

University of Alberta

The Effect of Mechanical Context on Attentional Cost in Unimanual Coordination

by

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Abstract

Nine right-handed participants performed rhythmic pronation and supination movements of the forearm in time with an auditory metronome. A secondary task, consisting of a pedal response to visual probe stimuli, was employed to infer the attentional costs of the coordination task. When the axis-of-rotation (AOR) was placed below the long axis of the forearm, the average time to react (RT) to the probe stimuli was greater for the supinate-on-the-beat condition than for the pronate-on-the-beat condition. Conversely, with the AOR above the forearm, RT for the pronate-on-the-beat pattern was greater than that for the supinate-on-the-beat pattern. Thus, the mechanical context of movement, which determines the neuromuscular configuration of the forearm, can alter the attentional cost of maintaining a coordination pattern in a forearm rotation task. This finding provides further evidence that the ease with which an action is performed by the sensorimotor system determines the attentional resources required to produce the movement.

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The Effect of Mechanical Context on Attentional Cost in Unimanual Coordination

A current perspective in the field of motor behaviour research proposes that sensorimotor coordination arises from the mutual interplay of constraints originating from various levels of description (Kelso, Fink, DeLaplain, & Carson, 2001). Constraints are factors that limit options or set boundaries for the system (Clark, 1995). An understanding of how constraints contribute to the emergence of goal-directed, coordinated movement is fundamental to the dynamic systems approach to motor behaviour. The dynamic systems approach emphasizes the physics of nonlinear dissipative systems as the basic explanatory tool for understanding the coordination and control of movement (Kelso, Holt, Rubin, & Kugler, 1980). From the dynamic systems perspective, constraints are essential for coordinated movement production because they function to reduce the number of variables in a movement system that must be controlled, and thus facilitate action by reducing top down regulatory requirements (Turvey, 1990). Stable coordination patterns emerge in a self-organized fashion from the cooperative coupling between components of a system.

It is likely that higher centers in the central nervous system contribute substantially to the production and maintenance of coordinated movements (Jirsa, Fuchs, & Kelso, 1998). A present challenge for movement scientists is to identify the mechanisms and principles through which the behavioural flexibility of voluntary movement arises from the interplay of higher-order planning elements and inherent system dynamics. A longstanding criticism of dynamic systems theory has been its inability to account for behavioural goal generation because of its rejection of the concept

of a central controlling mechanism or 'executive' (Aslin, 1993). However, several lines of research have shown that analysis of central nervous system (CNS) information processing activity can be incorporated into dynamical accounts of motor coordination.

Recent experimentation employing a novel combination of dynamic systems and information processing methods has addressed the role of intentional processes in the production of coordinated movement patterns. In a dual task paradigm, an inference of the attentional cost required for the execution a motor coordination task can be obtained from a performance outcome measure of a classical behavioural task, such as reaction time to a probe stimulus. In this context, attentional cost reflects the intensity of CNS processing activity necessary to maintain or stabilize a coordination pattern (Monno, Temprado, Zanone, & Laurent, 2002). The incorporation of higher-level influences, such as attention, with lower-level factors is an important step in accounting for the behavioural flexibility of the human sensorimotor systems. With this approach, it has been shown that the manipulation of certain constrains will affect the attentional cost of production of coordination patterns. Recently, two studies have demonstrated that the mechanical context of movement has an impact on the stability of unimanual coordination patterns (Byblow, Chua, & Goodman, 1995; Carson, Riek, Smethurst, Parraga, & Byblow, 2000). The primary aim of the current experiment was to determine if manipulation of mechanical context also influences the motor system at the relatively central level of attentional cost.

Coordination: The Degrees-of-Freedom Problem

One method of classification in the movement sciences groups problems into those concerning the *coordination* of a system's parts, and those that concern the *control*

of one part of a system by a higher-level component. The aim of understanding how the human control system manages to organize the cooperation of its many parts has developed into two lines of study. Neurophysiological approaches, often based on information processing theory, focus on the neural underpinnings of rhythmic and discrete coordination patterns, such as locomotion and bimanual coordination. The dynamic systems approach, on the other hand, is aimed at uncovering the equations of motion that govern movement. These two approaches should be considered complementary rather than mutually exclusive, and in recent years, there has been an emphasis on combining the two perspectives into a unified framework (Swinnen, Heuer, Massion, & Caeser, 1994).

A theme that has defined much of the motor coordination research of the past 30 years is the degrees-of-freedom problem. The Russian physiologist Nicolai Bernstein considered the essential problem of achieving coordinated behaviour to be the excess of independent dimensions that must be controlled concurrently by the motor system (Bernstein, 1967). This problem struck Bernstein as significant because of the apparent effortlessness of goal-directed behaviour in spite of the extreme complexity of the movement system (Turvey, 1990). The degrees-of-freedom of a system are the number of independent variables that are free to vary. In sensorimotor coordination, the relevant degrees-of-freedom are those that require individual control or regulation by a higher level of the system.

Degrees-of-freedom describe the number of options a system has for movement, and can be characterized at the level of joints, muscles, neural ensembles, or even individual cells. For example, each skeletal joint in the body is capable of motion around

one or more spatial axes; thus, the body consists of over 100 degrees-of-freedom when considering movement variables that arise exclusively from mechanical aspects of the anatomy (Turvey, 1990). The human arm, for example, has eight mechanical degrees-of-freedom, making it a redundant manipulator for motor tasks even at this low level of complexity. When analysis is shifted to a more microscopic perspective, the number of relevant degrees-of-freedom is compounded significantly.

Behavioural flexibility and degrees-of-freedom

From the perspective of the degrees-of-freedom problem, coordination is characterized as the process by which an individual constrains, or condenses, the available degrees-of-freedom into the smallest number necessary to achieve a movement goal (Abernethy & Sparrow, 1992). The existence of preferred modes of coordination (e.g. in-phase & anti-phase) and factors that limit the movement options of a system are ideal solutions to the degrees-of-freedom problem. However, behavioural flexibility necessitates that movements not always be carried out in an identical manner. If this were not the case, finely differentiated patterns of limb activity would not be possible.

Therefore, the flexible nature of action *requires* that there be excessive degrees-of-freedom available to the motor system. Although a system's degrees-of-freedom must be often be constrained or condensed to achieve task goals by reducing the system's options for motion, some degrees-of-freedom can later be re-released during task performance to provide flexibility and allow for more skilled coordinative actions (Turvey, 1990).

Bernstein proposed that process of skill acquisition involves learning to orchestrate the excess degrees-of-freedom ('freezing' and 'freeing') of the movement apparatus.

The control of the excess degrees-of-freedom of the motor system would present an extraordinarily complicated problem if a rigidly defined cortical mechanism (an executive) were required to direct the process of selecting, coordinating, and controlling all of the relevant degrees-of-freedom. However, it has been widely hypothesized that, rather than individual degrees-of-freedom, it is *actions* that are controlled by a cortical executive mechanism (R. A. Schmidt & Lee, 1999). The implication of this assumption is that the responsibility for bringing the relevant degrees-of-freedom into the task specific organization required for complex, skilled movements is shifted to a lower (more peripheral) level of the motor system. Because of differences in their underlying assumptions and in their focuses, the two prominent paradigms in the field of motor behaviour have differed in their success in resolving the degrees-of-freedom problem.

Information processing theory and degrees-of-freedom

The primary model used in the field of motor behaviour over the last half-century, the information processing perspective, is based on a computational metaphor of human functioning (see R.A. Schmidt & Lee, 1999 for a review). A central assumption of the information processing perspective is that prescriptive instructions, 'motor programs', from higher command centers provide templates for coordinated movements (Bingham, 1995). These symbolic knowledge structures stipulate the action that will take place when they are initiated by means of an intelligent executive (Newell, 1986). Motor programs are asserted to strongly influence the activity of the many independent degrees-of-freedom so they act as a single unit. However, the transfer of responsibility to a theoretical knowledge structure does not address how the various degrees-of-freedom are constrained. Whether an executive or a subordinate construct is required to control the

degrees-of-freedom of a system, production of even the simplest movements would require an extraordinary amount of calculation (Turvey, 1990). Despite its utility in many areas of motor behaviour research, the information processing approach has not been very successful in addressing the degrees-of-freedom problem.

Dynamic systems theory and degrees-of-freedom

Dynamic systems theory rejects computational solutions to the degrees-of-freedom problem and asserts that coordination emerges as a consequence of constraints that allow the system to self-organize in the most efficient manner possible. A central tenet of dynamic systems is that constraints, which are limiting boundaries/features, serve to eliminate certain possibilities for action (Clark, 1995). By stressing principles of self-organization and emphasizing the role limiting constraints, the dynamical approach adheres to the following requirements for a solution to the degrees-of-freedom problem: (a) minimize *the number* of variables to be individually regulated, (b) the number of executive instructions *per unit time*, (c) the number of executive decisions about *what type* of instruction to issue, and (d) the number of executive decisions about *when* to issue an instruction or command (Kugler, Kelso, & Turvey, 1980). The task specific limitations placed upon each component of the sensorimotor system by a coalition of constraints allow subsystems to function relatively autonomously, thus providing a framework for dealing with the degrees-of-freedom problem.

Dynamic Systems Approach: Overview

Dynamic systems is a multidisciplinary field of research aimed at understanding how organization and pattern arise in complex systems, independent of temporal scale and level of analysis (Kelso, 1995). This approach, also called synergetics (Haken, 1983),

has its origins in the physics of dissipative thermodynamics, and is concerned with how the many individual parts of systems cooperate to create novel spatiotemporal or functional structures (patterns) (Kelso & Haken, 1995). The application of the dynamic systems approach to the study of biological coordination is based on similarities between biological coordination and physical processes in which multiple components become self-organized. The goal of the dynamic systems approach is to uncover general laws and principles (the coordination dynamics) of biological coordination. These principles express the spatiotemporal relations between components of a system independent of the actual structural interactions (Fuchs & Kelso, 1994). Thus, rather than focus on understanding the properties of material objects, the dynamic systems approach is concerned with finding a minimum set of level-independent principles that can account for the production, maintenance of coordination patterns in complex systems. Because the dynamic systems perspective is primarily concerned with abstracting general organizational principles (essential features) of a system, the physical properties of a system are relevant only to the extent that they support or obstruct forms of organization (Kelso, 1992). The degree to which the anatomical and physiological aspects (structural constraints) influence or determine the resultant dynamics of a coordinative system has recently been a frequently debated topic in the literature (Kelso et al., 2001).

Pattern formation

Coordination is a product of the evolving process of self-organization, which is observable through the study of time-dependent pattern formation (Kelso, 1995). Understanding pattern formation requires knowledge of the parameters acting on a system, detailed information about the interacting component processes, and the patterns

or modes of coordination that emerge from the interaction between the processes and the environment (Fuchs & Kelso, 1994). In studying pattern formation one must have both essential information about a system (its current state), and a rule that describes how the state evolves with time (the dynamic) (Crutchfield, Farmer, Packard, & Shaw, 1986).

The first step to studying pattern formation is to identify the crucial variables that describe the relationship between the components of interest. Once appropriate variables are found, all consequences of the resulting theoretical formulation are then checked experimentally (Kelso, 1992). However, determining which variables are essential to a process is often difficult because movement forms, such as postural orientation and limb trajectories, are not constructed a priori, but emerge in response to the specific context in which a movement occurs (Sporns & Edelman, 1993). Because of this process of self-organization, coordination laws that capture the cooperative behaviour of a system cannot necessarily be inferred from the activities of its individual subcomponents of a system (Swinnen et al., 1994).

Identifying the appropriate essential variables allows the complex, high dimensional behaviour of a system to be reduced to a low dimensional description (Jeka & Kelso, 1989). In the language of dynamical systems, an essential variable that characterizes a coordination pattern is called a *collective variable* or order parameter. Plotting the time dependent values of a collective variable allows for the construction of the state space of a coordinative system. The collective state of the system at any point in time is represented as a point, and its temporal change (pattern) is represented as the point's trajectory in the state space (Robertson, Cohen, & Mayer-Kress, 1993). When a dissipative system is given time to settle down, it will arrange itself in a manner that

minimizes free energy, which results in its trajectory being preferentially drawn to certain portions of its state space. These equilibrium regions of a state space are known as dynamic attractors (Newell, Kugler, Van Emmerik, & McDonald, 1989).

Phase transitions

When a system, residing in a stable, preferred state, is perturbed, there are two possible outcomes. Small deflections of a trajectory that are not sufficient to take the system away from the current attractor will cause instability, but will not change the pattern of coordination. However, if a change in a critical parameter (e.g. movement frequency of limb oscillations) perturbs the system to a large degree, a qualitative transition to a different attractor may occur, which is often the only way the system can regain stability. These shifts between patterns are termed *phase transitions* (Kelso, 1984).

Variability in the motor system is a mechanism for the process of self-organization that underlies coordinative change, and is not considered to be superfluous noise (Newell & Slifkin, 1998). The instability in the system that induces the spontaneous (self-organized) shifts that occur between coordination patterns can be caused by many factors such as information processing limitations (Kelso, 1981; Kelso, 1984), energetic considerations (Hoyt & Taylor, 1981), or neural driving (Shik, Severin, & Orlovskii, 1966). Although not all behavioural changes occurs in this fashion, phase transitions can function as 'windows' into the basic organizational principles of pattern formation (Zanone & Kelso, 1992).

Dynamic Systems Approach: Sensorimotor Coordination

The application of the dynamic systems approach to research on sensorimotor coordination is important because it facilitates insight into the fundamental problem of

how the parts of the movement system are brought into an organized state to produce action without placing excessive responsibility on a rigidly defined cortical mechanism (Turvey, 1990). Coordinations in the motor system can be observed between or within limbs (behavioural level), between muscles acting at a common joint or between assemblies of neurons (neuromuscular level), or in the configuration of cellular and vascular activity (Turvey, 1990). Although the nervous system plays a large role in facilitating spatiotemporal organization at these levels, coordination dynamics have also been demonstrated in situations in which common neuronal pathways do not influence behaviour, such as in the coordinated actions between two or more people (R. C. Schmidt, Carello, & Turvey, 1990).

Interlimb coordination

Because the relationships between the components of a system are readily observable at the behavioural level, making it easier to extract the essential features of a system, much of the foundational work on the dynamics of sensorimotor coordination has been based on behavioural analyses of interlimb coordination tasks. Through the study of interlimb coordination tasks, coordinations can be observed in the patterning of body and limb motions relative to the patterning of environmental objects and events (Swinnen et al., 1994). Research on the organization and control of upper limb movements has received abundant attention because bimanual tasks can be very informative about the limitations of the central nervous system in dealing with the organization of more than one task at the same time (Swinnen et al., 2003).

In determining the dynamics of interlimb coordination, pattern formation is typically quantified by a measure of periodicity, such as the phase relationship between

two signals from oscillating components (e.g. limbs). Phase refers to the point of advancement of a signal within a cycle, or the current stage of periodic motion. The process of pattern formation is often formalized through dynamics of a variable called *relative phase*, which is defined as the phase difference between two oscillatory signals. Relative phase serves as a collective variable for the assessment of interlimb coordination because it characterizes the pattern of interest, which in bimanual coordination is the temporal relationship between the oscillating limbs (Robertson et al., 1993).

Recognition of relative phase as a collective variable facilitates identification of patterns of timing and spacing in coordinated movements that can be reliably maintained in the current context of movement. In this way, the number of variables that must be analyzed in order to describe a pattern of coordinated movement is greatly reduced. As well, the use of relative phase as a collective variable provides a measure of task performance, as achievement of a stable coordination pattern, and avoidance of phase transitions or high pattern variability, is considered a criterion for the acceptable execution of interlimb coordination tasks (Temprado, Zanone, Monno, & Laurent, 1999).

Early interlimb coordination research

Inspiration for the study of behaviour as pattern formation originated from research into simple rhythmic movements (Von Holst, 1973) and gait transitions (Hoyt & Taylor, 1981) in animals, but the seminal application of the phase transition based methodology to the study of human movement coordination was conducted by Scott Kelso (1981, 1984). In these tasks, subjects performed rhythmic oscillations of the hands (Kelso, 1984) or the fingers (Kelso, 1981) to match the tempo of an auditory metronome. Frequency of movement was used as a *control parameter* (no relation to control theory),

a factor that is capable of inducing changes in the movement system and driving it through its trajectory in the state space. Control parameters are similar to independent variables but are unique in that their values cannot be directly mapped onto a specific state of the system.

As the required frequency of oscillation increased, only two stable modes of coordination could be produced. These were an *in-phase* pattern, in which the phase relation between the limbs is 0° , and an *anti-phase* pattern, in which the phase relation between the limbs is 180° . It has since been well established that in the absence of any specific task requirements, in-phase and anti-phase are the only stable collective states toward which behaviour is spontaneously attracted (Zanone & Kelso, 1992). In general, no phase transitions will occur when the in-phase pattern is the target coordination state. Conversely, when the anti-phase pattern (or any other more complex pattern) is initially performed, an involuntary shift to the in-phase mode is normally observed as the cycling frequency increased. This switch between patterns corresponds to a non-equilibrium phase transition from a bistable (at 0 and 180 degrees) to a monostable (at 0 degrees) organization of the pattern dynamics. Because the in-phase pattern is the strongest attractor in the dynamics of interlimb coordination, when two limbs are moved simultaneously, there is a strong tendency toward synchronization. This coupling indicates that limb musculature is constrained to act as a single functional unit (coordinative structure) (Kelso, Southard, & Goodman, 1979).

The existence of inherent stable coordination patterns is not limited to bimanual movements; the intrinsic dynamics of the motor system have been shown to apply widely across conditions and are relatively independent of specific physiological

implementation. The pattern formation approach has been demonstrated in coordinations between many different anatomical structures at different levels (e.g. behavioural, electromyographical, neuronal) of the motor system (Jirsa et al., 1998; Kelso et al., 1998). For example, phase transitions have been demonstrated to be a mechanism of behavioural change in flexion and extension movements of the wrist and elbow of one arm (Buchanan & Kelso, 1993), ipsilateral and contralateral coordination of an upper and lower limb (Baldissera, Cavallari, & Civaschi, 1982; Baldissera, Cavallari, Marini, & Tassone, 1991), rotation of the distal upper limb (Byblow et al., 1995), and coordination of leg movements in two different people (R. C. Schmidt et al., 1990). Continuous oscillatory movements have been the primary focus of dynamics, but analysis is not restricted to periodic motion, as coordination dynamics have been shown to apply to the maintenance of posture and to discrete movements (Saltzman & Kelso, 1987; Schoner, 1994). That the same laws of coordination apply in many contexts and at different levels of analysis provides strong evidence for a dynamical conceptualization of motor coordination (Kelso et al., 2001).

Constraints

A central tenet of dynamic systems theory is that coordination emerges as a consequence of the constraints imposed upon a system. Constraints can be defined as limiting boundaries or features that restrict the motion of the system under consideration (Clark, 1995). Actions are not caused by these constraints, but rather some actions are excluded by them (Kugler et al., 1980). The presence of limiting constraints reduces the number of degrees-of-freedom to be controlled, which functions to reduce or eliminate the load of intelligence to an executive subsystem (Turvey, 1990). Non-intelligent

cooperation of the complex, interdependent components of a system allow patterns to emerge without each subsystem requiring independent specification and control. Thus, the laws and principles that govern coordination are not rigidly fixed, but are soft assembled in response to the existing coalition of constraints (Monno, Chardenon, Temprado, Zanone, & Laurent, 2000).

Constraints affecting coordination originate from the characteristics of a task performer, the surrounding environment, and the required motor task (Newell, 1986). These three elements are interconnected but distinct, meaning that they are causally related but cannot be reduced to one another (Bouffard, Streat, & Davis, 1998). The specific context in which movement takes place determines which constraints are of greater or lesser importance in delimiting degrees-of-freedom and determining the relative stability of movement patterns.

Some constraints are relatively simple, such as the anatomical structure of the body. Other constraints are less tangible and arise from complex interactions between components of the movement system. For example, movements that require the synchronization of flexion with the beat of a metronome are more easy to perform than those that require extension to be performed on the beat, presumably because of the differences between activation patterns of flexor and extensor muscles (Carson, 1996). Some constraints are relatively permanent while others are transient. Constraints that are enduring compared to the phenomena of interest are identified as structural constraints, while those that are more temporary are considered to be functional constraints (Kugler & Turvey, 1987). An important example of a functional constraint is oscillation

frequency during interlimb coordination tasks, which is often used as a control parameter to force the system to move between its collective states.

Structural constraints

There has been substantial debate in the literature about the extent to which general principles and laws of movement can be derived without reference to anatomical and physiological mechanisms (Kelso, 1995). The strategy of isolating the role of various constraints on coordinated movement has been shown to be both useful, in that it allows for the identification of factors responsible for pattern formation, and problematic, because it can lead to false dichotomies and radical reductionism (Kelso et al., 2001).

One perspective suggests that the stability of coordinated movements is exclusively regulated by fundamentally abstract, context-specific, informational quantities (Kelso, 1994). This point of view is based largely on findings that suggest that salient relationship in interlimb coordination is between movement landmarks and external events. For instance, when required to synchronize the peak flexion of the index finger either on or off the beat of an auditory metronome, the flex-off-the-beat pattern became unstable at high frequencies (Kelso, Delcolle, & Schoner, 1990). Such results are cited as proof that actions are planned in terms of abstract spatial relations, independent of their biological or physical implementation.

However, there is also strong evidence suggesting that the stability of coordination is profoundly influenced by the specific neuromuscular-skeletal configuration with which movements are generated. When flexion or extension movements of the index finger are synchronized with a metronome, transitions from extension-on-the-beat to flexion-on-the-beat patterns occurred at high movement

frequencies (Carson, 1996; Carson et al., 2000). This preference of flexors over extensors provided evidence that anatomical factors are a principle determinant of the stability of coordination (Carson, Chua, Byblow, Poon, & Smethurst, 1999).

Postural changes during bimanual or unimanual movements can also substantially influence pattern stability. In a 1993 study, Buchanan & Kelso showed that changes in posture could induce a loss of stability during rhythmical coordination of flexion and extension of the ipsilateral elbow and wrist. Depending on the position of the forearm (supine or prone), participants either simultaneously coordinated wrist flexion with elbow flexion (in-phase pattern) or wrist flexion with elbow extension (anti-phase pattern). Starting in either pattern, subjects rotated the forearm in 20 degree steps producing 15 cycles of in-phase or anti-phase motion at each step. The transitions that occurred between the two patterns were dependent on the direction of rotation and on the posture of the forearm, indicating that structural constraints played a significant role in determining the stability of coordination patterns.

Results such as these support the idea that both informational constraints and structural constraints originating from the anatomical properties of the motor system can profoundly affect the stability of coordination patterns. Therefore, a likely resolution is that these two perspectives should not be viewed as mutually exclusive; the laws governing the coordination of movement cannot exist without structures upon which they can be expressed. This implies that consideration of both general mathematical laws and biology-specific movement constraints is essential in the attempt to understand the principles of sensorimotor coordination (Kelso et al., 2001).

Mechanical context

The mechanical context of movement refers to the conditions in which muscles operate, such as their length and line of action. Mechanical context can strongly influence pattern stability. In forearm rotation tasks, which have often been used to study bimanual and unimanual coordination, participants grip the handle(s) of a joystick and alternately pronate and supinate their forearm(s). Changing the location of the external axis-of-rotation (AOR) in relation to the long axis of the forearm is one method of conveniently manipulating mechanical context.

It has been shown that manipulation of the position of the axis-of-rotation can alter the stability of bimanual or unimanual coordination patterns. While investigating bimanual asymmetry of coordination dynamics, Byblow et al. (1995) observed that when the AOR was situated below the long axis of the forearm, pronation movements synchronized with an external signal were more stable than those in which supination coincided with the signal. Carson et al. (2000) replicated this finding and expanded on it by establishing that supination-on-the-beat was the more stable pattern when the AOR was placed above the long axis of the forearm. As well, the stability of the pronation and supination patterns of movement were correlated with the degree of engagement of flexor carpi radialis, which was strongly activated during pronation when the AOR was below the long axis of the forearm, but not when the AOR was above the forearm. Carson et al. (2000) suggested that the altered activation profile of forearm flexors provided a neurophysiological basis for the greater stability of pronation-on-the-beat movements when the AOR was below the forearm.

The aforementioned findings from the Byblow et al. (1995) and Carson et al. (2000) studies supply evidence that changes in mechanical constraints influence the stability of coordination patterns during rhythmic limb movements. As well, the sensitivity of the neuromuscular system to changes in limb orientation observed in the Carson et al. (2000) study indicates that the position of the AOR may affect the amount of central nervous system involvement necessary to stabilize a movement pattern. Therefore, the degree to which the manipulation of the mechanical context of movement affects the higher level planning elements of coordination patterns remained a pertinent question that was addressed in the present study.

Central Contributions to Coordination

Both the dynamical properties of the motor system and the central processing cost of skilled task performance have been thoroughly investigated. Although often explored from an information processing perspective, central influences have not been prominent in dynamical accounts of coordination due to the emphasis placed on the functional independence of motor subsystems. This neglect has been perceived as a critical deficiency of dynamic systems theory (Aslin, 1993). Recently, consideration has been given to addressing this limitation by showing how higher influences, such as attention and intention, can modify the stability of spontaneous coordination dynamics between oscillating limbs.

Studies have shown that, with volitional input, it is possible to enhance or override the existing inherent dynamics of the system. Intentional influences can result in a switch between preferred coordination patterns (Carson, 1996; Scholtz & Kelso, 1990), delay or inhibition of transitions between patterns (Lee, Blandin, & Proteau, 1996), and

permanently stabilize a unique coordination pattern (Fontaine, Lee, & Swinnen, 1997). Thus, it is likely that the higher centers in the CNS play a significant role in producing and stabilizing coordination patterns. To explore the influence of higher influences from another perspective, several lines of research have addressed the connection between central processing cost and peripheral coordination dynamics. In particular, some researchers have used a dual task methodology to address the role of CNS processing activity in the production of simultaneous tasks that require the concurrent allotment of attentional resources.

Dual task experiments and attentional cost

Attention is often considered a mediator that distributes energetic resources (Navon, 1984) or effort (Kahneman, 1973). Attentional cost/load is regarded as a dedicated measure of such energy or effort (Monno et al., 2002). An operational assessment of the association between peripheral dynamics and central cost can be accomplished using a dual-task paradigm. The tradeoff in performance between two simultaneous tasks provides an inference of the attentional cost required to avoid a drop-off in task performance. Attention represents the intensity of CNS processing activity necessary for the maintenance of a coordination pattern (Zanone, Temprado, & Monno, 1999). In a dynamic systems version of a dual-task experiment, a primary coordination task is combined with a classical behavioural measure, such as simple reaction time (RT). Traditionally used to study skilled performance from the information processing perspective, reaction time can be utilized to infer processing requirements of the primary task. In this way, the attentional resources required for maintaining and stabilizing

coordination patterns can be assessed at a macroscopic level using a simple behavioural measure (Monno et al., 2002).

Through this approach, the characterization of coordination from both a dynamical perspective, assessed through stability measures, and an information processing perspective, assessed through attentional load measures, can be combined into one experimental design. An assumption required for use of the dual task method is that there exists a limited attentional capacity that can be distributed amongst concurrent tasks. If the difficulty of one task increases and requires more attentional resources than are available, less of the capacity will be allocated to the other task, resulting in a decline in secondary task performance (R. A. Schmidt & Lee, 1999). Another requisite assumption of this approach is that attention is not linked to a single cortical entity, but involves a finite set of brain processes and structures that mutually interact to generate the performance of coordinated movements (Monno et al., 2002).

Coordination dynamics and attentional cost

Significant attentional cost can be incurred in the process of maintaining coordination patterns. Using the dual task method described above, Zanone et al. (1999) compared the attentional cost of producing in-phase and anti-phase patterns of interlimb coordination. The main finding of this experiment was that RT for pressing a button was faster during performance of the (more stable) in-phase pattern than during performance of the (less stable) anti-phase pattern of coordination. Furthermore, when participants were instructed to focus their attention to either one of the tasks, the following trade-off between pattern stability (variability of relative phase) and reaction time occurred. When attention was directed to the anti-phase coordination task, performance of the

coordination task improved, while performance in the RT task worsened. Conversely, when attention was directed to the RT task, performance of the coordination task deteriorated, while performance on the RT task was enhanced. This finding was significant because it demonstrated that the attentional cost of maintaining coordination patterns could be inferred from chronometric measures.

Several other studies have extended on the Zanone et al. (1999) finding to further delineate the relationship between coordination dynamics and attentional cost. Monno et al. (2000) demonstrated that an increase in pattern stability resulting from increased attentional focus on the coordination task significantly delayed transitions from the anti-phase to the in-phase pattern. Similarly, Pellecchia & Turvey (2001) varied the intricacy of a cognitive task and found that the degree of central involvement required to maintain in-phase and anti-phase patterns was proportional to the level of difficulty of the cognitive task. The attentional demand of voluntary movement has also been shown to be sensitive to changes in wrist posture. Orientation of the wrist during flexion and extension of the index finger altered the RT for pedal responses to a probe stimulus (Carson et al., 1999).

In a 2001 study, Zanone, Monno, Temprado, & Laurent found that increasing oscillation frequency of required movement patterns in bimanual coordination task altered the stability of both bimanual coordination (variability of relative phase) and attentional cost (reaction time) in a similar manner. Pattern variability increased in a quadratic fashion as oscillation frequency increased, indicating that movement patterns have a preferential frequency at which they are most stable. This contrasted original

dynamical models (i.e. Haken, Kelso, & Bunz, 1985) that predict low frequencies of oscillation should be the most stable

The findings reported here are noteworthy because they provided a conceptual link between attentional load, which is typically evaluated within the framework of information processing, and coordination dynamics, evaluated within the theoretical framework of optimized self-organization. The correspondence between the variability of a coordination pattern and the attentional resources required for movement production indicates that a compromise exists between pattern stability and central cost, and that these two parameters may share common dynamical underpinnings.

Inertial constraints and attentional cost

If pattern stability and central cost are linked dynamics, factors (constraints) that affect pattern stability should also alter the attentional demands required to stabilize coordination patterns. However, manipulation of inertial constraints has been shown to have no impact on the attentional cost of maintaining task performance during bimanual coordination. The addition of a 0.5 kg mass to the distal end of joysticks destabilized bimanual patterns of forearm rotation but did not affect reaction time (Temprado, Chardenon, & Laurent, 2001). This result was unexpected because it was predicted that a change in attractor layout induced by an increase in rotational inertia should increase both the attentional demands of movement and pattern variability (Monno et al., 2000).

It is possible that changes to the pendular dimensions of a limb do not affect central processes because they influence coordination dynamics at a more peripheral level than other structural constraints. This idea was supported by Swinnen, Dounskaia, Levin, & Duysens (2001), who, upon noting that limb interference did not occur with the

alteration of biomechanical constraints, suggested that force specification occurs at a relatively low level of the motor system and can be easily dissociated between effectors. However, because of the limited consideration that has been given to the relation of biomechanical constraints and attentional cost, further research is necessary to determine the extent to which changes to structural constraints affect the central levels of the motor system.

Summary

A main challenge for movement scientists is to gain an understanding of the fundamental processes that allow biological systems to produce the wide range of functional responses of which they are capable. The dynamical approach to coordination has supplied a robust methodology for accomplishing this goal through the analysis of phase transitions in human movement coordination. However, because of limitations to both dynamical and computational approaches to motor behaviour, a complete theory of coordination is unlikely to arise from exclusive consideration of either perspective alone, and a combination of methods is almost certainly necessary for future study of sensorimotor coordination (Van Gemmert & Van Galen, 1997). With the incorporation of classical information processing measures into a dynamical approach, connections between movement constraints and central mechanisms have become clearer, allowing for a more complete description of the features of coordinated movement.

Research on the interplay of attention and coordination dynamics has been limited and there remain relevant questions concerning this issue that have not been addressed. The intention of this study was to expound upon one such problem. The effect of the mechanical context of movement on the attentional cost of producing rhythmic

coordinated movements was an unexplored issue of potential theoretical relevance. Differences in forearm muscle activation profiles caused by changing the position of the AOR has indicated that the neuromuscular system is sensitive to changes in mechanical context (Carson et al., 2000), but the relationship between mechanical context and the cost incurred by the CNS in maintaining a coordination pattern had not been studied explicitly.

Purpose

The primary aim of the current experiment was to determine if manipulation of the mechanical context of movement influences the motor system at the relatively central level of attentional cost. Specifically, would changing the position of the axis-of-rotation during a forearm rotation task alter the time required to respond to a visual probe stimulus. A secondary aim was to replicate previous results regarding the effect of mechanical context on pattern stability. To address these issues, this study used a classical dual-task paradigm combining a unimanual coordination task with a probe reaction time task.

Method

Participants

Nine volunteers (7 males and 2 females; mean age 31.8 years) with normal or corrected normal vision participated in the study. Recruitment took place in agreement with the University of Alberta procedures for the ethical treatments of human participants as approved by the Faculty of Physical Education and Recreation Research Ethics Board. Participants were able-bodied and free of apparent musculo-skeletal injury to the upper or lower limbs. The final criteria for inclusion in the study was based on right-handedness, which was evaluated with a modified (six item) version of the Crovitz handedness inventory (see Appendix A) (Bryden, 1977).

Apparatus

A custom-built manipulandum was used to register pronation and supination movements of the forearms (see Figure 1). The manipulandum consisted of a vertical bar (length six inches, diameter one inch) that was held in a relaxed four-finger grip and a second vertical bar fixed to a rotating horizontal shaft. The height of the shaft was altered to change the position of the axis-of-rotation. The two adjustable heights of the AOR were 2.5 inches above the long axis of the forearm, and 2.5 inches below the long axis of the forearm. The orientation of the manipulandum in the frontal plane was recorded with a potentiometer and digitized at a sampling rate of 1000 Hz. Participants were seated in such a way that they were able to grip the apparatus with their elbow at approximately 90 degrees of flexion. The right forearm was secured on top of padded wooden blocks with a Velcro strap to restrict the movement of the forearm to rotation around its long axis.

Pedal responses to a visual probe were obtained from a force sensitive resistor (FSR) sampling at 1000 Hz, which was located under that ball of the left foot.

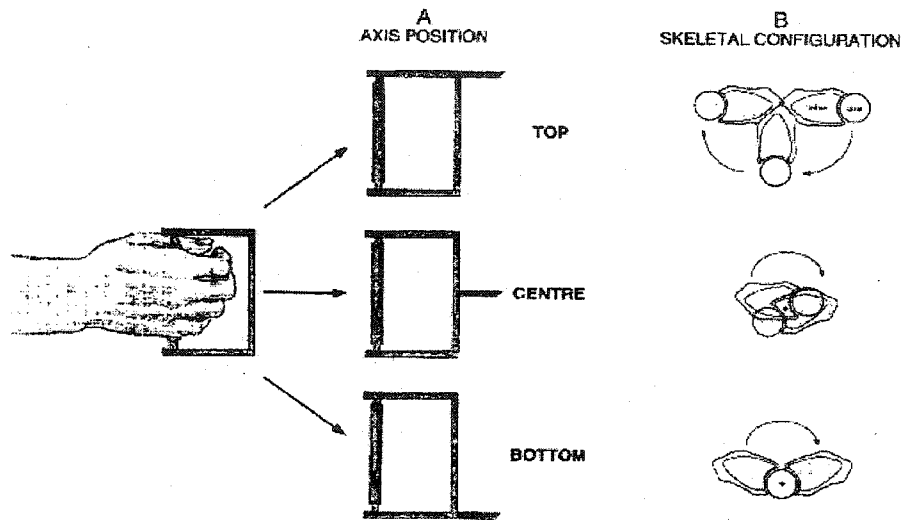


Figure 1. Manipulandum and forearm configurations during pronation-supination. A) In the Top configuration, the external AOR is above the long axis of the forearm. In the Bottom configuration, the external AOR is below the long axis of the forearm. B) Skeletal configuration of the distal radius-ulna joint during pronation-supination movements for the two AOR conditions. Adapted from Carson et al. (2000).

The pacing signals (auditory metronome) for the coordination task were presented through a tone generator (50ms duration) placed approximately one meter in front of the subject. A computer-generated image (5cm x 5cm white square) of 100 ms duration positioned directly in the participants' line of sight functioned as a visual probe stimulus. Outputs from each facet of the experiment were captured using an Optotrak Digital Acquisition Unit (ODAU). Presentation® software (Version 0.70, www.neurobs.com) was used to produce the stimuli, control timing of experimental events, and trigger data

collection on the ODAU. All testing took place in the Perceptual Motor Behaviour Laboratory, located within the Van Vliet Centre on the University of Alberta campus.

Procedure

The primary task of the experiment was to synchronize either the maximum pronation or maximum supination phase of movement with the beat of an auditory metronome. The secondary task was to respond to a visual probe by pressing a foot switch. A pedal response to a visual probe stimulus was employed instead of an upper limb response to reduce the potential for within-modality competition which was not the focus of the study (Duncan, Martens, & Ward, 1997).

Participants performed oscillatory rotation of the right forearm in one of two modes of coordination, pronate-on-the-beat or supinate-on-the-beat. In the pronate-on-the-beat condition, participants synchronized maximum forearm pronation with the beat of the metronome. When the arm is extended horizontally, a pronated position is one in which the forearm is rotated so that the palm faces down. Likewise, in the supinate-on-the-beat condition, participants attempted to match maximum forearm supination (forearm rotated so that the palm faces up) with the metronome signal. In addition, there were two axis-of-rotation conditions, either above or below the long axis of the forearm. To complete the required coordination task successfully, one full cycle of movement (i.e. pronation to supination to pronation) was to be completed for each beat of the auditory metronome while maintaining the prescribed mode of coordination for the trial.

The frequency of the auditory metronome used in experimental trials was individually determined in preliminary trials for each participant. After participants were given a chance to briefly practice timing their movements with the metronome, a series of

30-second trials was conducted in which participants performed a supinate-on-the-beat pattern with the AOR below the forearm, starting at a frequency of 1.5 Hz. If a participant was able to maintain the pattern throughout the trial, frequency increased by 0.25 Hz for the next trial. However, if there was evidence of loss of stability (phase transition or elevated pattern variability), the frequency did not change for the next trial. The critical pacing frequency (CF) was defined as the frequency at which participants failed to adequately maintain the required coordination pattern for three consecutive trials (Carson et al, 1999).

After a five-minute rest period, experimental trials began. Trials were blocked for AOR position, and within each block, alternated between pronate-on-the-beat and supinate-on-the-beat patterns. This resulted in 16 trials (8 per condition) in each block, for a total of 32 trials. The order of block presentation and the initial coordination pattern were counterbalanced across participants. A five-minute rest period was given between blocks of trials and short breaks with a trial block were permitted upon the request of a participant.

Experimental trials were 70 seconds in duration. The frequency of movement for each trial was held constant at 0.1 Hz above CF ($TF = CF + 0.1\text{Hz}$). This was done to ensure that the task demands of maintaining a coordination pattern were of sufficient difficulty; individuals are capable of sustaining patterns of coordination at movement rates above their normal transition frequency with a cost to other dimensions of the task (Lee et al., 1996). Eight visual probes were presented at pseudo-random intervals (seven to nine seconds apart) throughout each trial to prevent anticipatory responses.

Participants were instructed to react as quickly as possible to the visual probes by pressing on a force sensor beneath their left foot, and to attempt to maintain the required coordination pattern at the metronome frequency throughout the trial. Participants were also told to attempt to share attention (effort) between the coordination task and the RT task; that is, they were to attempt to perform as well as possible on both tasks and not to exclusively focus on either task alone.

Data Reduction

A power spectrum analysis of the displacement time series revealed that the frequency distribution was predominantly below 4 Hz. Based on an absence of any significant higher frequency components of the potentiometer signal, it was determined that low-pass filtering would not be required (see Figure 2). A custom MATLAB analysis program calculated the instantaneous relative phase relation between the positional data series and the pulses from the auditory metronome. Conversion of the metronome pulse series allowed for the alignment of peaks of the cosine function with the onsets of the metronome pulses. The instantaneous phase of the analytic signal was used to provide an estimate of the continuous phase of each data series.

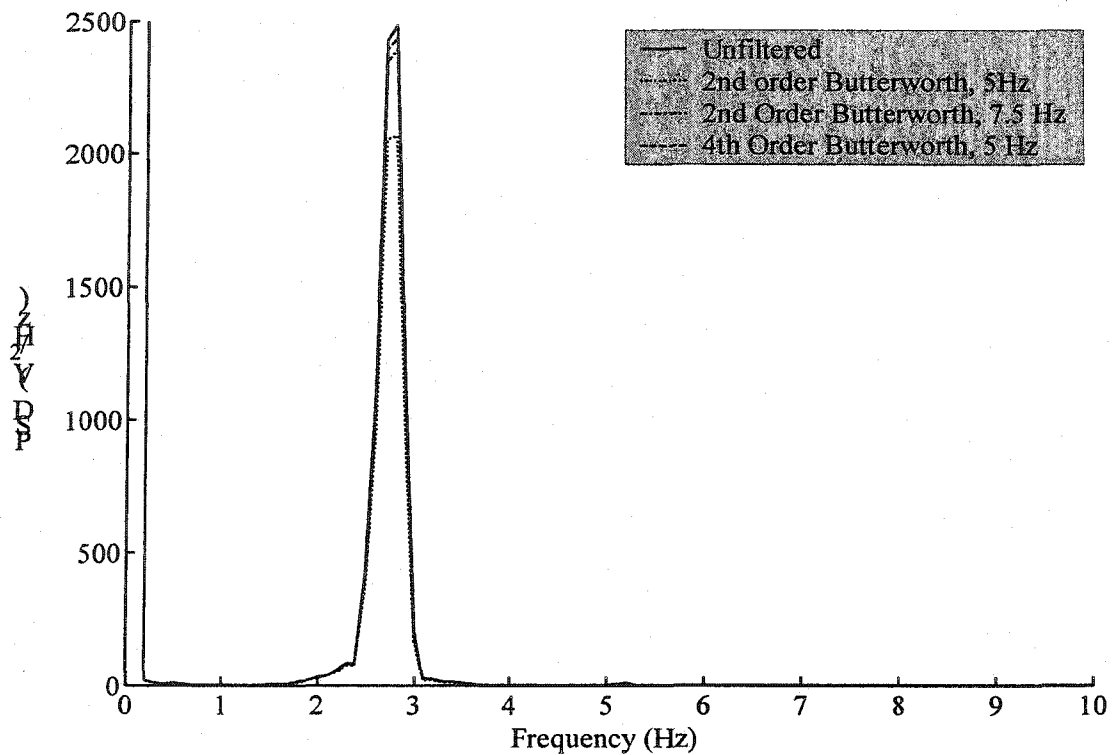


Figure 2. Sample power spectrum analyses of the time series data for pronation-supination of the right forearm. The large peak represents the signal from the potentiometer during a 2.75 Hz trial. Note the absence of any higher-frequency peaks of significant amplitude.

The MATLAB analysis program also provided summary statistics for each of the probe stimuli in a trial. These consisted of the RT to the probe stimulus and a summary of relative phase variables for the four-second interval prior to each probe: mean relative phase, uniformity of relative phase, and the Rayleigh value. Probe stimuli were set to occur at least seven seconds after the previous response to allow time for the re-acquisition of the required movement pattern. Reaction time responses were calculated as three SD +/- the pre-stimulus mean of the transducer channel.

To infer attentional cost differences from performance changes in the secondary task, only probe responses captured when the requirements of the primary task was

adhered to were used in analysis of the secondary RT task. First, the Rayleigh test of uniformity (Mardia, Kent, & Bibby, 1979) was used to eliminate responses made when the coordination pattern was not sufficiently stable. Second, responses to probe stimuli in which mean relative phase for the four-second interval preceding the stimuli was not within 45 degrees of the target pattern were also excluded. Finally, reaction time outliers that were not within the inner fences of the distribution for each participant were removed (Carson et al., 1999). This resulted in 1121/2295 (49 %) of responses being kept for further analysis. See Appendix B (Table 2 and Table 3) for a breakdown of the eliminated probe responses.

Dependent Measures

The study employed a 2 Axis (above, below) x 2 Pattern (pronate-on-beat, supinate-on-beat) within-subject factorial design. The simple reaction time to a probe stimulus was used to analyze secondary task performance, and thus infer the attentional requirements of the primary task. The dependent measures used to evaluate the performance of the primary coordination task were mean relative phase and uniformity of relative phase.

The mean direction (average tendency) of relative phase was used to determine adherence to the specified movement pattern in each trial. Mean relative phase indicates the degree of departure of a coordination pattern from the target value. To determine average deviation from the target pattern, the absolute values of the mean relative phase scores were calculated for individual probe responses (transformed to the range $0\pm 180^\circ$). The average value of these scores within each experimental condition provided an estimate of the accuracy with which the pattern was performed in that condition.

The uniformity of relative phase is a circular index of variability that indicates the stability of a coordination pattern, and is the directional equivalent of the inverse of (linear) sample standard deviation. Therefore, uniformity is a measure of the stability of a coordination pattern. However, unlike measures of variability on a line, which assume values from zero to infinity, circular variance consists of values in the range zero to one. The following transformation was used to produce a measure of circular variance in the range $(0, \infty)$

$$s_o = \{-2 \log_e (1-S_0)\}^{0.5},$$

where S_0 is uniformity in the range $(0, 1)$, and s_o is the transformed uniformity measure (Mardia, 1972). The result of the transform corresponds to the inverse of the ordinary standard deviation on a line and can be used in inferential tests based on standard normal theory (Burgess-Limerick, Abernethy, & Neal, 1991; Byblow et al., 1995). Mean relative phase and uniformity of relative phase were used in combination to ensure adequate primary task performance.

Results

Pre-Trials

The critical frequency (CF) for all participants was either 2.50Hz or 2.75Hz (see Table 1). For four of the nine participants, CF was 2.50 Hz, and the resulting frequency for their experimental trials was 2.60 Hz. The CF for the other five participants was 2.75 Hz; these participants completed their experimental trials at 2.85 Hz. The mean critical frequency of all the participants in the study was 2.64Hz (s.d. = 0.13). Participants did not exhibit phase transitions from the required supinate-on-the-beat pattern (AOR below) to the more stable pronate-on-the-beat pattern. Therefore, pre-trials were judged to be unacceptable when periods of phase wandering were substantially frequent and/or large in amplitude.

Reaction Time

A 2 x 2 (axis x pattern) within-subject ANOVA was carried out on the reaction time variable. This analysis indicated a significant interaction ($F_{1,8} = 7.60, p < 0.03$). As shown in Figure 3, when the AOR was placed below the forearm, RT scores obtained during performance of pronate-on-the-beat pattern were faster (mean = 273.5ms, s.d. = 36.3ms) than those attained during the supinate-on-the-beat pattern (mean = 287.6ms, s.d. = 51.3ms). Conversely, when the axis was located above the forearm, the pattern of results for RT was reversed, and the responses from the supinate-on-the-beat pattern were faster (mean = 276.1ms, s.d. = 37.5ms) than those from the pronate-on-the-beat pattern (mean = 287.6ms, s.d. = 43.5ms).

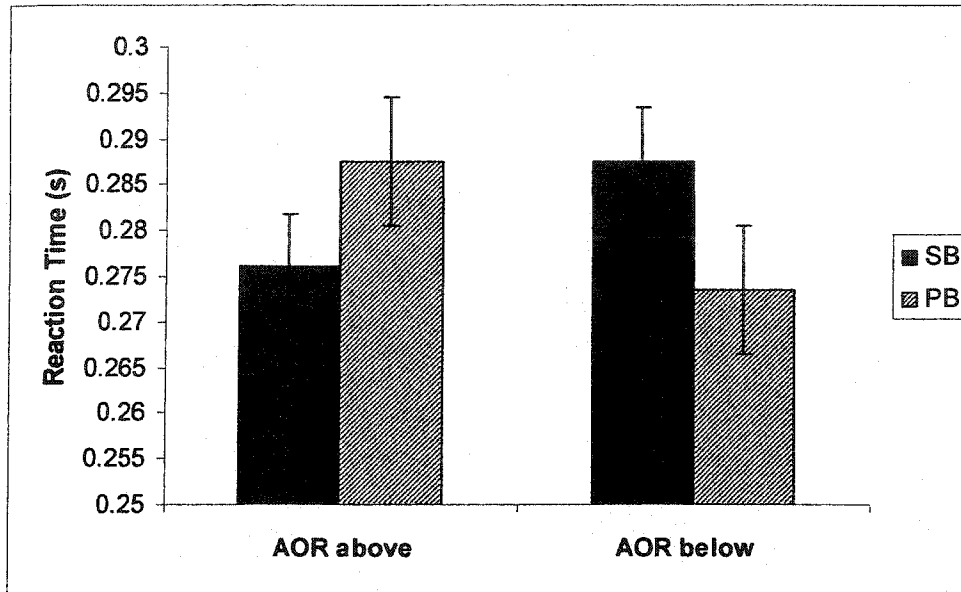


Figure 3. Mean simple reaction times obtained during the supinate-on-the-beat and pronate-on-the-beat modes of coordination with the AOR positioned above or below the forearm. The solid bars represent the supinate-on-the-beat pattern and the hatched bars represent the pronate-on-the-beat pattern. Error bars correspond to standard error.

The magnitude of the interaction effect was evaluated using partial eta squared (f), which is the ratio of the variation due to an individual independent variable over the sum of the variation due to the variable and the unexplained variation. The size of the interaction effect was 0.49, indicating that 49% of the variation in the RT scores was attributed to the interaction between the axis and pattern conditions. When considering each axis-of-rotation independently, the effect sizes between patterns in the above condition ($f = 0.38$) than in the below condition ($f = 0.36$) were quite similar.

Mean Relative Phase

Mean relative phase (deviation from the required pattern) scores were very similar in all conditions (see Figure 4). With the AOR above the forearm, the average deviation from the target pattern was 23.49 degrees for the supinate-on-beat pattern (s.d. = 9.13) and 21.72 degrees for the pronate-on-beat pattern (s.d. = 4.38). With the AOR

below the forearm, the average deviation from the target pattern was 18.61 degrees for the supinate-on-beat pattern (s.d. = 3.75) and 19.43 degrees for the pronate-on-beat pattern (s.d. = 5.37). A 2 (axis) x 2 (pattern) ANOVA revealed that neither main effect for axis ($p = 0.22$) or pattern ($p = 0.84$), nor the interaction effect ($p = 0.32$) reached conventional levels of significance. It also does not seem that participants engaged in a trade-off between pattern stability and pattern accuracy; there was no evidence of a systematic relationship between mean relative phase and uniformity of relative phase.

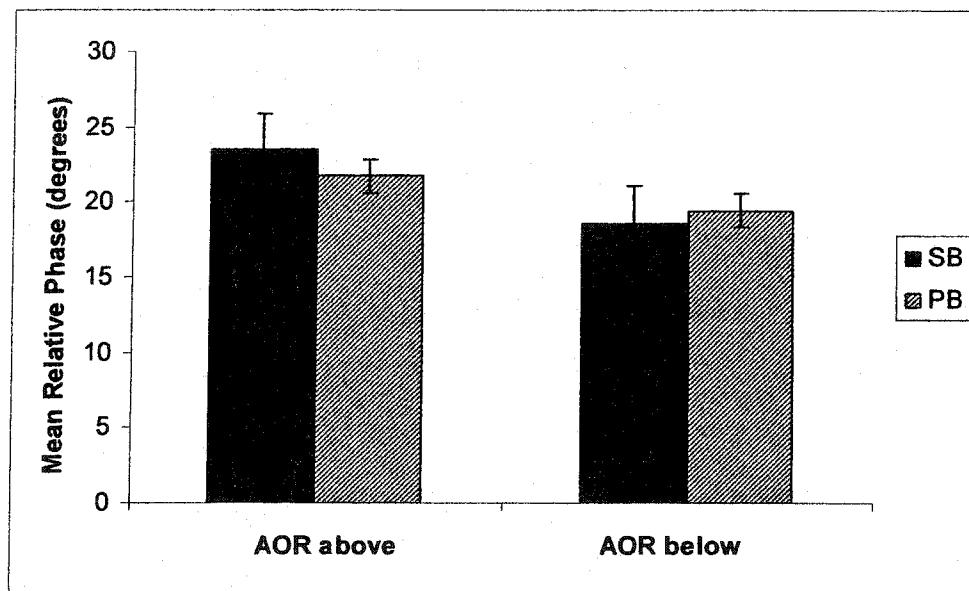


Figure 4. Mean relative phase during the supinate-on-the-beat and pronate-on-the-beat modes of coordination with the AOR positioned above or below the forearm. The solid bars represent the supinate-on-the-beat pattern and the hatched bars represent the pronate-on-the-beat pattern. Error bars correspond to standard error.

Uniformity of Relative Phase

Uniformity of relative phase was not systematically altered by changes to the mechanical context of movement. With the AOR both above (supinate-on-beat: mean = 2.789 s.d. = 0.061; pronate-on-beat: mean = 2.760 s.d. = 0.081) and below (supinate-on-beat: mean = 2.776 s.d. = 0.071; pronate-on-beat: mean = 2.750 s.d. = 0.042) the forearm,

uniformity scores were similar between coordination patterns. Thus, the anticipated interaction effect of the 2 x 2 (axis x pattern) ANOVA for axis and pattern was not observed ($p = 0.95$). Main effects present for both pattern ($p = 0.08$) and axis ($p = 0.45$) also failed to reach significance at $\alpha = 0.05$. The relatively low uniformity of relative phase value for the pronate-on-the-beat, AOR below condition (mean = 2.750) was the most apparent deviation from expected results (see Figure 5).

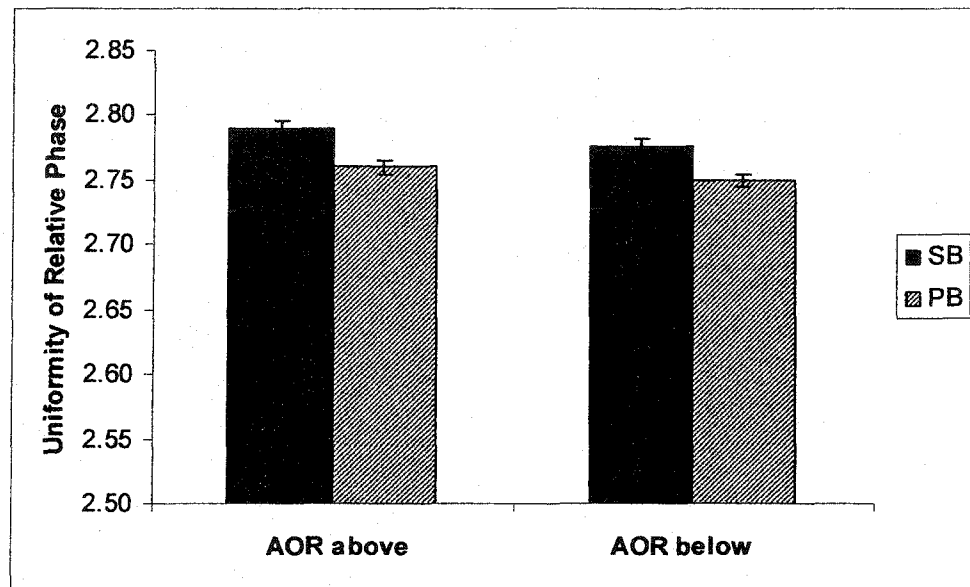


Figure 5. Uniformity of relative phase during the supinate-on-the-beat and pronate-on-the-beat modes of coordination with the AOR positioned above or below the forearm. The solid bars represent the supinate-on-the-beat pattern and the hatched bars represent the pronate-on-the-beat pattern. Error bars correspond to standard error.

Uniformity of relative phase was further analyzed without first excluding probe responses with low pattern uniformity and/or reaction time outliers. This analysis produced the expected rank ordering between task conditions (see Figure 6), although differences between conditions still did not reach conventional levels of significance ($p = 0.31$). With the AOR above the forearm, supinate-on-beat (mean = 2.487; s.d. = 0.060) was more stable than pronate-on-beat (mean = 2.407; s.d. = 0.074). With the AOR below

pronate-on-beat (mean = 2.435; s.d. = 0.053) was produced in a more stable fashion than supinate-on-beat (mean = 2.409; s.d. = 0.073).

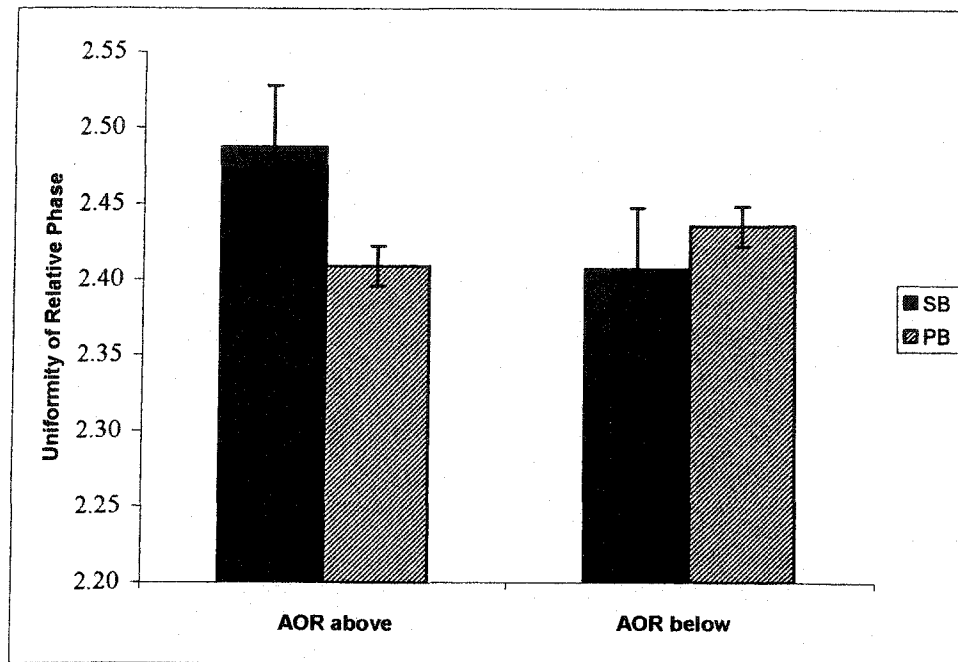


Figure 6. Uniformity of relative phase during the supinate-on-the-beat and pronate-on-the-beat modes of coordination with the AOR positioned above or below the forearm without exclusion of probe responses. The solid bars represent the supinate-on-the-beat pattern and the hatched bars represent the pronate-on-the-beat pattern. Error bars correspond to standard error.

Discussion

The emergence of stable patterns of coordination is governed by task-specific, soft-assembled dynamics arising from the neural, biomechanical, muscular, metabolic, environmental, and cognitive constraints. However, higher level influences from the CNS also often contribute to maintaining and stabilizing coordination patterns (Carson, 1996; Fuchs & Kelso, 1994; Jirsa et al., 1998; Kelso, 1997). Understanding how these two levels of the motor system relate is an important step in acquiring a complete theory of motor behaviour. Recently, the relationship between pattern stability and CNS information processing activity has been investigated through an attentional cost measure in a dual-task paradigm. This methodology allows for a macroscopic assessment of the attentional resources required to produce and maintain patterns of coordinated movement. The primary aim of this study was to determine if changes to the mechanical context of movement during a unimanual pronation-supination task would alter the higher level planning elements (attentional cost) of the movement.

Attentional Cost

The main finding of the present experiment was that manipulation of the mechanical context of movement does affect the motor system at the level of attentional cost. The amount of CNS information processing activity required to maintain a coordination pattern, as inferred from the time to react to visual stimuli, was altered systematically by changes to the position of the external axis-of-rotation. Combined with previous results demonstrating the effect of AOR position on the stability of unimanual forearm rotation (Byblow et al., 1995; Carson et al., 2000), this finding confirms that

small changes to movement context can affect both the peripheral coordination dynamics and the higher-level cognitive aspects of producing a coordination pattern. Therefore, both central and peripheral levels of the motor system are influenced by the ease with which a movement is produced by the neuromuscular-skeletal system (Carson et al., 1999).

The variations in muscle length and orientation that occur during pronation and supination of the forearm are complex. Changing the position of the fixed point around which the long axis of the forearm rotates during pronation-supination alters the skeletal dynamics of the forearm. When the AOR is below the long axis of the forearm, the radius moves in an arc around the relatively stationary ulna (see Figure 1). When the AOR is above the forearm, however, the ulna travels around the radius. These biomechanical differences in turn alter the length and line of action of the musculature involved in pronation and supination movements.

The relative dominance of the pronation and supination phases of forearm rotation in interlimb coordination tasks is in part dependent on the degree of engagement of a primary forearm flexor (Carson et al., 2000). Flexor carpi radialis (FCR) is substantially recruited during the pronation phase of movement when the AOR is below the forearm and minimally recruited when the AOR is above (Carson et al., 2000). Because the forearm flexors are capable of generating greater peak moments at the wrist than are the forearm extensors (Colebatch & Gandevia, 1989; Delp, Grierson, & Buchanan, 1996), movement patterns in which the forearm flexors are activated require a smaller number of motor units to produce the same amount of force (Vallbo & Wessberg, 1993). Therefore, the amount of cortical activity required for a coordination task is reduced when the

forearm flexors contribute substantially. More cortical processes (resources) would then become available for the secondary task. However, there is limited data in the literature regarding the action of forearm flexors and extensors during pronation-supination (Murray, Delp, & Buchanan, 1995). Because of this scarcity, and because the contribution of FCR during pronation movements is not completely responsible for context dependent differences in the performance of rhythmic forearm rotation, more research is needed to determine the role of individual musculature in pronation-supination of the forearm.

In the present experiment, changing the mechanical context of movement was expected to affect both biomechanical and neuromuscular constraints of the upper limb (Carson et al., 2000). Biomechanical constraints are considered to arise from the pendular dimensions of the limb or limb segments. In contrast, neuromuscular constraints consist of nervous and metabolic processes. Although both of these types of constraints affect the stability of interlimb coordination, only changes to neuromuscular constraints have been reported to affect the system at a central level (Carson et al., 1999; Stinear & Byblow, 2001). Exclusive manipulation of biomechanical constraints does not seem to alter attentional cost, likely because inertial limb constraints affect the system at a more peripheral level than oscillation frequency or changes to neuromuscular constraints (Temprado et al., 2001). Therefore, in forearm pronation-supination, differences in the rapidity of response to the visual RT probe is likely dependent upon variation in the neuromuscular constraints of the upper limb that are induced by changes to the AOR position.

Pattern Stability

The original intention of this study was to determine the effect of mechanical context on attentional cost *and* replicate previous results concerning mechanical context and pattern stability. The primary aim of the study was achieved as it was verified that the mechanical context of movement does affect the attentional cost of rhythmic forearm rotation. However, no significant differences were observed between conditions with respect to the uniformity of relative phase. It is likely that one of the following explanations or a combination thereof, is responsible for absence of an effect of mechanical context on pattern stability.

First, it is possible that the nature of the design used in this experiment is incompatible with the type analysis of relative phase measures that is used in continuous coordination tasks. Because the coordination task in this experiment was performed in short segments that were interrupted by responses to visual probes, this may have caused a disruption and subsequent re-acquisition of the required coordination pattern after each RT probe response. Visual analysis of individual trials revealed that the disruptive effect of responding to a probe varied substantially (see Figure 6), but provided some support for this conjecture (Figure 6b). If the accuracy and stability of relative phase was artificially (intentionally) re-stabilized following each probe disruption, the recording period preceding each probe RT response may not have been long enough to allow the constraints of the more difficult conditions to more significantly hinder coordination task performance. Comparison with a previous experiment that used a very similar experimental setup was not possible because uniformity of relative phase scores were not reported (Carson et al., 1999).

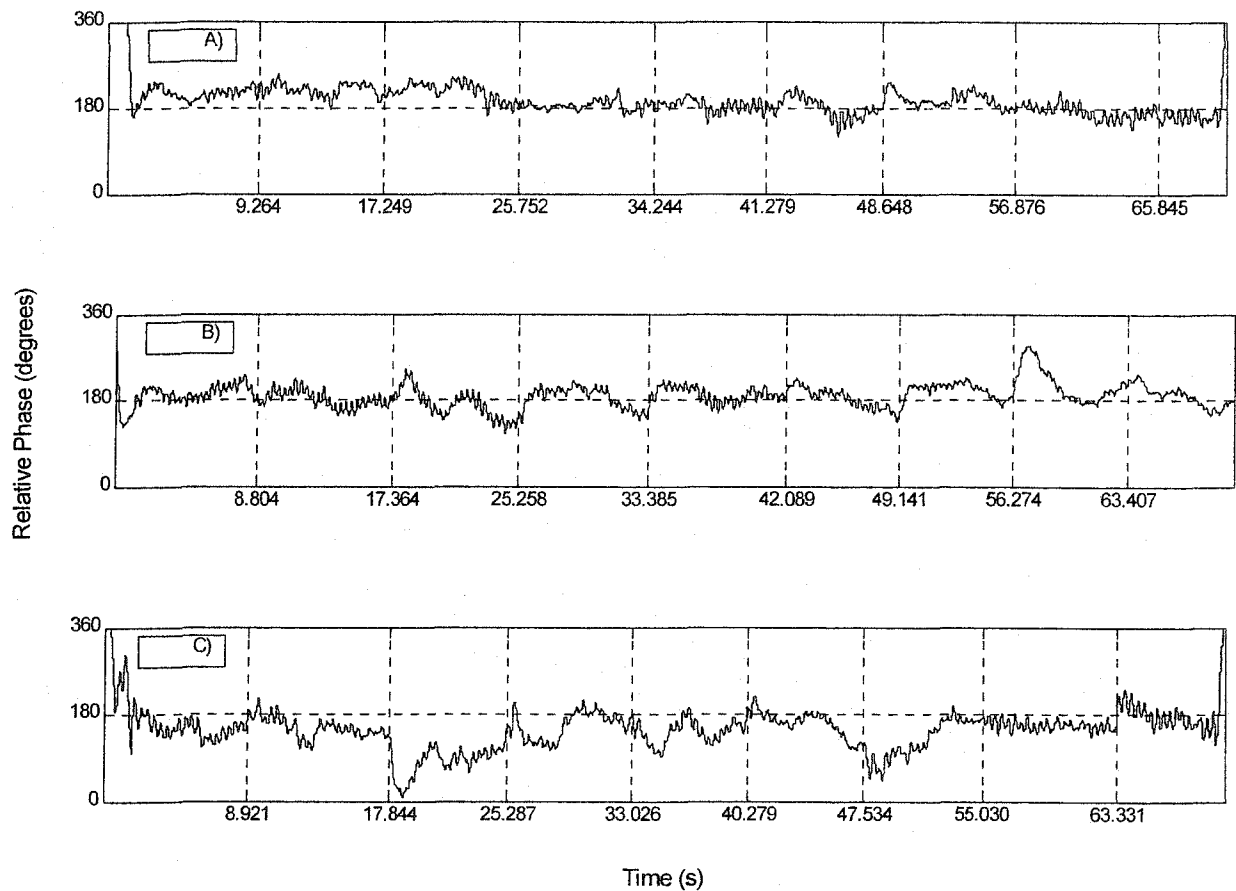


Figure 7. Representative relative phase plots for three participants during the course of a pronate-on-the-beat trial with the AOR positioned below the forearm. Dashed horizontal line indicates the target pattern of 180 degrees relative phase. Dashed vertical lines indicate the onset of pedal responses to reaction time probes. A) Participant 4: Uniformity of RP was minimally affected by probe responses. B) Participant 6: Uniformity was more significantly affected by RP probe responses. C) Participant 9: Response to RP probe responses varied, as substantial phase wandering was present throughout trial.

The second alternative is that participants may not have placed equal emphasis on completing the two tasks of the experiment. In the fixed capacity model of attentional processing, if more attentional resources are allocated to the coordination task, it would be performed more skillfully, while the reduced capacity available for the RT task would be observable in a performance drop-off. Therefore, an increased attentional focus on the coordination task during difficult task conditions may have contributed to the absence of significant uniformity of RP findings.

The third potential contributor to the lack of effect for pattern stability is a possible shortcoming in the physical setup of the experiment. Ideally, movement in this type of coordination task is completely limited to one degree-of-freedom: pronation and supination of the forearm. This requirement was partially satisfied by the presence of a Velcro strap across the upper forearm that maintained the position of the forearm with respect to the apparatus. However, elbow angle was not kept constant throughout the experiment, which may have introduced variability in the neuromuscular configuration of the forearm. For instance, the peak flexion-moment arm of the biceps brachii occurs in an extended elbow position (Murray et al., 1995). Participants may have adjusted their posture to maximize such contributions during the more difficult task conditions, and thus compensate for the mechanically induced constraint changes that would normally have resulted in performance drop-offs.

Changes and Recommendations

Several modifications could be implemented in future studies to improve upon the methodology used in the present experiment. First, as discussed in the previous section, further measures should be taken to ensure that motion of the forearm is restricted to one

degree-of-freedom. A wide Velcro strap used to fasten upper arm to torso would be an optimal solution that would help maintain a constant elbow angle throughout the experiment.

A single task component should be included in the design of future studies using this type of experimental paradigm. To determine the attentional demands of the coordination task, it was necessary to eliminate responses that were produced while the primary task was not being performed correctly. As well, the disruption and re-acquisition of the coordination pattern required because of the probe responses possibly confounded the measurement of pattern stability. Therefore, to confirm the effect of a constraint manipulation on pattern stability, a portion of the experiment should be conducted with no secondary RT task component to first confirm the affect of AOR position on the uniformity of relative phase.

Investigation of the relationship between peripheral coordination dynamics and central processing cost is a relatively new field of study. Therefore, there is a great deal of room for further experimentation on defining the role of various constraints on the higher-level components of the motor system. The results of the present experiment point toward two possibilities for future research within this framework. First, the hypotheses presented here concerning the lack of a significant effect of mechanical context on pattern stability should be tested. Because changes to neuromuscular configuration were expected to affect central and peripheral levels of the motor system in a parallel fashion, the lack of correspondence between reaction time and uniformity measures in this dual-task paradigm needs to be accounted for. Second, the lack of literature regarding how muscles of the upper limb are involved in upper limb pronation and supination

necessitates further investigation into the activation patterns of the muscles responsible for forearm rotation.

From a wider perspective, a perceptible direction for future research is in determining the neural underpinnings of the relationship between movement constraints and attentional cost. Attention involves a finite set of brain processes and structures that mutually interact to generate the performance of coordinated movements (Monno et al., 2002). Although a reaction time dual-task paradigm provides a macroscopic inference of attentional cost, an understanding at more microscopic levels could provide greater insight into how the central nervous system maintains a pattern of coordination. One suggestion that bears further investigation is that attentional demand represents the amount of response competition between overlapping cortical representations of the muscles involved in concurrent tasks (Carson et al., 1999). Advances in both theory and in brain mapping/scanning techniques that afford greater resolution of neural activity may provide methods of identifying the structures that contribute to attentional processes and the mechanisms by which they affect peripheral coordination dynamics.

Significance

Current consensus suggests that the laws governing coordination must be considered in conjunction with the structures upon which they are expressed (Kelso et al., 2001). Therefore, it is important to recognize how constraints affect various levels of the motor system in order to understand exactly how fundamental principles and laws are influenced by the specific mode of implementation. Because the connection between higher motor centers and peripheral coordination dynamics has recently become a topic of interest in the field of human movement science, determining which constraints are

most responsible for the stability and the central cost of maintaining a coordination pattern is a useful strategy for attempting to connect dynamic and hierarchical approaches to coordination.

By providing evidence that neuromuscular constraints affect the motor system at the relatively central level of attentional cost, the present experiment contributes to this process in two ways. First, when the findings of the this study are considered in conjunction with previous results demonstrating the context dependence of the activation profile of forearm muscles (Carson et al., 2000), it indicates that multiple levels of the neuromuscular system are sensitive to changes in limb orientation during rhythmic upper limb movements. Therefore, interlimb coordination does not occur independently of central influences, a standpoint that conflicts with hierarchical views stressing a disconnection between motor behaviour and central processes (Monno et al., 2002). Second, previous research on this topic has been limited to simple flexion-extension tasks of the wrist (Stinear & Byblow, 2001) and the index finger (Carson et al., 1999). Thus, the more complex context of forearm pronation-supination used in this study signifies that the importance of neuromuscular configuration in determining the central processing cost can be generalized to a greater extent.

The broad contribution of this research is to further the development of theory in the field of human motor behaviour, and more specifically, the study of complex coordinated movement. Because the dual-task methodology employed in this study provides an experimental connection for the dynamic systems and the information processing paradigms, two approaches that have often been considered mutually exclusive, it may provide a more comprehensive approach to the study of sensorimotor

coordination (Monno et al., 2002). Although this type of research is basic in nature, progression in understanding models of movement coordination may lead to novel study designs and interpretations of acquired and developmental motor disorders (Carson & Swinnen, 2002).

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Appendix A: Handedness Questionnaire

M.P. Bryden's Modification of Crovitz Handedness Questionnaire

Name _____ Sex _____ Age _____

Circle appropriate answer.

	Always use left hand	Usually use left hand	Use both equally	Usually use right hand	Always use right hand	Don't know
1) Writing	1	2	3	4	5	6
2) Holding <i>Nail to hammer</i>	1	2	3	4	5	6
3) Throwing	1	2	3	4	5	6
4) Drawing	1	2	3	4	5	6
5) Using scissors	1	2	3	4	5	6
6) Using toothbrush	1	2	3	4	5	6

Handedness score

Figure 8. Bryden modification of the Crovitz handedness questionnaire. Scores over 20 indicated right-handedness for the purposes of this study.

Appendix B: Pre-trial & Probe Elimination Data

Table 1. Pre-Trial Testing Results for Critical Frequency Determination

Participant	1.5 Hz		1.75 Hz		2.0 Hz		2.25 Hz		2.5 Hz		2.75 Hz			Critical frequency
1	✓		✓		✓		✓		✓		X	X	X	2.75 Hz
2	✓		X	✓	X	✓	✓		X	✓	X	X	X	2.75 Hz
3	✓		✓		✓		✓		X	X	X			2.50 Hz
4	X	✓	✓		✓		X	X	✓	X	X	X		2.50 Hz
5	✓		✓		✓		✓		✓		X	X	X	2.75 Hz
6	✓		✓		✓		✓		X	✓	X	X	X	2.75 Hz
7	✓		✓		✓		X	✓	X	X	X			2.50 Hz
8	✓		✓		✓		X	✓	X	X	X			2.50 Hz
9	✓		✓		X	✓	✓		✓		X	X	X	2.75 Hz

X = fail (redo trial at same frequency); ✓ = pass (continue to higher frequency)

Table 2. Breakdown of the Elimination of Probe Responses by Participant and Type of Error

Participant	Total Probes	Probes Included	Probes Eliminated	Relative Phase Error	Reaction Time Error	Both Errors
1	254	170	84	71	13	7
2	256	133	123	109	14	7
3	255	126	129	124	5	10
4	256	105	151	148	3	9
5	255	131	124	111	13	9
6	255	180	75	63	12	1
7	255	76	179	173	6	10
8	256	43	213	205	8	23
9	253	157	96	77	19	7
Total	2295	1121	1174	1081	93	83

Table 3. Breakdown of the Elimination of Probe Responses by Experimental Condition and Type of Error

Participant	Total Probes	Probes Included	Probes Eliminated	Relative Phase Error	Reaction Time Error	Both Errors
Axis Above - Supinate-on-beat	574	271	303	279	24	14
Axis Above - Pronate-on-beat	573	277	296	277	19	21
Axis Below - Supinate-on-beat	575	291	284	258	26	33
Axis Below - Pronate-on-beat	573	282	291	267	24	15
Total	2295	1121	1174	1081	93	83

Appendix C: Individual Participant Data

Table 4. Simple Reaction Time Scores for Axis-of-Rotation and Coordination Pattern Conditions (in milliseconds)

Participant	Axis above forearm		Axis below forearm	
	Supinate-on-beat	Pronate-on-beat	Supinate-on-beat	Pronate-on-beat
1	258.2	255.8	283.7	269.3
2	244.4	276.9	257.4	253.6
3	271.6	295.3	285.7	274.4
4	296.8	288.6	326.4	309.1
5	218.4	220.1	219.0	209.5
6	273.6	275.9	236.6	238.3
7	326.9	361.4	334.7	301.5
8	334.0	346.3	380.2	325.2
9	261.2	267.8	264.7	280.3
Overall Mean	276.1	287.6	287.6	273.5

Table 5. Average Uniformity of Relative Phase Scores for Axis-of-Rotation and Coordination Pattern Conditions

Participant	Axis above forearm		Axis below forearm	
	Supinate-on-beat	Pronate-on-beat	Supinate-on-beat	Pronate-on-beat
1	2.788	2.831	2.796	2.838
2	2.900	2.811	2.856	2.746
3	2.853	2.773	2.803	2.770
4	2.754	2.672	2.695	2.733
5	2.792	2.726	2.742	2.758
6	2.760	2.766	2.786	2.770
7	2.790	2.612	2.646	2.695
8	2.683	2.770	2.862	2.736
9	2.783	2.879	2.801	2.706
Overall Mean	2.789	2.760	2.776	2.750

Table 6. Average Uniformity of Relative Phase Scores for Axis-of-Rotation and Coordination Pattern Conditions Without Elimination of Probe Responses

Participant	Axis above forearm		Axis below forearm	
	Supinate-on-beat	Pronate-on-beat	Supinate-on-beat	Pronate-on-beat
1	2.595	2.642	2.656	2.623
2	2.686	2.593	2.214	2.139
3	2.568	2.086	2.353	2.508
4	2.358	2.409	2.412	2.384
5	2.383	2.580	2.561	2.520
6	2.589	2.418	2.662	2.625
7	2.524	2.246	2.257	2.434
8	2.063	2.041	1.978	2.216
9	2.624	2.651	2.589	2.472
Overall Mean	2.488	2.407	2.409	2.435

Table 7. Mean Relative Phase Scores for Axis-of-Rotation and Coordination Pattern Conditions (in degrees)

Participant	Axis above forearm		Axis below forearm	
	Supinate-on-beat	Pronate-on-beat	Supinate-on-beat	Pronate-on-beat
1	2.44	15.43	16.38	30.52
2	32.65	18.58	17.37	18.04
3	18.68	19.89	16.77	22.27
4	26.84	27.52	21.53	14.09
5	23.98	23.34	20.42	14.72
6	26.77	21.92	15.92	18.22
7	20.19	26.40	13.26	19.72
8	29.35	16.62	25.92	23.30
9	30.47	25.75	19.90	13.96
Overall Mean	23.49	21.72	18.61	19.43

Appendix D: Analysis of Variance Tables

Table 8. Analysis of Variance for Axis-of-Rotation and Coordination Pattern on Reaction Time

Source	SS	df	MS	F	Sig.
Axis	15.471	1	15.471	0.037	0.852
Error (axis)	3346.759	8	418.345		
Pattern	16.267	1	16.268	0.123	0.735
Error (pattern)	1059.882	8	132.485		
Interaction	1472.001	1	1472.001	7.596	0.025
Error (interaction)	1550.219	8	193.777		
Total	7460.600	9			

Table 9. Analysis of Variance for Axis-of-Rotation and Coordination Pattern on Uniformity of Relative Phase

Source	SS	df	MS	F	Sig.
Axis	0.00117	1	0.00117	0.622	0.453
Error (axis)	0.01507	8	0.00189		
Pattern	0.00685	1	0.00685	3.983	0.081
Error (pattern)	0.01376	8	0.00172		
Interaction	0.00002	1	0.00002	0.004	0.951
Error (interaction)	0.03932	8	0.00492		
Total	0.07621	9			

Table 10. Analysis of Variance for Axis-of-Rotation and Coordination Pattern on Uniformity of Relative Phase without Elimination of Probe Responses

Source	SS	df	MS	F	Sig.
Axis	0.00576	1	0.00576	0.178	0.684
Error (axis)	0.25844	8	0.03231		
Pattern	0.00652	1	0.00652	0.857	0.382
Error (pattern)	0.06090	8	0.00761		
Interaction	0.02562	1	0.02562	1.199	0.305
Error (interaction)	0.17100	8	0.02138		
Total	0.52823	9			

Table 11. Analysis of Variance for Axis-of-Rotation and Coordination Pattern on Mean Relative Phase

Source	SS	df	MS	F	Sig.
Axis	115.652	1	115.652	1.815	0.215
Error (axis)	509.694	8	63.712		
Pattern	2.022	1	2.022	0.041	0.843
Error (pattern)	388.809	8	48.601		
Interaction	15.064	1	15.064	1.139	0.317
Error (interaction)	105.788	8	13.223		
Total	1137.031	9			