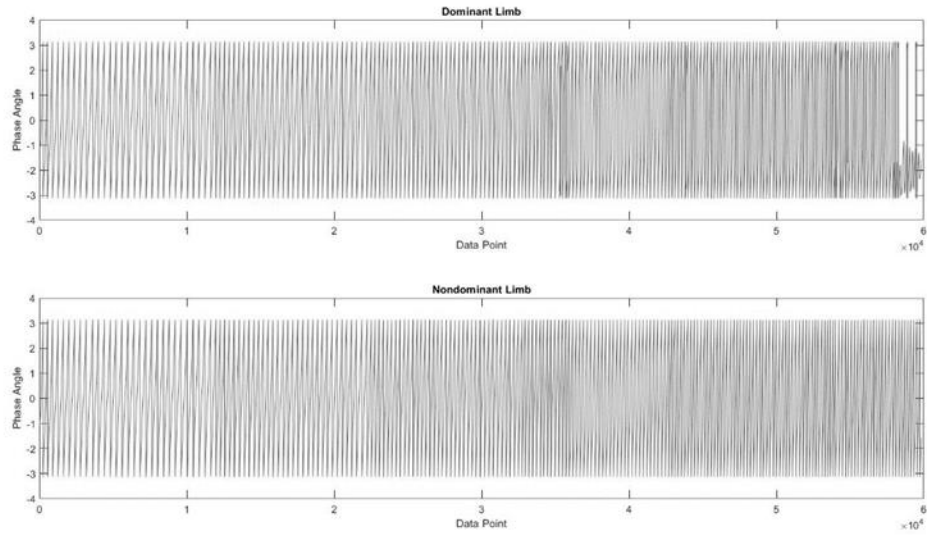


Figure 13 - Phase angle from a bimanual in-phase task. The method of transformation is detailed in Equation 8. The phase angle is measured in radians and is bound between $\pm\pi$.

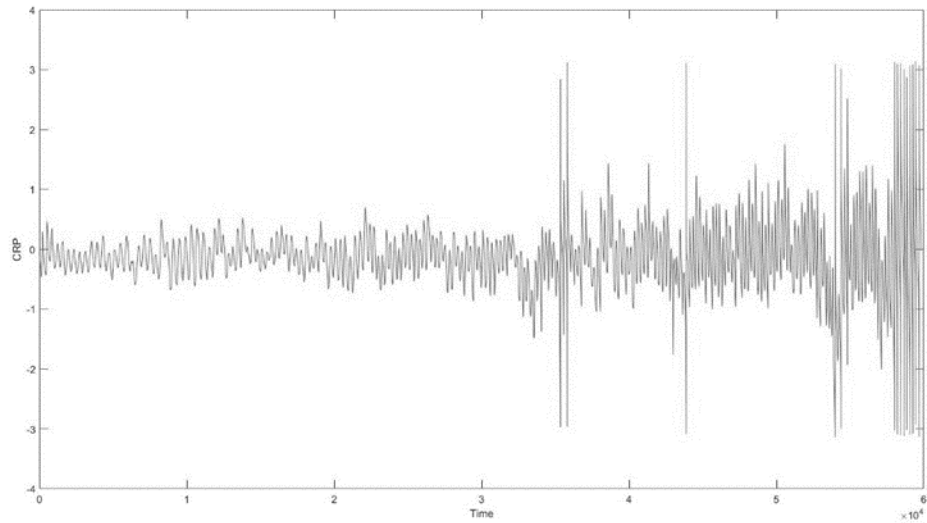


Figure 14 - Continuous relative phase (CRP) of a bimanual in-phase task. The method of transformation is detailed in Equation 9. CRP is measured in Radians and is bound between $\pm\pi$.

Experimental Set-up and Tasks

Recording and Measurement Devices

The kinematic data were recorded using an electric goniometer, and the metronome tone was created by a smart device (Smart Phone), which was administered via a speaker placed in front of the participant. The pitch and duration of the tone were set to 955 Hz and ten milliseconds, respectively. Both the goniometer and metronome data were recorded at 1000 Hz through custom code implemented in LabVIEW. The metronome data was captured through a microphone placed by a second speaker, which was fed through an amplifier and recorded.

Equipment Set-up

The electric goniometer was adhered firmly to the ulnar side of the forearm and hand using both straps and tape; this was done by marking the wrists' centre of rotation and placing the electric goniometers' centre of rotation over these marked locations (*Figure 15*).



Figure 15 - Photos of electric goniometer placement on participant's wrists.

Participants sat with the ulnar portion of their forearms on a stiff, flat block of foam with their hands over the edge. The foam was placed slightly forward to prevent the shoulders and elbow from assisting in the action (see *Figure 16*). The participant's hands were closed with the palms facing each other; the transverse plane's orientation is vital as gravity will not influence flexion or extension of the participant's wrist (*Figure 16*). To prevent the hands from contacting each other, ample room was given between the limbs.

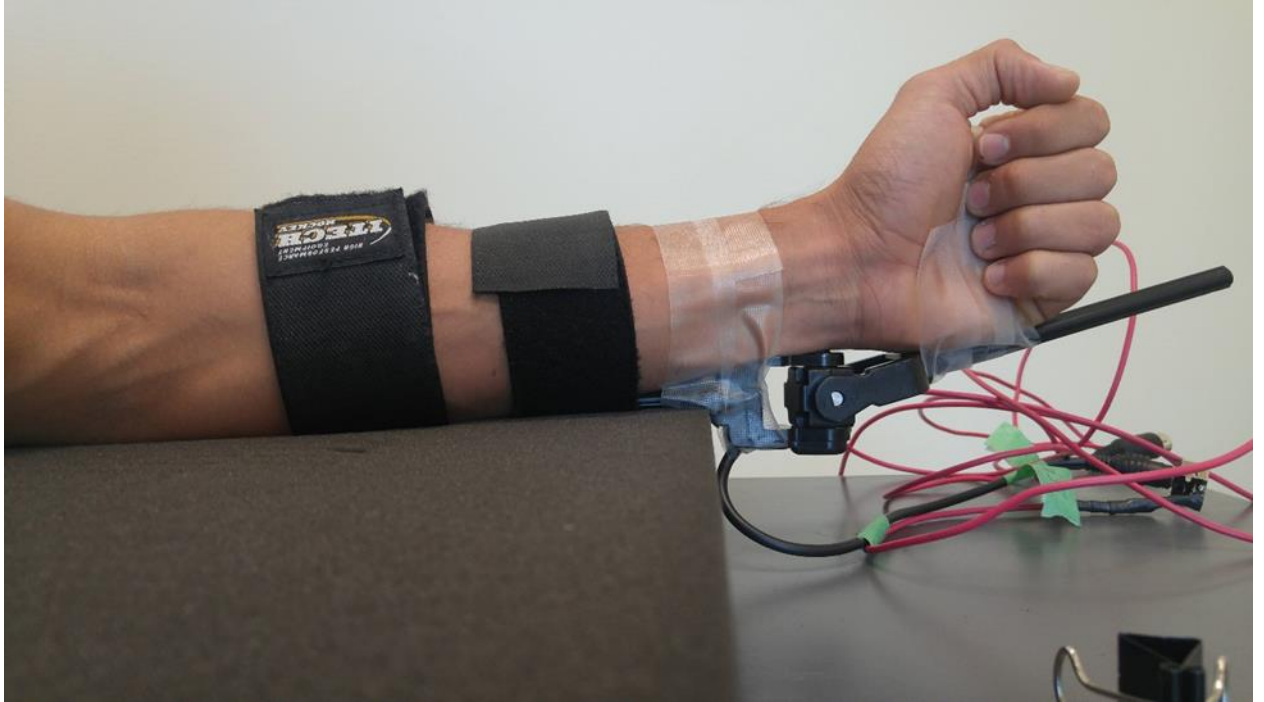


Figure 16 - Photo of the participant's arm and wrist position during the experiment. The foam block is placed under the forearm to allow for unhindered wrist flexion and extension.

Tasks

The tasks were similar to those of Serrien (2008) and consisted of the participants moving their wrists to a metronome's beat that progressively increased in frequency. Each participant was given 10 seconds to familiarize themselves with each task.

The tasks consisted of six wrist coordination tasks administered in random sequence:

1. Unimanual Dominant In-phase
2. Unimanual Dominant Anti-phase
3. Unimanual Non-dominant In-phase

4. Unimanual Non-dominant Anti-phase
5. Bimanual In-phase
6. Bimanual Anti-phase

In-phase tasks required maximum wrist flexion on the metronome beat and maximum wrist extension for anti-phase for the phase relations. The only exception to this rule was for the bimanual anti-phase task, where the dominant limb achieved maximum wrist flexion on the beat, and the non-dominant limb completed maximum wrist extension. Taking inspiration from previous research (Buchanan et al., 1997; Kelso, Scholz, and Schöner, 1986; Milliex, Calvin, and Temprado, 2005; Schöner, Haken, and Kelso, 1986), the metronome began at 2.5 Hz and increased by 0.5 Hz every 10 seconds for 60 seconds (2.5 to 5 Hz). As fatigue can affect the participant's ability to complete the tasks, a single two-minute break was given between trials. If more time was required, another two-minute break was provided.

Results

Given the nature of the data, neither normality nor equal variance was achieved; as such, robust statistical methods were used to determine significance. Specifically, robust repeated measures ANOVAs were used to determine the significance of each hypothesis tested. The Bonferroni correction was implemented to account for the increase in family-wise error. In summary, four robust repeated measures ANOVAs ($\alpha = 0.013$) with fifteen yuen's trimmed mean t-test post hoc analyses trimmed to 20% were used ($\alpha = 3.33e-03$).

Hypothesis 1 – Handedness (UDM < UNM)

The first hypothesis determined if the dominant limb would have a lower RPV than the nondominant limb for both phase relations tested. The summary of the data is located in Table 1 and *Figure 17*. The results of the robust repeated measures ANOVA indicated a significant effect between the handedness and/or phase relation at the $\alpha = 0.013$ level [$F(1.86, 20.49) = 16.882, p = 6.00e-05$] (Table 2). However, from the post hoc analyses, no significant difference was found between the couplings at the $\alpha = 3.33e-03$ level.

Phase Relation	Handedness	N	RPV	StdDev	StdErr	95%CI
Anti-phase	Dom	20	3.693	0.758	0.169	0.355
Anti-phase	Non	20	3.427	0.679	0.152	0.318
In-phase	Dom	20	2.153	0.663	0.148	0.310
In-phase	Non	20	2.613	0.900	0.201	0.421

Table 1 - Summary of handedness data for hypothesis 1. RPV – Mean Relative Phase Variability, Dom - Dominant Hand, Non - Nondominant Hand, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.

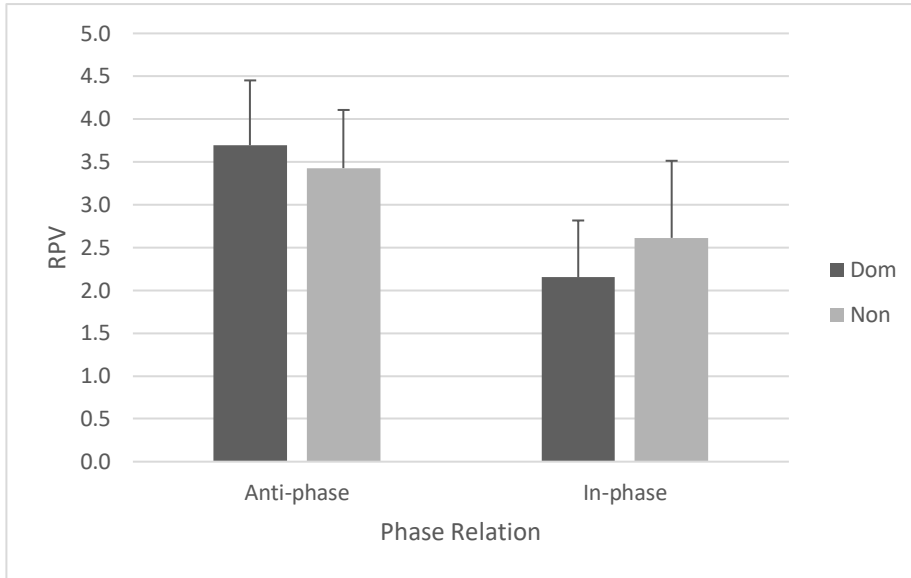


Figure 17 - Plot of mean relative phase variance from Table 1. Error bars are standard deviation from Table 1.

Variable	F-Statistic	DF1	DF2	p-value	p-crit
Handedness*Phase Relation	16.882	1.86	20.49	6.00E-05	0.013

Table 2 - Results of the robust repeated measures ANOVA for hypothesis 1.

Comparison	Phase Relation	Test Statistic	df	p-value	ψ_{hat}	95% CI - Lower	95% CI - Upper	Effect Size
UDM v UNM	Anti-phase	-3.365	11	0.0063	-0.327	-0.541	-0.113	0.34
UDM v UNM	In-phase	1.989	11	0.0722	0.422	-0.045	0.889	0.38

Table 3 - Results of yuen's trimmed mean t-test post hoc analysis for hypothesis 1. UDM - Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling, ψ_{hat} – the difference between test means.

Hypothesis 2 & 3– Hands (Dominant/Nondominant) (BDM ≠ UDM, BNM < UNM)

The second hypothesis focused on RPV's difference between the bimanual and unimanual variants for the dominant limb tasks in both phase relations. The summary of the data used in hypothesis 2 is in Table 4 and *Figure 18*. From the results of the robust repeat measure ANOVA, a significant effect was found at the $\alpha = 0.013$ [$F(2.32, 25.51) = 23.931, p = 6.13e-07$] (Table 5). However, from the post hoc analysis (Table 6), no significant difference was found between interest interactions at the $\alpha = 3.33e-03$ level.

Phase Relation	Hands	N	RPV	StdDev	StdErr	95%CI
Anti-phase	Bimanual	20	2.945	0.735	0.164	0.344
Anti-phase	Unimanual	20	3.693	0.758	0.169	0.355
In-phase	Bimanual	20	2.248	0.675	0.151	0.316
In-phase	Unimanual	20	2.153	0.663	0.148	0.310

Table 4 - Summary data of the dominant limb hypothesis 2. RPV - Relative Phase Variance, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.

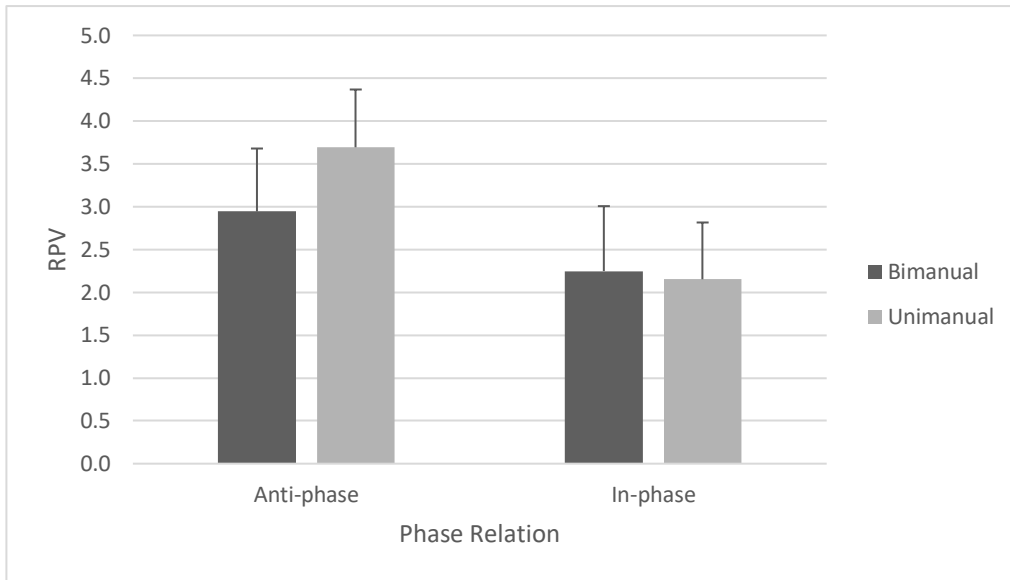


Figure 18 - Plot of mean relative phase variance from Table 4. Error bars are standard deviation from Table 4.

Variable	F-Statistic	DF1	DF2	p-value	p-crit
Hands*Phase Relation	23.931	2.32	25.51	6.13E-07	0.013

Table 5 - Results of the robust repeated measures ANOVA for hypothesis 2.

Comparison	Phase Relation	Test Statistic	df	p-value	ψ_{hat}	95% CI - Lower	95% CI - Upper	Effect Size
BDM v UDM	Anti-phase	3.712	11	3.43E-03	0.865	0.352	1.379	0.71
BDM v UDM	In-phase	-0.431	11	0.67495	-0.060	-0.367	0.247	0.06

Table 6 - Results of the yuen's trimmed mean t-test post hoc analysis for hypothesis 2. UDM - Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling. ψ_{hat} – the difference between test means.

Like the second, the third hypothesis looked to see if the nondominant limb's bimanual variant had a lower RPV than the unimanual for both phase relations. A

summary of the data used in Hypothesis 3 is in Table 6 and *Figure 19*. From the results of the robust repeat measure ANOVA, a significant effect was found at the $\alpha = 0.013$ [$F(2.27, 25.0) = 13.492, p = 6.00e-05$] (Table 7). However, from the post hoc analysis, no significant difference was found between the interactions of interest (Table 9).

Phase Relation	Hands	N	RPV	StdDev	StdErr	95%CI
Anti-phase	Bimanual	20	3.293	0.473	0.106	0.221
Anti-phase	Unimanual	20	3.427	0.679	0.152	0.318
In-phase	Bimanual	20	2.230	0.596	0.133	0.279
In-phase	Unimanual	20	2.613	0.900	0.201	0.421

Table 7 - Summary of data used for hypothesis 3. RPV – Relative Phase Variability, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.

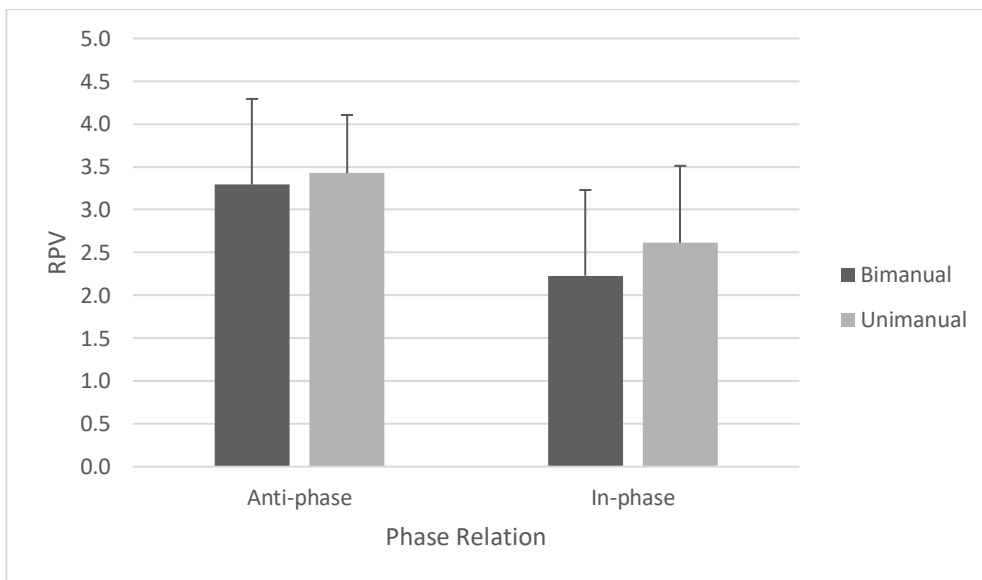


Figure 19 - Plot of mean relative phase variance for hypothesis 3 from Table 7. Error bars are standard deviation from Table 7.

Variable	F-Statistic	DF1	DF2	p-value	p-crit
Hands*Phase Relation	13.492	2.27	25	6.00E-05	0.013

Table 8 - Results of the robust repeated measures ANOVA for hypothesis 3.

Comparison	Phase Relation	Test Statistic	df	p-value	ψ_{hat}	95% CI - Lower	95% CI - Upper	Effect Size
BNM v UNM	Anti-phase	0.894	11	0.391	0.152	-0.223	0.528	0.2
BNM v UNM	In-phase	1.903	11	0.084	0.378	-0.059	0.816	0.33

Table 9 - Results of the yuen's trimmed mean t-test post hoc analysis for hypothesis 3. UDM -

Unimanual Dominant Metronome coupling, UNM - Unimanual Metronome coupling. ψ_{hat} – the difference between test means.

Hypothesis 4 – Coupling (BDN = BDM < BNM)

The fourth hypothesis sought to determine if the RPV differed between the bimanual dominant-nondominant limb (BDN) and the bimanual dominant-metronome coupling (BDM), moreover, to see if these tasks had a lower RPV than the bimanual nondominant-limb coupling (BNM). The summary of the data used in hypothesis 4 is in Table 10 and *Figure 20*. Based on the results of the robust repeated measures ANOVA (Table 11), there was a significant effect on RPV for coupling and phase relation at the $\alpha = 0.013$ level [$F(2.42, 26.64) = 69.407, p = 5.74e-12$] (Table 11). For the post hoc analysis, nine were completed comparing the different couplings given the same phase relation (6) and phase relation given a coupling (3). Six significant post hoc results were found at the $\alpha = 3.33e-03$ level (see Table 12).

Coupling	Phase Relation	N	RPV	StdDev	StdErr	95%CI
BDN	Anti-phase	20	4.579	1.131	0.253	0.529
BDN	In-phase	20	0.383	0.223	0.050	0.105
BDM	Anti-phase	20	2.945	0.735	0.164	0.344
BDM	In-phase	20	2.248	0.675	0.151	0.316
BNM	Anti-phase	20	3.293	0.473	0.106	0.221
BNM	In-phase	20	2.230	0.596	0.133	0.279

Table 10 - Summary of the data used for hypothesis 4. Both – Dominant and Nondominant coupling, Dom – Dominant limb, Non – Nondominant limb, StdDev – Standard Deviation, StdErr – Standard Error, 95%CI – 95% Confidence Interval.

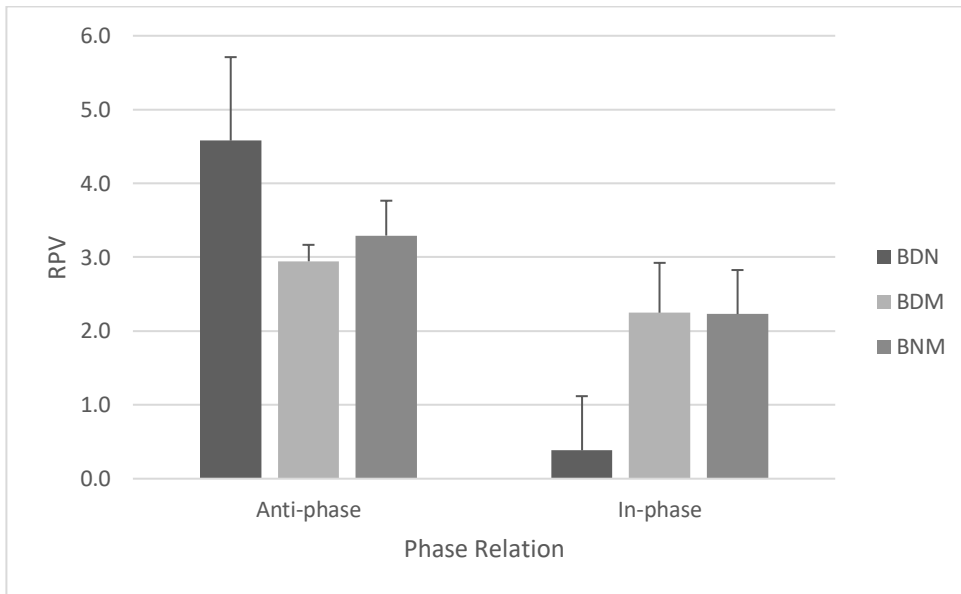


Figure 20 - Plot of mean relative phase variance for hypothesis 4 from Table 10. Error bars are standard deviation from Table 10.

Variable	F-Statistic	DF1	DF2	p-value	p-crit
Coupling*Phase Relation	69.407	2.42	26.64	5.74E-12	0.013

Table 11 - Results of robust repeated measures for hypothesis 4.

Comparison	Phase Relation	Test Statistic	df	p-value	ψ_{hat}	95% CI - Lower	95% CI - Upper	Effect Size
Dom v Non	In-phase	0.232	11	0.821	0.016	-0.139	0.172	0.02
Dom v Both	In-phase	12.214	11	9.70E-08	1.866	1.530	2.202	0.99
Non v Both	In-phase	12.573	11	7.29E-08	1.850	1.526	2.173	0.96
Dom v Non	Anti-phase	-1.878	11	0.087	-0.386	-0.838	0.066	0.46
Dom v Both	Anti-phase	-4.643	11	7.10E-04	-1.726	-2.544	-0.908	0.87
Non v Both	Anti-phase	-4.131	11	1.67E-03	-1.340	-2.054	-0.626	0.84
Dom v Dom	In v Anti-phase	-3.651	11	3.81E-03	-0.681	-1.091	-0.271	0.65
Non v Non	In v Anti-phase	-6.108	11	8.00E-05	-1.083	-1.473	-0.693	0.94
Both v Both	In v Anti-phase	-12.627	11	6.88E-08	-4.273	-5.018	-3.528	0.95

Table 12 - Results of the yuen's trimmed mean t-test post hoc analysis for hypothesis 4. Dom – Bimanual Dominant Metronome coupling, Non – Bimanual Nondominant Metronome coupling, Both – Bimanual Dominant Nondominant coupling. ψ_{hat} – the difference between test means.

Discussion

In addressing the gaps in the current literature, furthering our understanding of the CNS's two-tiered model is the main focus. To achieve this improved understanding, we have analyzed three gaps in the current literature. The first is how the coupling at the CNS level contributes to a rhythmic task; specifically, how the asymmetries between paired oscillators at the spinal level influence motor behaviour. The second is to understand how the asymmetries in coupling strength between dominant and non-dominant limbs affect rhythmic motor task performance. The third is to determine if differences in coupling strengths exist between limbs performing a bimanual rhythmic task. We will have more insight into the two-tiered model and its pertinence to human movement by addressing these gaps.

The four variables that have been manipulated to test the two-tiered model are handedness, hands, coupling, and phase relation. Handedness is used to determine if differences in task performance exist between limbs. The number of hands used is manipulated to address differences in performance between the tasks' bimanual and unimanual variants. Coupling was manipulated to compare the performances of the three bimanual couplings: dominant-to-nondominant, dominant-to-metronome, and nondominant-to-metronome. Finally, phase relation was included with each primary variable to see if significant interactions occurred. From manipulating these variables, a greater understanding of the two-tiered model will be achieved.

Handedness (UDM < UNM)

The first characteristic to be analyzed is the difference in handedness during the Unimanual tasks. The goal is to determine if preferred handedness affected the ability to synchronize with the audible tone; moreover, the difference in phase relation (in-phase vs anti-phase) relative to the metronome affected the performance. In prior research (Treffner and Turvey 1995, 1996; Beek et al., 2002), asymmetries in coupling strengths between the dominant and nondominant limbs have been identified; however, no significant difference in RPV was found between the dominant or non-dominant limbs. However, it should be noted that the anti-phase task was not significant due to a lack of statistical power from family-wise error corrections. Given that, the results are still unexpected, as no difference was found in the in-phase task. In summary these, results do not support current literature regarding the current HKB model and limb entrainment

(Tognoli and Kelso, 2014, Beek et al., 2002; Peper et al., 2004; de Poel, Peper, and Beek, 2007; Treffner and Turvey 1995, 1996).

Regarding the current HKB model (Tognoli and Kelso, 2014), it is expected that the increase in movement speed (frequency) would produce a decreased ability of the nondominant limb to manipulate its eigenfrequency compared to the dominant limb (*Equation 5* variables *a*, *b*, *c*, and *d*); however, from the results, no difference in performance regarding handedness is present. As such, it appears that the nondominant limb may have a similar ability to manipulate its eigenfrequency as the dominant limb and thus a similar level of control with simple rhythmic tasks.

As these results relate to the two-tiered model, they address the differences (or lack thereof) between the information pathway between the metronome to the effector limb. The results show that the pathway - or ability to manipulate this pathway - is similar between the dominant and non-dominant limbs. In contrast to the possibility of two oscillators at the spinal level, the results can also be explained by a single oscillator at the spinal level. With only a single oscillator, it would better suit the findings given that the addition of two components could increase the chance of RPV differences between limbs: two CPGs with unique characteristics would most likely produce different behaviours. Moreover, the difference in the coupling between the limbs and the single component could still provide the difference in performance found in previous research (Treffner and Turvey 1995, 1996; Beek et al., 2002) given that differences in information exchange between the limb and the spinal level could still exist. In general,

regarding the first hypothesis, the results do not support the notion of differences in performance between the dominant and nondominant limb.

Hands (BDM \neq UDM, BNM $<$ UNM)

The second characteristic to be analyzed is how an additional limb's presence affects the RPV of the task. In terms of directionality, it was hypothesized that the dominant limb would not significantly differ between the bimanual and unimanual variants; as for the non-dominant limb, it was expected that the bimanual variant would perform better than the unimanual variant. In general, these directionalities were predicted as prior research has demonstrated differences in coupling strength between limbs (Treffner and Turvey 1995, 1996; Beek et al., 2002); hence it was hypothesized that the dominant limb's RPV would not differ between tasks given the low coupling strength with the non-dominant limb. For the non-dominant limb, its RPV would improve with the bimanual task given the higher coupling strength with the dominant limb.

The results show no significant difference in RPV between the bimanual and unimanual tasks for either the dominant or non-dominant limbs. These results matched the dominant limb's expectations as the nondominant limb's presence in the tasks was not expected to significantly affect RPV given the low coupling strength in the dominant to non-dominant limb direction (see *Figure 6* above). However, these results are surprising for the nondominant limb as it goes against previous work regarding coupling

strength and task performance (Peper et al. 2002, Peper et al. 2004, and Ridderikoff et al. 2004). Even with the task's increasing difficulty, the unimanual RPV did not significantly differ from the bimanual task. This result appears to indicate that the coupling strength from the non-dominant to dominant limb direction (see *Figure 7* above) may not be as strong as initially proposed and may have less of an effect than initially hypothesized.

As with prior research on coupling strength (Peper et al. 2002, 2004), the limbs were manipulated using manipulandum (pendulums). This distinction is essential as this may contribute to the different outcomes of this study. In particular, the presence of a manipulandum may provide a more significant challenge to the nervous system by inducing changes to the limbs' eigenvalues and eigenfrequencies as the limbs would have a different mass and levels of torque required to manipulate the wrists. In contrast, our study imposed movement speed increases, thus not directly altering limbs' eigenvalues or eigenfrequencies. However, as no difference is present, it can be argued that these values did not differ initially. In other words, it appears that only when physical limitations are imposed on the limbs will the difference in the limbs' ability to compensate for these differences become apparent. For this study, it does not appear that the increase in movement speed alone posed enough difficulty to elicit the differences found in the prior research (Peper et al. 2002, 2004). From this result, we can speculate that the limbs' eigenvalues and eigenfrequencies may not differ substantially, but their ability to compensate for challenges may. This would allow the limbs to perform with a similar degree of accuracy given more manageable tasks (movement speed increases)

and differently given difficult tasks (changing the limb's mass and torque required to move). This differing capacity to compensate then could be explained by varying neurological components and the ability to manipulate a limb's attractor landscape to a higher degree (Kelso, 2012).

Regarding the two-tiered model, the results do not directly support the notion of two oscillators at the spinal level. Continuing with the notion that the couplings' eigenvalues did not differ enough to elicit differences in RPV, the model could be simplified to a single oscillator at the spinal level. With the reduction to one oscillator, the nervous system would reduce the degrees-of-freedom by simplifying the limbs' control scheme. Moreover, as the limb's eigenvalue is altered beyond what the nervous system can control (the information exchange between limb and CNS), differences could be observed.

Coupling (BDN = BDM < BNM)

The third variable, coupling, addresses the RPV of the three bimanual couplings. The purpose of testing the couplings was to determine which one (limb-to-limb or limb(s)-to-stimulus) was dominant. It was expected that the dominant-nondominant limb coupling (BDN) RPV would equal that of the dominant limb-metronome coupling (BDM) and that the nondominant limb-metronome coupling (BNM) would have a higher RPV (BDN = BDM < BNM) for both phase relations. The directionality for this hypothesis was based on the CNSs' ability to manipulate the performance variables of

Equation 5. Given that the dominant limb's pathway was expected to have a higher degree of control through preferred use, it would have a greater capacity to adjust its coupling strength with the non-dominant limb. This unequal coupling strength would allow for couplings to have different RPVs; in particular, the BDM coupling was expected to have increased control allowing it to decrease its coupling strength with the non-dominant limb a lower RPV than the BNM coupling. As for the between limb couplings, this asymmetric coupling strength was also expected to produce a similar effect by relying more on the dominant limb for control. This, in turn, would then cause the BDN RPV to be similar to the BDM coupling (*Figure 8*). However, the results do not agree with this hypothesis.

As for the dominating coupling(s), it was found that phase relation played a role in which coupling(s) had the lowest RPV. The BDN coupling produced the lowest RPV for the in-phase task, while no significant difference was found for the metronome couplings. The in-phase task results were in partial agreement with the original hypothesis stating that the between limb coupling would be one of the dominant couplings; however, both the BDM and BNM couplings had significantly greater RPVs. For the anti-phase couplings, the opposite occurred, with the metronome couplings having the lowest RPVs. As both phase relations indicate deviations from the original hypothesis, we reviewed the relative phase distributions of the task for further insight into the couplings' behaviours.

By analyzing the relative phase distribution plots, we can visually interpret the coupling data from both general performance and as the couplings evolve with movement frequency increases (Steps). Starting with the in-phase couplings (*Figures 21, 22, and 23*), an evident shift to the left in each plot indicates a favouring to 0° (In-phase). As well, one can see the similarities between the metronome couplings' phase distribution plots. This is not surprising given that they were found not to differ significantly; however, as no new information is gained, we move to analyze the step phase distribution plots.

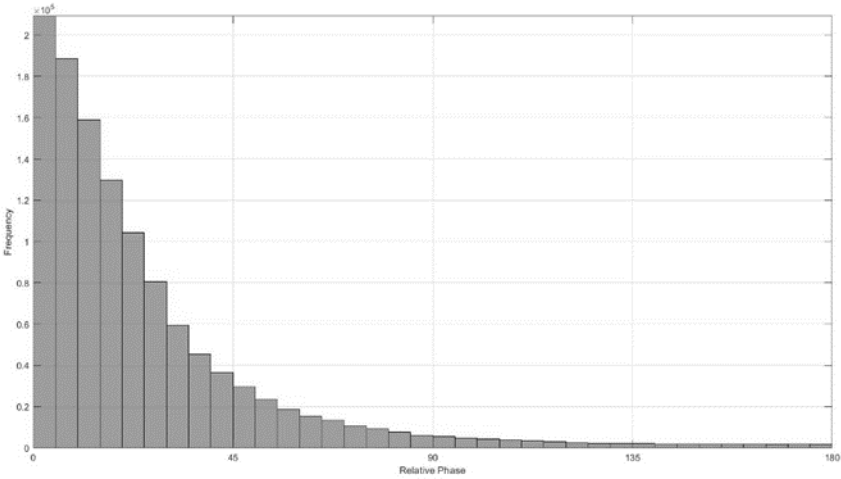


Figure 21 - Phase distribution plot of the in-phase BDN coupling.

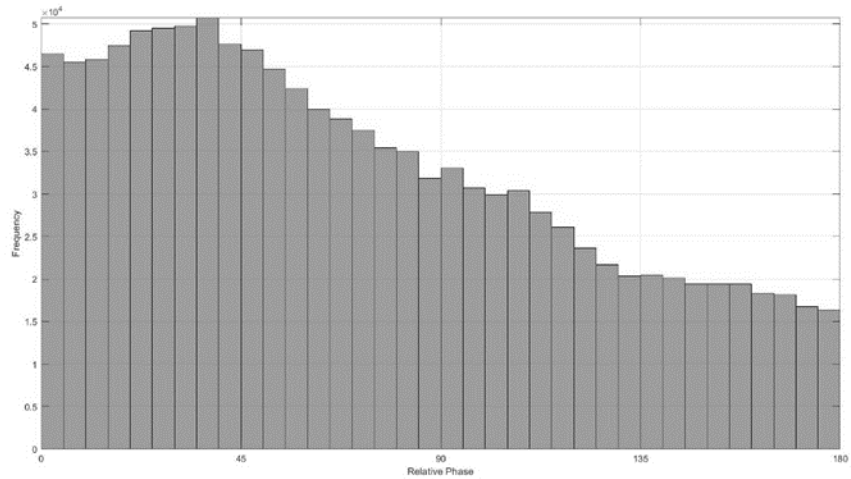


Figure 22 - Phase distribution plots of in-phase BDM coupling.

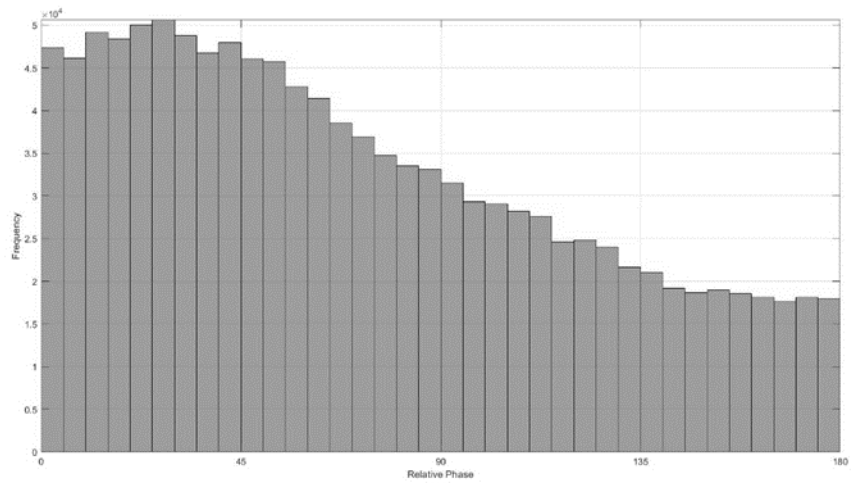


Figure 23 - Phase distribution plots of in-phase BNM coupling.

The next step of analysis is to compare how the in-phase couplings changed with movement frequency increases (*Figures 24, 25, and 26*). This is of particular importance, given that the HKB model predicts changes in task performance as

movement speed increases; moreover, it will allow us to see how the couplings adjust to the changes. Comparing the BDN (*Figure 24*) and BDM (*Figure 25*) couplings, it is clear how strong the BDN coupling is by its superior favouring to in-phase (0°). While the BDM coupling phase distribution begins to shift towards a phase running behaviour at Stage 4, the BDN (*Figure 26*) still retains a strong favouring of in-phase. When comparing the BNM coupling, it is almost identical to the BDM. Just as before, this is not surprising given the statistical results. What stands out from the plots is how drastically different the BDN coupling compared to the metronome couplings are. A possible explanation for this is that the information exchange between the limbs must play a much larger role in bimanual rhythmic wrist tasks than initially hypothesized. Even in Stage 1, the BDN coupling had more than triple the relative phase occurrences within 10° of the intended 0° . In general, the visual analysis agrees with the statistical findings for the in-phase couplings.

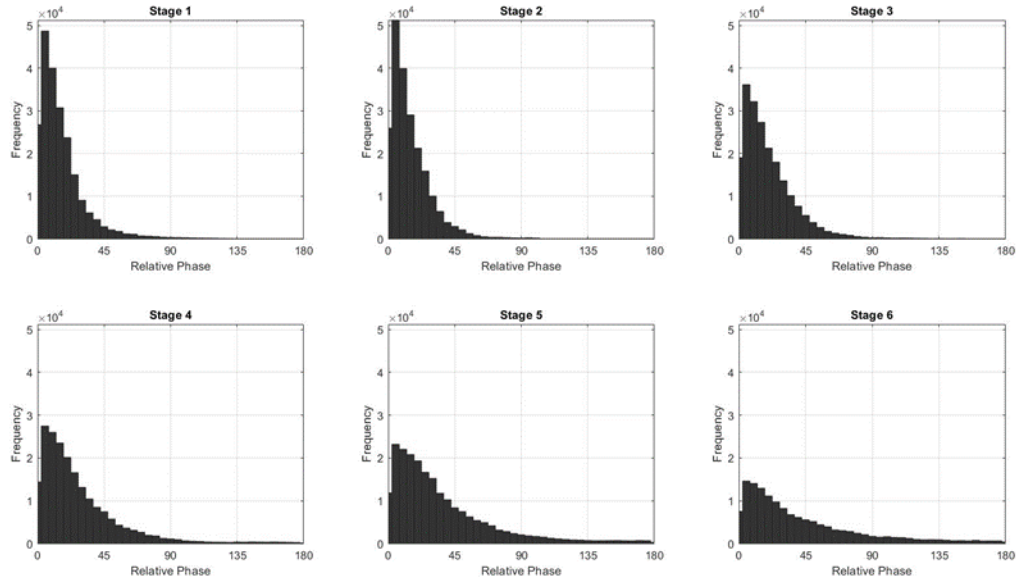


Figure 24 - Group steps phase distribution plot of the in-phase BDN coupling.

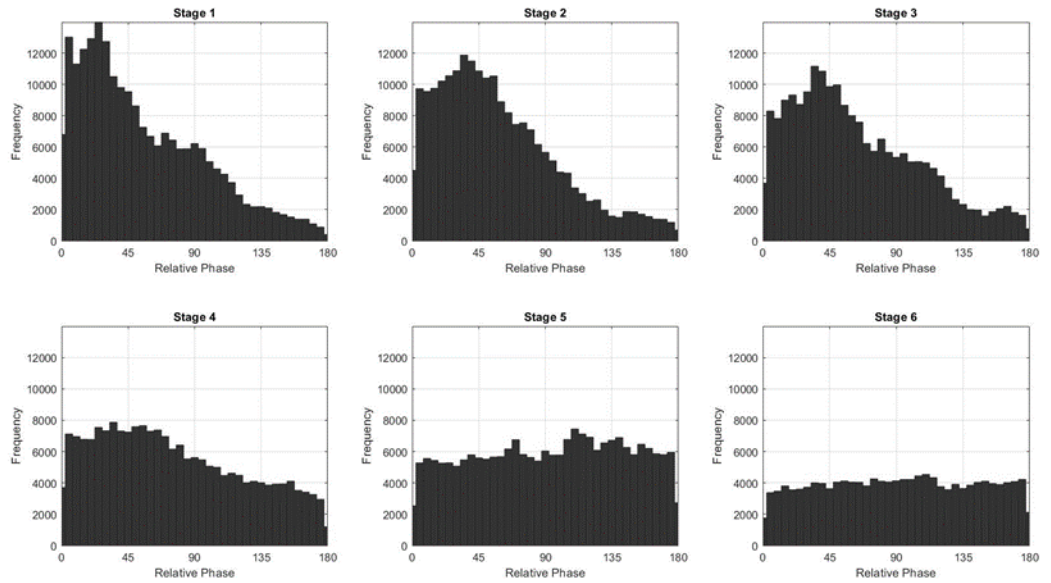


Figure 25 - Group steps phase distribution plot of in-phase BDM coupling.

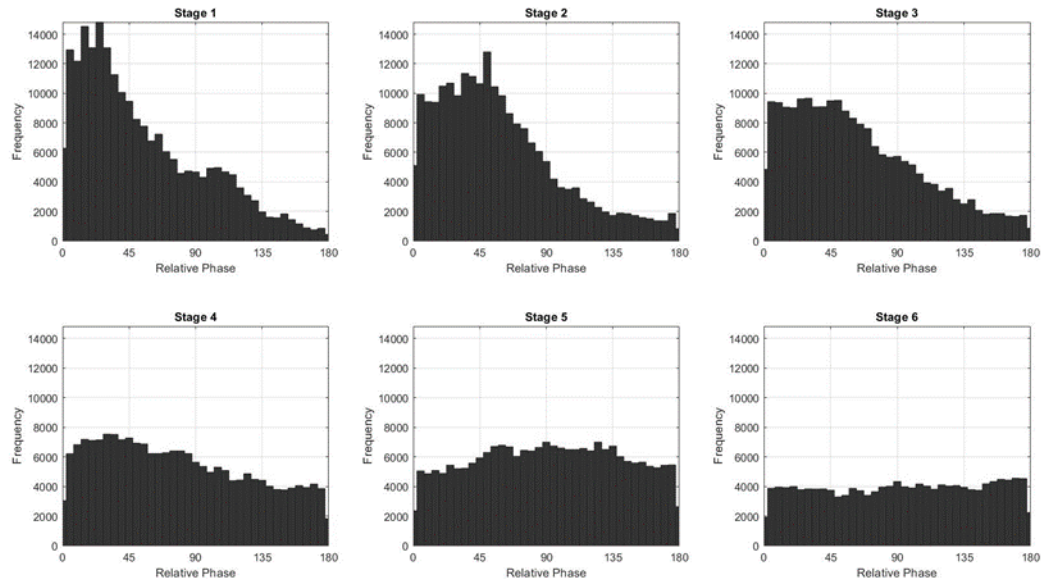


Figure 26 - Group steps phase distribution plot of in-phase BNM coupling.

Turning our attention to the anti-phase couplings, we can again see that the BDN (*Figure 27*) coupling has a more significant shift towards its intended relative phase (180°) compared to the others: BDM – 0° in-phase (*Figure 28*) and BNM – 180° anti-phase (*Figure 29*). Unlike the in-phase task, the anti-phase task was asymmetrically designed with the dominant limb achieving maximum flexion as the nondominant limb reaches maximum extension. This leads to the BDM’s relative phase distribution plot showing a shift towards 0° (in-phase). From the full task phase distribution plots, it is evident that the BDN coupling differs given its favouring of anti-phase. What still is not clear is what might be occurring in the metronome couplings. As the BDM coupling’s intended phase was in-phase, it is unclear why it did not differ from the theoretically less

stable BNM moving in anti-phase. Again, we move to analyze the step relative phase distribution plots.

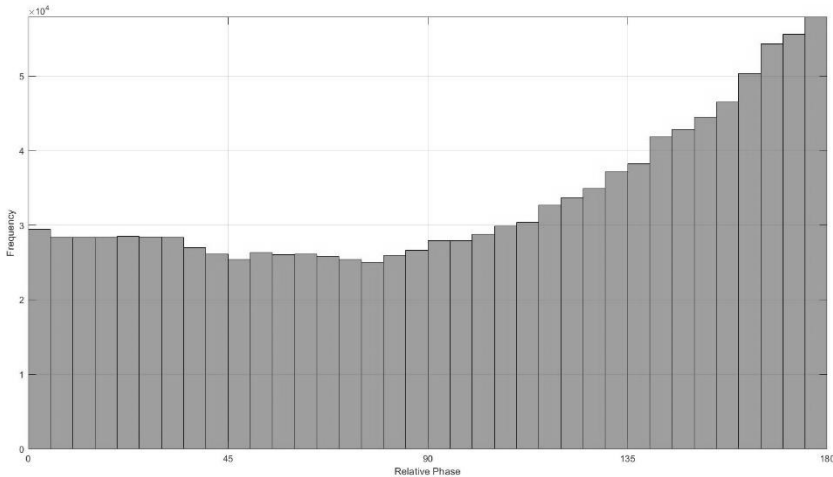


Figure 27 - Phase distribution plot of the anti-phase BDN coupling.

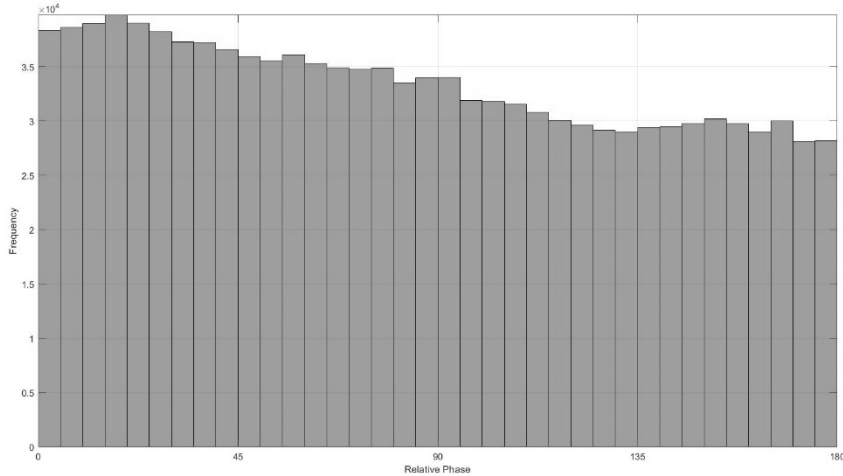


Figure 28 - Phase distribution plots of anti-phase BDM coupling. Note – For the anti-phase tasks, the dominant limb moved in-phase (0°).

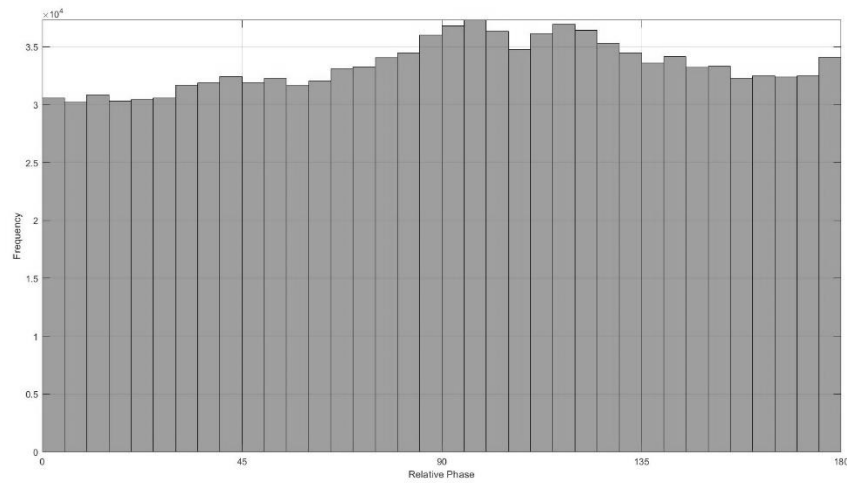


Figure 29 - Phase distribution plots of anti-phase BNM coupling. Note – For the anti-phase tasks, the nondominant limb moved anti-phase (180°).

Looking at the anti-phase step relative phase distribution plots, behavioural similarities and differences between the BDN (*Figure 30*) and metronome couplings (*Figures 31 and 32*, for BDM and BNM, respectively) become apparent. Comparing the BDN coupling first, again, we see a distinct favouring towards anti-phase for the first two Stages – with a noticeable decrease in anti-phase frequency during the second stage – but then demonstrates a running solution after that. This is in line with the HKB model predictions that the anti-phase task will inevitably destabilize with increased movement frequency. The smoothing and subsequent loss of anti-phase after Stage 2 are most likely caused by the limbs' inability to rely on the incoming information from each other: competitive movement information conflict. As the limbs were attempting to complete opposing tasks (flexion and extension), the information would oppose each

other and could lead to phase transitions if the limbs could not adjust their coupling strengths (a segregative characteristic).

This inability to segregate is evident in Stage 2 for both metronome couplings. In Stage 2, both limbs transition into a phase running solution with the metronome. This limited ability of the limbs to adjust its coupling strength further reinforces the results of hypotheses 2 and 3, demonstrating that the limbs may not have asymmetric control over their coupling strengths as asymmetric control would appear as one limb-metronome coupling maintaining the intended phase longer than the opposing limb-metronome coupling. However, both fall into a running solution in Stage 2, indicating that they may have an equal inability to adjust their coupling strengths.

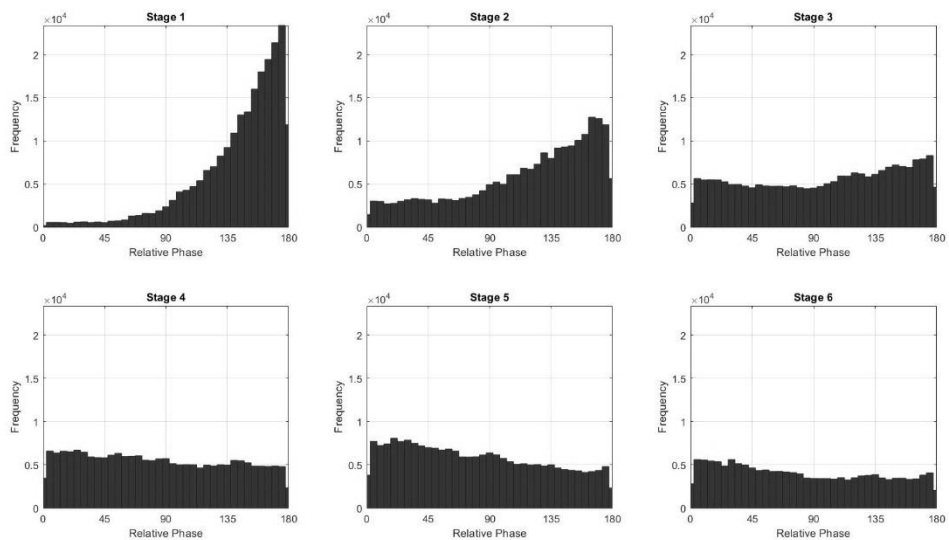


Figure 30 - Group steps phase distribution plot of the anti-phase BDN coupling.

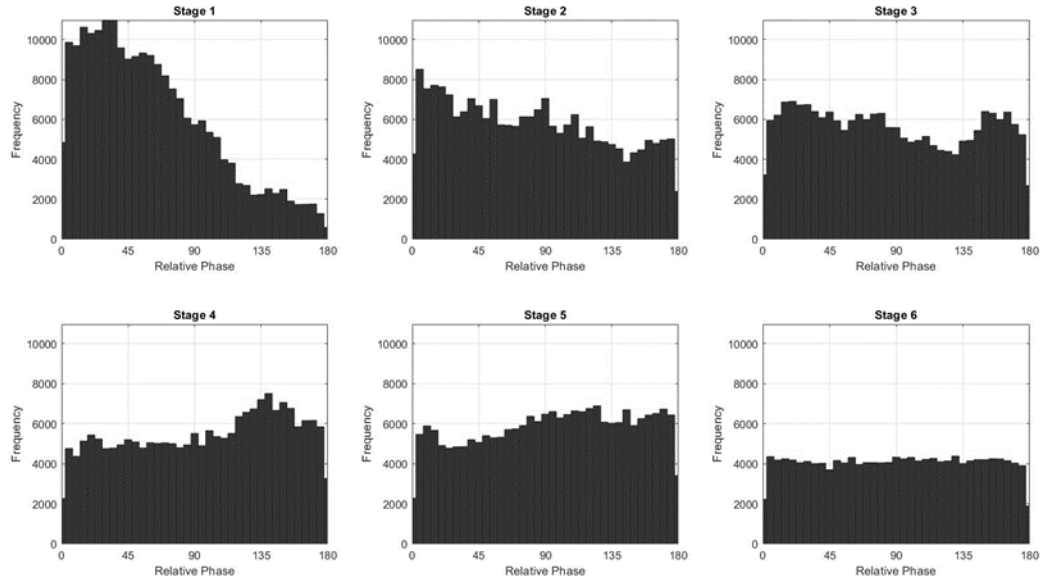


Figure 31 - Group steps phase distribution plot of the anti-phase BDM coupling.

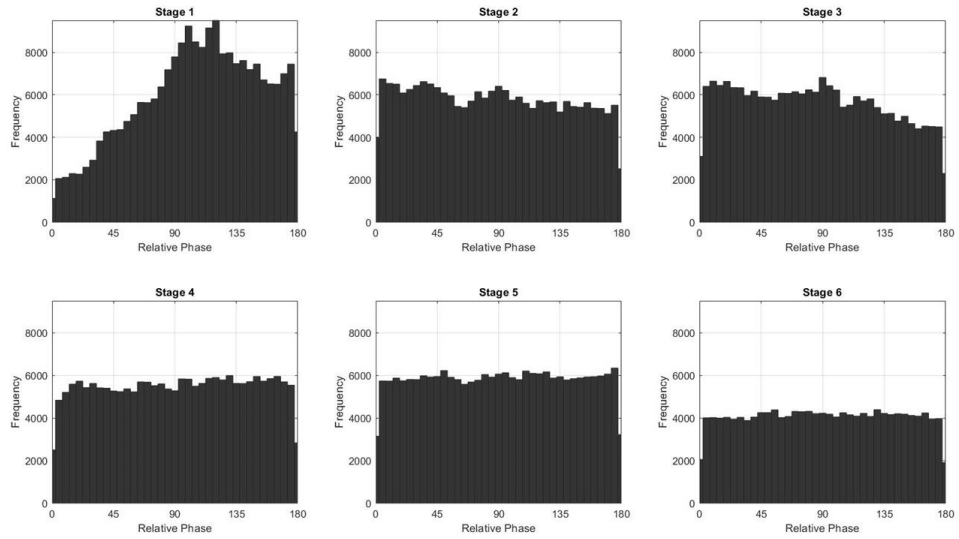


Figure 32 - Group steps phase distribution plot of the anti-phase BNM coupling.

Concerning the two-tiered model, the results do not align with the characteristics of a two-tiered model. Beginning with the BDN coupling results, they fall in line with how a single oscillator would behave, specifically, how it deals with in-phase and anti-phase tasks. For in-phase, a single oscillator would handle this easily as the information exchange would be cooperative (both limbs moving in the same phase relation), allowing the greatest task performance level (lower RPV). More importantly, the anti-phase task results also agree with a single oscillator model. As the information exchange was competitive, the single oscillator would not have the same neural resources as a two-oscillator model to maintain two distinct tasks. For a two-oscillator model to be supported, the anti-phase BDN coupling would have needed to display an increased ability to adjust for the presence of competitive information: maintaining the intended phase longer. However, the anti-phase BDN coupling produced the largest RPV compared to both the in-phase BDN and anti-phase metronome couplings.

The results of the metronome couplings variable, specifically the anti-phase coupling, also support the single-oscillator model. A single oscillator would be expected to have a decreased ability to asymmetrically adjust the coupling strengths are given that only one set of performance variables can be manipulated (a and b in *Equation 4*). The limbs would lose the intended relative phase faster than a two-oscillator model with two sets of performance variables to control (a and b , and c and d of *Equation 5*). Furthermore, it would be expected that a two-oscillator model's limbs would lose the intended relative phase depending on the ability to manipulate coupling strength, thus enabling a preferred pathway to maintain the relative phase longer. Given that this

asymmetric control was not present and that the anti-phase BNM coupling RPV did not differ from the anti-phase BDM coupling, the two-oscillator system is not supported. In general, further research will be needed to determine the effect of competitive movement information on different oscillator setups in the human CNS.

The final part of hypothesis 4 statistical analysis compared the difference in RPV between the couplings phase relations (In-phase vs anti-phase). The results indicate that phase relation affected RPVs of the BNM and BDN couplings; however, given the implemented corrections for family-wise error, the BDM coupling was nonsignificant but followed the lower RPV trend for in-phase. These results are expected, given the HKB model predicts that in-phase is more stable than anti-phase, thus producing a lower RPV. As this relates to the purpose of hypothesis 4 – identifying the dominant coupling – the results further support that the BDN coupling is dominant; in particular, how much phase relation affected performance. The $\hat{\psi}$ (the difference between test means, see Table 12) was greatest between the in-phase and anti-phase for the BDN coupling. This may indicate that it had the greatest susceptibility to the influences of phase relation. This falls in line with the effects of cooperative and competitive movement information discussed earlier. Given that the differences in cooperative and competitive movement information were found within tasks, it is not surprising that an effect also occurred between phase relations.

Limitations

Statistical Methodology

For the statistical methodology, limitations in statistical power are present due to the corrections for family-wise error. Moreover, we were unable to utilize a traditional parametric method due to assumption violations; thus, this non-traditional approach could be viewed as a limitation to the results' power.

Performance Metrics

In the study of chaotic systems, understanding the relationship between initial conditions and trajectory is paramount to predicting how a system will behave through time. However, this relationship is no simple task to formulate; given small differences in initial conditions, system trajectories may converge and diverge at various rates and reach substantially different endpoints. As such, predicting the effects of these inputs can be challenging to quantify. Lyapunov Exponents (LE) can quantify the dominant behaviour: precisely, by finding the largest LE. By knowing the system's dominant behaviour, we can determine if a system is genuinely stable or unstable.

In terms of this study, LE is the ideal metric to measure stability; thus, it directly measures a system's stability. Unfortunately, we were unable to produce valid results with this method. Specifically, when using systems of known stabilities – Duffing Equation – (Falanga, 2014), inaccurate LE values were calculated: steady-state system with positive LE and converging systems with positive LE values. Given the

unreliability of available methods of calculating LE and the primary researcher's limited skill in utilizing the essential mathematics, LE was not used. Due to this, stability itself was not measured in this study.

It is highly recommended for future works to identify adequate methods of calculating LE of biological time-series data. Having information regarding the tasks' trajectory would provide more information about the system beyond its movement variability. This is critical as two systems may differ in variability, but both be on stable trajectories. Thus, utilizing LE may provide different results to that of this study.

Summary

In summary, the results do not support the presence of multiple neural components at the spinal level. As the results could be explained through a two-tiered model (*Equation 5*), it is also possible to reason with a single component (*Equation 4*) at the spinal level. Given this conclusion, it is appropriate to favour the single oscillator model, given that it can provide the same results with the least number of assumptions (Occam's razor). However, a model describing the organization of the CNS must be able to address the issues of Peper et al. (2000), Becket al. (2002), and Peper et al. (2004) in which a single oscillator model was not able to account for the stochastic characteristics found in movement data. With this in mind, more work is required to determine if multiple organization levels are present, precisely, at the spinal level. Moreover, methodologies should be selected that provide a wide array of difficulty levels to ensure

that instability is introduced into the system and that the metrics directly measure the system's stability.

Conclusion

In conclusion, significant findings were only present for the fourth hypothesis (Coupling); in particular, the couplings between the limbs appeared to be most susceptible to the tasks having the lowest and highest RPVs for in-phase and anti-phase respectively. As for the other hypotheses, no significant difference was found for either preferred handedness (Hypothesis 1) or the number of hands used during the task (Hypotheses 2 and 3). As such, the results do not indicate the presence of a two-tiered model in the human CNS.

Bibliography

- Arshavsky, Y. I., Deliagina, T. G., & Orlovsky, G. N. (2016). Central Pattern Generators: Mechanisms of Operation and Their Role in Controlling Automatic Movements. *Neuroscience and Behavioral Physiology*, 46(6), 696–718.
<https://doi.org/10.1007/s11055-016-0299-5>
- Arya, K. N., & Pandian, S. (2014). Interlimb neural coupling: Implications for poststroke hemiparesis. *Annals of Physical and Rehabilitation Medicine*, 57(9–10), 696–713. <https://doi.org/10.1016/j.rehab.2014.06.003>
- Beek, P. J., Peper, C. E., & Daffertshofer, A. (2002). Modelling rhythmic inter-limb coordination: beyond the Haken-Kelso-Bunz model. *Brain and Cognition*, 48(1), 149–165. <https://doi.org/10.1006/brcg.2001.1310>.
- Beek, P. J., Peper, C. E., Daffertshofer, A., Dessain, P., & Windsor, L. (2000). Timekeepers versus nonlinear oscillators: how the approaches differ. *Rhythm perceptions and productions*, 9-33.
- Beek, P. J., Rikkert, W. E., & Van Wieringen, P. C. (1996). Limit cycle properties of rhythmic forearm movements. *Journal of Experimental Psychology Human Perception and Performance*, 22, 1077-1093.
- Berkowitz, A. (2019). Expanding our horizons: Central pattern generation in the context of complex activity sequences. *Journal of Experimental Biology*, 222(20).
<https://doi.org/10.1242/jeb.192054>
- Bernshteĭn, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

- Brainard, M. S. and Doupe, A. J. (2013). Translating birdsong: songbirds as a model for basic and applied medical research. *Annu. Rev. Neurosci.* 36, 489-517.
doi:10.1146/annurev-neuro-060909-152826
- Bressler, S. L., & Kelso, J. A. S. (2016). Coordination dynamics in cognitive neuroscience. *Frontiers in Neuroscience*, 10(SEP), 1–7.
<https://doi.org/10.3389/fnins.2016.00397>
- Brown, T.G. (1911). The intrinsic factors in the act of progression in the mammal. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*, 84, 308-319, doi: 10.1098/rspb.1911.0077
- Buchanan, J. J., Kelso, J. A. S., DeGuzman, G. C., & Ding, M. (1997). The spontaneous recruitment and suppression of degrees of freedom in rhythmic hand movements. *Human Movement Science*, 16(1), 1–32. [https://doi.org/10.1016/S0167-9457\(96\)00040-1](https://doi.org/10.1016/S0167-9457(96)00040-1).
- Bussel, B., Roby-brami, A., Azouvi, P. H., Biraben, A., Yakovleff, A., & Held, J. P. (1988). Myoclonus in a patient with spinal cord transection: Possible involvement of the spinal stepping generator. *Brain*, 111(5), 1235–1245.
<https://doi.org/10.1093/brain/111.5.1235>
- Calancie, B. (2006). Spinal myoclonus after spinal cord injury. *Journal of Spinal Cord Medicine*, 29(4), 413–424. <https://doi.org/10.1080/10790268.2006.11753891>
- Chen, C.-C., Kilner, J. M., Friston, K. J., Kiebel, S. J., Jolly, R. K., & Ward, N. S. (2010). Nonlinear coupling in the human motor system. *The Journal of*

Neuroscience : The Official Journal of the Society for Neuroscience, 30(25), 8393–9. <https://doi.org/10.1523/JNEUROSCI.1194-09.2010>

Daffertshofer, A. (1998). Effects of noise on the phase dynamics of nonlinear oscillators. *Physical Review E*, 58(1), 327.

Daun-Gruhn, S., & Buschges, A. (2011). From neuron to behaviour: Dynamic equation-based prediction of biological processes in motor control. *Biological Cybernetics*, 105(1), 71–88. <https://doi.org/10.1007/s00422-011-0446-6>

de Poel, H. J., Peper, C. (Lieke) E., & Beek, P. J. (2007). Handedness-related asymmetry in coupling strength in bimanual coordination: Furthering theory and evidence. *Acta Psychologica*, 124(2), 209–237. <https://doi.org/10.1016/j.actpsy.2006.03.003>

Dietz, V., Fouad, K., & Bastiaanse, C. M. (2001). Neuronal coordination of arm and leg movements during human locomotion. *European Journal of Neuroscience*, 14(11), 1906–1914. <https://doi.org/10.1046/j.0953-816X.2001.01813.x>

Duque, J., Davare, M., Delaunay, L., Jacob, B., Saur, R., Hummel, F., ... Olivier, E. (2010). Monitoring coordination during bimanual movements: where is the mastermind? *Journal of Cognitive Neuroscience*, 22(3), 526–42. <https://doi.org/10.1162/jocn.2009.21213>

Fink, P. W., Kelso, J. A. S., & Jirsa, V. K. (2009). Perturbation-induced false starts as a test of the jirsa-kelso excitator model. *Journal of Motor Behavior*, 41(2), 147–157. <https://doi.org/10.3200/JMBR.41.2.147-157>

- Forrester, L., & Whittall, J. (2000). Bimanual finger tapping: Effects of frequency and auditory information on timing consistency and coordination. *Journal of Motor Behavior*, 32(2), 176–191. <https://doi.org/10.1080/00222890009601369>.
- Glover, G. H. (2011). Overview of functional magnetic resonance imaging. *Neurosurg Clin N Am*, 22(2), 133–139. <https://doi.org/10.1016/j.nec.2010.11.001>.Overview
- Golowasch, J. (2019). Neuromodulation of central pattern generators and its role in the functional recovery of central pattern generator activity. *Journal of Neurophysiology*, 122(1), 300–315. <https://doi.org/10.1152/jn.00784.2018>
- Guertin, P. A. (2013). Central pattern generator for locomotion: Anatomical, physiological, and pathophysiological considerations. *Frontiers in Neurology*, 3 FEB(February), 1–15. <https://doi.org/10.3389/fneur.2012.00183>
- Haken, H. (1978). *Synergetics: An introduction: nonequilibrium phase transitions and self-organization in physics, chemistry, and biology*. Berlin: Springer-Verlag.
- Haken, H. (January 01, 1975). Cooperative phenomena in systems far from thermal equilibrium and in nonphysical systems. *Reviews of Modern Physics*, 47, 1, 67-121.
- Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A Theoretical Model of Phase Transitions in Human Hand Movements. *Biol. Cybern*, 51, 347–356. <https://doi.org/10.1007/BF00336922>

- Hughes, G. M., & Wiersma, C. A. G. (1960). The co-ordination of swimmeret movements in the crayfish, *Procambarus clarkii* (Girard). *Journal of Experimental Biology*, 37(4), 657-670.
- Jantzen, K. J., Steinberg, F. L., & Kelso, J. a S. (2009). Coordination dynamics of large-scale neural circuitry underlying rhythmic sensorimotor behavior. *Journal of Cognitive Neuroscience*, 21(12), 2420–2433.
<https://doi.org/10.1162/jocn.2008.21182>
- Kay, B. A., Saltzman, E. L., & Kelso, J. A. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 17(1), 183–197.
<https://doi.org/10.1037/0096-1523.17.1.183>
- Kay, B. A., Saltzman, E. L., & Kelso, J. A. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 17(1), 183.
- Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, Mass: MIT Press.
- Kelso, J. A. S., & Tognoli, E. (2007). Toward a complementary neuroscience: Metastable coordination dynamics of the brain. *Understanding Complex Systems*, 2007, 39–59. https://doi.org/10.1007/978-3-540-73267-9_3

- Kelso, J. A. S., DelColle, J. D., & Schöner, G. (1990). Action-Perception as a Pattern-Formation Process. *Attention and Performance XIII: Motor Representation and Control*, 139–169 Hillsdale, N.J: L. Erlbaum..
- Kelso, J. A. S., Dumas, G., & Tognoli, E. (2013). Outline of a general theory of behavior and brain coordination. *Neural Networks*, 37, 120–131.
<https://doi.org/10.1016/j.neunet.2012.09.003>
- Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: critical fluctuations. *Physics Letters A*, 118(6), 279–284. [https://doi.org/10.1016/0375-9601\(86\)90359-2](https://doi.org/10.1016/0375-9601(86)90359-2).
- Lamb, P. F., & Stöckl, M. (2014). On the use of continuous relative phase: Review of current approaches and outline for a new standard. *Clinical Biomechanics*, 29(5), 484–493. <https://doi.org/10.1016/j.clinbiomech.2014.03.008>
- Lorenz, E. N. (1963). Deterministic nonperiodic flow. *Journal of the atmospheric sciences*, 20(2), 130-141.
- MacKay-Lyons, M. (2002). Central pattern generation of locomotion: a review of the evidence. *Physical Therapy*, 82(1), 69–83. <https://doi.org/10.1152/jn.00056.2009>
- Meyer-Lindenberg, A., Ziemann, U., Hajak, G., Cohen, L., & Berman, K. F. (2002). Transitions between dynamical states of differing stability in the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, 99(17), 10948–10953. <https://doi.org/10.1073/pnas.162114799>

- Meyns, P., Bruijn, S. M., & Duysens, J. (2013). The how and why of arm swing during human walking. *Gait and Posture*, 38(4), 555–562.
<https://doi.org/10.1016/j.gaitpost.2013.02.006>
- Millieux, L., Calvin, S., & Temprado, J. J. (2005). Limiting the recruitment of degrees of freedom reduces the stability of perception-action patterns. *Human Movement Science*, 24(2), 218–233. <https://doi.org/10.1016/j.humov.2005.04.004>
- Mooney R. (2009). Neural mechanisms for learned birdsong. *Learning & memory* (Cold Spring Harbor, N.Y.), 16(11), 655–669. <https://doi.org/10.1101/lm.1065209>
- Nobili, R. (2009). New perspectives in brain information processing. *Journal of Biological Physics*, 35(4), 347–360. <https://doi.org/10.1007/s10867-009-9163-y>
- Peper, C. E., & Beek, P. J. (1999). Modeling rhythmic inter-limb coordination: The roles of movement amplitude and time delays. *Human Movement Science*, 18(2–3), 263–280. [https://doi.org/10.1016/S0167-9457\(99\)00011-1](https://doi.org/10.1016/S0167-9457(99)00011-1).
- Peper, C. E., Beek, P. J., & Daffertshofer, A. (2000). Considerations regarding a comprehensive model of (poly)rhythmic movements. In P. Desain & L. Windsor (Eds.), *Rhythm perception and production* (pp. 35–49). Lisse: Swets & Zeitlinger.
- Peper, C. E., Ridderikhoff, A., Daffertshofer, A., & Beek, P. J. (2004). Explanatory limitations of the HKB model: Incentives for a two-tiered model of rhythmic inter-limb coordination. *Human Movement Science*, 23(5), 673–697.
<https://doi.org/10.1016/j.humov.2004.10.007>

- Pollok, B., Gross, J., Müller, K., Aschersleben, G., & Schnitzler, A. (2005). The cerebral oscillatory network associated with auditorily paced finger movements. *NeuroImage*, 24(3), 646–655. <https://doi.org/10.1016/j.neuroimage.2004.10.009>
- Roby-Brami, A., & Bussel, B. (1992). Inhibitory effects on flexor reflexes in patients with a complete spinal cord lesion. *Experimental Brain Research*, 90(1), 201–208. <https://doi.org/10.1007/BF00229272>
- Rossignol, S., Dubuc, R., & Gossard, J. P. (2006). Dynamic sensorimotor interactions in locomotion. *Physiological Reviews*, 86(1), 89–154. <https://doi.org/10.1152/physrev.00028.2005>
- Russell, D. M., Kalbach, C. R., Massimini, C. M., & Martinez-Garza, C. (2010). Leg asymmetries and coordination dynamics in walking. *Journal of Motor Behavior*, 42(December 2014), 157–168. <https://doi.org/10.1080/00222891003697962>
- Sainburg, R. L. (April 01, 2015). Should the Equilibrium Point Hypothesis (EPH) Be Considered a Scientific Theory? *Motor Control*, 19, 2, 142-148.
- Schmidt, R. a. R. (1975). A Schema Theory of Discrete Motor Skill Learning. *Psychological Review*, 82(4), 225–260. <https://doi.org/10.1037/h0076770>
- Schneider, S., Askew, C. D., Abel, T., & Strüder, H. K. (2010). Exercise, music, and the brain: is there a central pattern generator? *Journal of Sports Sciences*, 28(12), 1337–1343. <https://doi.org/10.1080/02640414.2010.507252>

- Scholz, J. P., Kelso, J. A. S., & Schöner, G. (1987). Nonequilibrium phase transitions in coordinated biological motion: Critical slowing down and switching time. *Physics Letters A*, *123*(8), 390–394. [https://doi.org/10.1016/0375-9601\(87\)90038-7](https://doi.org/10.1016/0375-9601(87)90038-7)
- Schöner, G., Haken, H., & Kelso, J. a. (1986). A stochastic theory of phase transitions in human hand movement. *Biological Cybernetics*, *53*, 247–257. <https://doi.org/10.1007/BF00336995>
- Serrien, D. J. (2008). Coordination constraints during bimanual versus unimanual performance conditions. *Neuropsychologia*, *46*(2), 419–425. <https://doi.org/10.1016/j.neuropsychologia.2007.08.011>
- Serrien, D. J., & Sovijärvi-Spapé, M. M. (2015). Hemispheric asymmetries and the control of motor sequences. *Behavioural Brain Research*, *283*, 30–36. <https://doi.org/10.1016/j.bbr.2015.01.021>
- Shirakawa, T., Honma, S., & Honma, K. I. (2001). Multiple oscillators in the suprachiasmatic nucleus. *Chronobiology international*, *18*(3), 371-387.
- Tognoli, E., & Kelso, J. A. S. (2009). Brain coordination dynamics: True and false faces of phase synchrony and metastability. *Progress in Neurobiology*, *87*(1), 31–40. <https://doi.org/10.1016/j.pneurobio.2008.09.014>
- Tognoli, E., & Kelso, J. A. S. (2014). Enlarging the scope: grasping brain complexity. *Frontiers in Systems Neuroscience*, *8*(June), 122. <https://doi.org/10.3389/fnsys.2014.00122>

- Tognoli, E., & Kelso, J. A. S. (2014). The Metastable Brain. *Neuron*, 81(1), 35–48.
<https://doi.org/10.1016/j.neuron.2013.12.022>
- Treffner, P. J., & Turvey, M. T. (1995). Handedness and the asymmetric dynamics of bimanual rhythmic coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 21(2), 318.
- Treffner, P. J., & Turvey, M. T. (1996). Symmetry, broken symmetry, and handedness in bimanual coordination dynamics. *Experimental Brain Research*, 107(3), 463-478.
- von Holst, E. (1937). On the nature of order in the central nervous system. *Naturwissenschaften* 25, 625-631. doi:10.1007/BF01496490
- von Holst, E. (1973). *The Behavioural Physiology of Animals and Man, Volume One: The Collected Papers of Erich von Holst*. Coral Gables, FL: University of Miami Press.
- Wilson, D. M. (1961). The central nervous control of flight in a locust. *Journal of Experimental Biology*, 38(2), 471-490.
- Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Attention, Perception, & Psychophysics*, 14(1), 5-12.
- Zehr EP. (2004). Evidence for spinal CPG activity in the control of rhythmic arm movement. *Proc Physiol Can*. Forthcoming.
- Zehr, E. P., & Duysens, J. (2004). Regulation of arm and leg movement during human locomotion. *Neuroscientist*, 10(4), 347–361.
<https://doi.org/10.1177/1073858404264680>

Appendix

Informed Consent Form for Adult Participants

Research Title: Stability Analysis of Rhythmic Unimanual and Bimanual Wrist Coordination Tasks

Researcher: Troy Wilson, Faculty of Kinesiology, University of New Brunswick

Supervisor: Tim McGarry, Faculty of Kinesiology, University of New Brunswick

Introduction

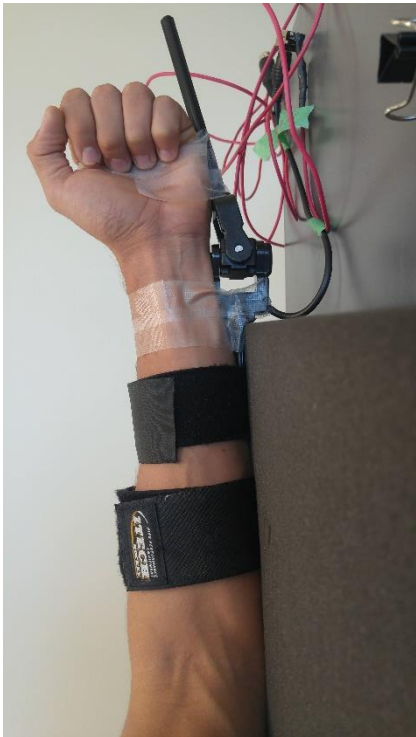
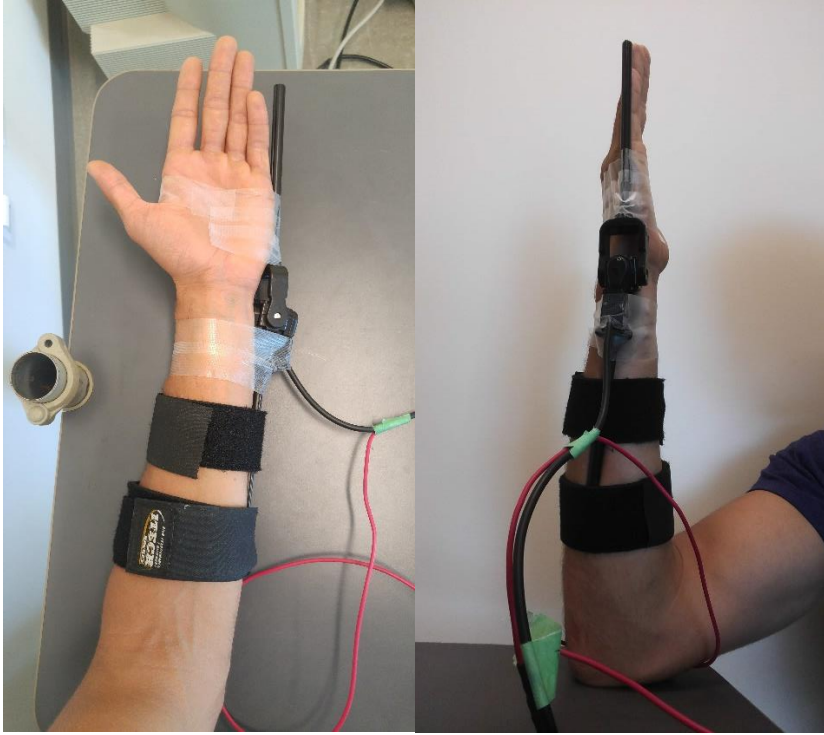
Hello, my name is Troy Wilson and I am a Graduate Student at the University of New Brunswick. I am completing research in the field of Motor Control and Learning; specifically, my research focuses are on how the human nervous system is able to coordinate movement. I will be providing you with information regarding how you can be a part my research. Feel free at any time to ask me questions if you are unsure of something in this document. As well, you have the right at any time to withdraw from the experiment with no consequences and all data pertaining to you will be destroyed.

Purpose of the Research

Movement, though common in everyday life, is an incredibly complex and intricate behaviour. Though many theories have been proposed to explain it, such as motor programs and muscle memory, they have failed to answer all of the questions associated with movement. The goal of my research is to further a theory of movement called *Coordination Dynamics Theory*. Not only does this theory provide solid grounds for how movement is created, but it also fills the holes left from other theories. The goal of this research is to further our understanding of this theory by means of testing different rhythmic coordination tasks to a metronome.

Type of Research Intervention

These tasks will require flexing and extending your wrist(s) to a metronome that increases in speed. During the tasks, the angle of your wrists will be recorded with an electricgoniometer (See pictures below); with this data and the metronome data, I will be to determine how your body controls your wrists during the tasks. Each task will last one minute with the speed of the metronome increasing every ten seconds.



Participant Selection

As I am interested in how the nervous system coordinates human movement, I need to ensure that there are no other contributing factors that may affect your ability to produce rhythmic wrist movements. Therefore, by selecting young individuals without neurological, hearing, or wrist impairments I am ensuring the data is the best representation of the target population; in this case, healthy individuals between the ages of 19 and 35.

Voluntary Participation

Your participation in the research is entirely voluntary and you have the choice to stop participating during any point of the experiment. No negative repercussions will follow if you choose to withdraw from the study; moreover, your data will be destroyed promptly.

Risk

For the risks involved in the experiment, they do not pose more than minimal risk as per Chapter 2, Section B of the Tri-Council Policy. The risks that are present include possible fatigue of the forearm, possible skin irritation from tape, possible skin irritation from straps, and marks left from the electric goniometer. The irritation of the skin may occur when removing the tape from the hands and wrist; as well, the straps and electricgoniometer may leave marks on the underside of your arms. These discomforts are temporary and should resolve themselves quite quickly (eg. Within 24 hours). It is my goal to ensure that you are as comfortable as possible during the experiment as this will not only ensure more accurate results but will ensure that this research must pose more benefit than risk to the participants.

As such, it is important to know of any allergies/sensitivities to tapes or materials; this will allow me to ensure that placement of the electricgoniometers will not lead to future discomfort.

Do you have any allergies/sensitivities to any adhesives or other materials?

Circle one: **Yes** **No**

If yes please inform the researcher to this sensitivity.

Benefits

The information that you provide will be used to further the research in the field of Coordination Dynamics and improve our understanding of how the human nervous system coordinates rhythmic movement. As well, this data will help set the foundation for my future research which aims to develop neurologically integrated prosthetics further.

Duration

The total length of the procedure should not exceed 30-45 mins. This time will consist of 16 minutes for the experiment itself with the other 14-29 minutes allotted to paperwork and experimental set-up.

Procedures and Protocol

Before the Trials Begin

- Your hand dominance will first be determined with the Modified Edinburgh Handedness Inventory (Milenkovic and Dragovic 2013).
 - This provides a better definition of hand dominance relative to simply asking which hand you prefer.
- You will then be fitted to the apparatus.
 - This will be done by either raising or lowering the seat and placing a mat under your forearms so that you may freely move your wrists without hitting the table portion of the apparatus.
- The electric goniometers will then adhere to the underside of your forearms so that the center of rotations of your wrists and the electric goniometers are aligned.

- Straps and tape will be used to anchor the electricgoniometers to the underside of your forearms.
- Before the electricgoniometers are fully attached, I will periodically ensure that the tape/straps are not interfering with your range of motion.
- You will then be given time to familiarize yourself with the different tasks.
 - This is to prevent any confusion during the experiment.
 - The metronome will also be provided during the practice trials.
- At this time during the set-up, feel free to inform me of any discomforts that may arise so that they can be addressed.

During the Trials

- You will complete each of the trails in a predetermined random order.
 - Right hand with the metronome on the beat
 - Left hand with the metronome on the beat
 - Right hand with metronome offbeat
 - Left hand with metronome offbeat
 - Both hands with the metronome on the beat
 - Both hands with one hand on the metronome on the beat and the other on metronome offbeat
- For the single hand trails, you will need to move the selected hand with the metronome on the beat (reaching maximum wrist flexion on the downbeat of the metronome) or on the metronome offbeat (reaching maximum wrist extension on the off-beat).
- For both hands conditions, you will need to move both hands with the metronome on the beat (both hands reaching maximum flexion to the beat of the metronome) or with one hand moving with the metronome on the beat and the other hand moving to the metronome offbeat (your dominant hand reaching maximum flexion and your non-dominant hand reaching maximum extension to the beat of the metronome).
- It is important that you try to maintain the tasks (on the beat or offbeat) for as long as possible.
 - If coordination is lost, continue the task to the best of your ability.
- Between each trial, you will be given 2 minutes break to prevent fatigue from affecting the next trial.
 - If, by the end of the 2 minutes, you still feel fatigued, another 2 minutes will be provided.

Confidentiality

All documentation linking your name to your data will be completely confidential; only I, Troy Wilson, and will be able to access any data linking your identity with your participation in the study or data. The data will be contained on my personal computer, which is password protected; moreover, your full name will not be used as a three-digit code will be used to identify your data (i.e. S01, S02, S03, etc.).

The code will be placed on your signed consent form and will not be labelled as an identifying code. Moreover, the signed consent forms will be locked in a cabinet in the Motor Control and Learning Lab, which only I will have access to. Any data containing your name will be destroyed after five years.

Sharing of Results

If you are interested in the outcome of the experiment, please provide your email below. This will not be given to anyone else and will only be used for sending you the results of the research. Moreover, I will not be sending out confidential information, only the data that would be published.

Email:

Right to Refuse or Withdraw

You have the right to withdraw from the study at any point in time and to have your data destroyed. In doing this, **you will suffer NO penalties or repercussions for withdrawing** from the study before, during, or after the experiment. Moreover, by agreeing to the terms of this experiment, **you have NOT waived any rights to legal recourse** in the event of research-related harm.

This project has been reviewed by the Research Ethics Board of the University of New Brunswick and is on file as REB 2018-121.

The REB is tasked to ensure that research participants are protected from harm that could occur as a result of participating in research at the university. If you wish to find out more information regarding the REB, you can contact them at 3 Bailey Drive, Sir Howard Douglas Hall, Rm 215, (506) 453-5189, ETHICS@unb.ca.

I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it, and any questions that I have asked have been answered to my satisfaction. I voluntarily consent to participate as a participant in this research.

Print Name of Participant: _____

Signature of Participant: _____

Signature of Primary Investigator: _____

Date: _____

DD/MM/YY

Modified Edinburgh Handedness Inventory (Milenkovic and Dragovic 2013)

Date: _____

Participant Code: _____

Data Collector: _____

This tool will be used to determine your hand preference; it is a modified version of the Edinburgh Handedness Inventory, which has been changed to remove problematic tasks, improve internal consistency and validity.

Indicate your preference of hand use for the following tasks:

Task	Strong Right	Slight Right	No Pref	Slight Left	Strong Left
Writing					
Throwing					
Scissors					
Toothbrush					
Knife					
Spoon					
Striking a match					
Total (T)					
T x Value	x 5	x 4	x 3	x 2	x 1
Handedness ([Total x Value]/7)					

Curriculum Vitae

Candidate's full name:

Troy Gregory Wilson

Universities attended:

University of New Brunswick, 2016

Bachelor of Science in Kinesiology Honours

GPA of 4.0

Conference Presentations:

UNB Kinesiology Research Day - 2016

UNB 3MT Competition – 2017

Academic Awards:

2012 – 13: 2 x Governor Thomas Carleton Scholarship

2012 – 2015: 6 x Purdy MacDonald Scholarship & Bursaries

2014 – 2015: 2 x New Brunswick Students Scholarships UNBF

2014 – 2018: 5 x CIS/U-sport Academic All-Canadian

2015 – 2016: 4 x Dr. Jed B. Sutherland Memorial Scholarship

2013 – 2016: Dean's List

2016: Graduate Research Award

2016: Graduate Teaching Assistantship

2017: Graduate Teaching Assistantship