The Pennsylvania State University

The Graduate School

College of Health and Human Development

COORDINATION DYNAMICS IN REDUNDANT AND NON-REDUNDANT MOTOR TASKS

A Dissertation in

Kinesiology

by

Eric G. James

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2009

The dissertation of Eric G. James was reviewed and approved* by the following:

Karl M. Newell
Professor of Kinesiology
Head of the Department of Kinesiology
Dissertation Adviser
Chair of Committee

Semyon M. Slobounov
Professor of Kinesiology

John H. Challis
Professor of Kinesiology

Peter Molenaar
Professor of Human Development and Family Studies

*Signatures are on file in the Graduate School.

ABSTRACT

This thesis investigated the dynamics of redundant (i.e. with multiple movement solutions) and non-redundant (i.e., in which a movement pattern is the task goal) postural coordination tasks. Previous studies of postural coordination have shown phenomena such as bidirectional phase transitions and transfer of learning that are inconsistent with the established parallel effects in bimanual coordination. The finding of stability in only the in-phase and antiphase patterns in postural coordination may have been confounded by methodological issues, including the analysis of group averaged data. These issues were investigated by testing the hypothesis that there are different hierarchical control structures for redundant and non-redundant coordination tasks and by analyzing individual rather than group-averaged data. In 3 Experiments participants performed a redundant and a non-redundant hip-ankle postural task under a range of experimental conditions. The results showed that transfer between these tasks was negative, transitory and occurred only from the non-redundant task to the redundant. Different timescales of change were found to operate within and between these hierarchical control structures. It was also shown that the prior findings of only in-phase and antiphase coordination patterns in hip-ankle coordination were an artifact of the analysis of group-averaged data. The majority of individuals used more than two coordination patterns in the redundant postural task. The collective pattern of the findings led to the conclusion that: a) there are different hierarchical control structures for redundant and non-redundant coordination tasks; b) these control structures mediate the inconsistent findings previously found in these two types of coordination tasks, and c) different dynamics occur in each type of movement task which leads to the conclusion that the dynamics of the redundant task are different than those captured by the HKB model. It

was hypothesized that the relation between the control structures for redundant and non-redundant coordination tasks involves a cooperation and competition between the intrinsic dynamics and properties of the organism, environment and task.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.0. Brief Background to Dissertation

How are the many degrees of freedom within the human body controlled to produce actions that effectively and reliably meet environmental and task demands? This is in essence the question posed by Bernstein (1967, 1996) as the 'degrees of freedom problem'. That is, out of an infinite number of potential organizations of the system, how is it that specific movement solutions are produced to meet task demands? It has been hypothesized that a structure is needed that simplifies the control of the many degrees of freedom within the body, thereby solving the degrees of freedom problem, freeing attention and allowing other levels of control to deal with task and environmental demands. The control structure that solves the degrees of freedom problem ideally would itself be controlled in a low-dimensional, relatively simple fashion by a higher level control structure or structures (Turvey, Shaw, & Mace, 1978).

The organization of the control of human motor behavior has long been attributed to a hierarchy of control structures within the nervous system (Brooks, 1986; Jackson, 1932; Kandel, Schwartz, & Jessel, 2000). Hughlings Jackson (1932) classified behavior into four levels, ranging in their degree of automaticity. From a high to low degree of automaticity, Jackson theorized the spinal cord, brain stem, motor cortex and premotor cortical areas, respectively, to be principally responsible for the organization of behavioral responses

Bernstein (1996) hypothesized a hierarchical system of control in which a level termed synergies (or muscular-articular links) assembles coordinated movement patterns. In his view a higher level of control, that of space, adapted the internally consistent coordination patterns produced by the level of synergies to meet external demands. In this way the level of synergies organizes the redundant segments of the body while the level of space utilizes the lower dimensional control afforded by the synergy level to adapt it's output to an environmental context (Turvey, 2007).

The term 'hierarchy' is used in a general sense. Rather than one level being entirely and unilaterally under the control of another, an interdependence between levels is likely to exist with different levels interacting and affecting the functioning of the others (Turvey, 2007). The goal of this study is to investigate the relation between the level of control that solves the degrees of freedom problem and the level of control that adapts this structure to satisfy higher level task requirements.

A large body of research in the fields of human motor control and learning has examined the degrees of freedom problem (Latash, Krishnamoorthy, Scholz & Zatsiorsky, 2005; Newell & Vaillancourt, 2001; Todorov & Jordan, 2002; Turvey, 1977, 1990). One approach to the study of coordination is to examine how movement patterns spontaneously emerge in redundant coordination tasks. In this type of task multiple coordination patterns could potentially be used to satisfy the task goal. Extensive previous research has examined redundant coordination tasks and how these patterns change with learning (Haibach, Daniels, & Newell, 2004; Ko, Challis, Stitt, & Newell 2003; Anderson & Sidaway 1994).

Another strategy for elucidating the organization of coordinated behavior is to require the production of specific coordination patterns (Kelso, 1984; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Salter, Wishart, Lee, & Simon, 2004; Treffner & Turvey, 1996). Recent research using this approach has examined bimanual and other types of coordination from the dynamical perspective. It has been found that certain rhythmic coordination patterns are intrinsically stable, while others are not, and that a transition can occur between stable patterns as task conditions change (Bardy, Ouillier, Bootsma, & Stoffregen, 2002; Kelso, 1984).

Bernstein (1996) hypothesized the existence of a hierarchy of control in which internally consistent movement patterns are controlled by a level called *synergies* that is hierarchically lower than the level of control, denoted as *space,* that utilizes the former to meet functional task demands. While a substantial literature exists on the properties of synergies and the coordinated behavior they are hypothesized to produce (Latash et al., 2005; Treffnor & Turvey, 1997; Turvey, 2007), research has only begun to examine the dynamics of how these control structures (i.e., synergies) that produce coordinated movement patterns are adapted by another level of control (e.g., space) to meet environmental and task demands. There is research on the coordination dynamics of both redundant and non-redundant coordination tasks involving the same effector system (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy et al., 2002; Faugloire, Bardy, Merhi, & Stoffregen, 2005; Faugloire, Bardy, & Stoffregen, 2006; Faugloire, Bardy, & Stoffregen, 2009). Little is currently known about the dynamics defining the interaction of control structures involved in each of these types of tasks or how change at each of these levels affects the other.

Initial research that has examined the use of both synergy and space level control in the same effector system has hypothesized that the dynamics operating in tasks controlled by the level of synergies will be the same as those controlled by the level of space (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2009). However, preliminary research findings are inconsistent with this hypothesis and bring this fundamental assumption into question (Bardy et al., 2002; Faugloire et al., 2005; Faugloire et al., 2006). Accordingly, the focus of this study is to investigate the relation between the assembly of coordinated movement and the adaptation of these movement patterns to meet environmental and task demands.

1.1. Focus of Dissertation

Research on coordination dynamics in the hip-ankle effector system has produced results that are both consistent (Bardy et al., 1999; Bardy et al., 2002) and inconsistent (Faugloire et al., 2005; Faugloire et al., 2006; Faugloire et al., 2009) with prior coordination dynamics research. Understanding these inconsistencies and unanswered questions regarding coordination dynamics of the hip-ankle effector system may benefit from the application of additional theoretical perspectives. To date, no research has explicitly addressed the relation between the dynamics of redundant and non-redundant coordination tasks. It is possible that the coordination dynamics governing the production of specific coordination patterns and those governing the emergent coordination in redundant coordination tasks are distinct.

Insight into why these inconsistencies occur may be gained by applying the paradigm of hierarchical levels of control (Bernstein, 1996; Brooks, 1986; Jackson, 1932, Kandel et al., 2000) to the study of coordination dynamics in different types of tasks. In terms of Bernstein's theoretical paradigm, it is not known what the relation is between the dynamics operating when the level of synergies is leading a movement (e.g., a task of producing a specific coordination pattern) and those operating when the level of space is leading (e.g., in a redundant coordination task).

In examining transfer between coordination tasks prior studies have generally not considered that this transfer may occur between the level of synergies (e.g., learning a new relative phase pattern) and the level of space (e.g., performance of a redundant task). Based upon Bernstein's (1996) theoretical hierarchy in which higher levels of control depend upon the proper functioning of lower levels it is hypothesized that learning at the level of synergies will transfer to the level of space. However, Bernstein's hierarchy is ambiguous as to whether lower levels of control are influenced by higher levels. A traditional account of transfer, namely the Identical Elements Theory (Thorndike, 1903; Thorndike & Woodworth, 1901) predicts that positive transfer is accounted for by the separateness or similarity of functions involved in tasks.

Elements that have been considered to constitute the similarities between tasks include structural and surface characteristics (Holyoak, 1985). Structural elements are those that are causally related to the attainment of the task goal. Surface elements are those that contain no such relationship but that cause performers to perceive a similarity between tasks. Transfer has been hypothesized to result from even the perception of similarity between tasks. A perceived similarity between tasks will trigger memory retrieval and cause the learner to attempt transfer. Whether transfer is positive or negative will be determined by the features of each task (Gick & Holyoak, 1987). The amount of transfer is a function of perceived similarity between tasks while the direction of transfer is a function of structural similarity (Holyoak, 1985).

A modified version of the Identical Elements Theory considers that the similarity between stimulus and response requirements produces transfer (Ellis, 1965; Osgood, 1949; Schmidt & Young, 1987). A theoretical transfer surface has been hypothesized that can be tipped toward positive or negative transfer depending upon the similarity of stimulus and response in two tasks (Osgood, 1949). When responses in a second task are identical or similar to those in an original learning task the transfer surface is tipped in the positive direction with the highest point equating to the sharing of identical responses. When stimuli remain the same but the responses differ the surface is tipped downward in the negative direction, due to interference. Much of this theoretical transfer surface is flat, equating to the occurrence of no transfer.

The processing that occurs during task performance has also been considered to potentially affect transfer between tasks. Positive transfer has been considered more likely when performers process tasks in a similar way (Bransford & Franks, 1976; Bransford, Franks, Morris, & Stein, 1979; Lung & Dominowski, 1985; Morris, Bransford, & Franks, 1977). Learning a task that requires the combination of a new response with a stimulus from a previously learned task will result in negative transfer (Siipola, 1941).

Faugloire et al. (2009) found that positive transfer occurs from a learned non-redundant coordination pattern to the entire range of potential non-redundant coordination patterns (i.e., across the intrinsic dynamics). It has also been concluded that the learning of a new hip-ankle relative phase pattern causes the intrinsically stable in-phase and antiphase coordination patterns to be attracted toward the learned pattern (Faugloire et al., 2006). However, this phenomenon may be due to another underlying mechanism. The attraction of the spontaneous (i.e., redundant) in-phase and antiphase patterns toward a learned pattern may be due to the creation of new stable patterns that transfer from the non-redundant to the redundant task. Here it is hypothesized that learning a new non-redundant hip-ankle relative phase pattern, along with the increased stability across the intrinsic dynamics this causes (Faugloire et al., 2009), would transfer to the redundant coordination task and cause more than the initial two patterns (in-phase and antiphase) to emerge in the redundant coordination task.

The experimental approach of this dissertation was to measure transfer from the performance of coordinated movements of the hip-ankle effector system with the level of synergies leading movement to a task, using the same effectors, in which the level of space was leading, and vice versa. One manipulation used to potentially create transfer was the scanning task previously utilized in studies of coordination dynamics (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997). This task consists of performing multiple coordination patterns that span the range of all possible 1:1 frequency coordination patterns using the hip and ankle while in the standing position. According to Bernstein's (1996) hierarchy of control the level of synergies leads movement in this task. The principle variable measured in this task was the variability of the hip-ankle relative phase patterns.

Another task studied was the redundant coordination task of tracking an oscillating target by moving the head and body in the antero-posterior direction. Concurrent feedback was given allowing the participants to make corrective action as needed to minimize tracking error. Dependent variables estimated tracking task performance and the variability of hip-ankle coordination patterns. Both the scanning and tracking tasks were utilized in all experiments, with different characteristics of each task manipulated to create independent variable conditions appropriate for testing the experimental hypotheses. In each experiment a transfer test was performed to estimate how a manipulation at one level of the system (i.e., synergies or space) affected the other.

An additional task used was the scaling of movement frequency during the postural tracking task. Participants tracked an oscillating target by swaying with their body in an antero-posterior direction across 20 movement frequencies that increased or decreased in a continuous fashion. This task was performed both before and after practicing a novel hip-ankle coordination pattern and over 3 days. Intra-individual coordination patterns were examined across movement frequencies to determine the number of consistent coordination patterns observed.

1.2. Hypotheses

The hypotheses of this project were based upon not only prior experimental data but also Bernstein's theory of hierarchical control of movement by the nervous system. Bernstein (1996) hypothesized that a hierarchical relation exists between levels of control within the nervous system, with the proper functioning of higher levels dependent upon the functioning of lower levels. This project investigated whether Bernstein's theoretical hierarchy of control predicts the dynamics of redundant coordination tasks.

The HKB model of bimanual coordination captures a process of learning and transfer within the intrinsic dynamics of a system (Haken et al., 1985). A general hypothesis in the present study is that, while the HKB model may capture the dynamics of non-redundant (e.g., bimanual) coordination tasks, it may not capture redundant coordination task dynamics. The operation of different dynamics in redundant coordination tasks may explain some inconsistencies previously found between hip-ankle and bimanual coordination dynamics.

The following hypotheses were tested regarding transfer of learning between redundant and non-redundant coordination tasks in healthy young adults ranging from 18 to 29 years of age.

1. Uni-directional transfer hypothesis Part 1: Based upon Bernstein's (1996) hierarchy of control in which higher levels (e.g., space) depend upon the functioning of lower levels (e.g., synergies) it was hypothesized that a reorganization at the level of synergies, due to the performance of novel coordination patterns, would cause poorer performance (i.e., negative

retroactive transfer) in the redundant tracking task. Based upon the adaptive properties of the nervous system this transfer was hypothesized to be transitory in nature.

Prediction: Performing a non-redundant relative phase scanning task with the hip and ankle joints would negatively transfer to the performance of a redundant tracking task.

2. Uni-directional transfer hypothesis Part 2: While in Bernstein's (1996) theoretical hierarchy of control higher levels depend upon lower levels for their proper functioning, it is ambiguous as to whether lower levels depend upon higher levels. In contrast to this, the Identical Elements Theory would predict the same type of transfer between redundant and non-redundant coordination tasks. It was hypothesized that a hierarchy of control exists and that performance of the tracking task results in neutral transfer (i.e., would have no effect) to the scanning protocol. This hypothesis would support the theory of hierarchical control and was contrary to the Identical Elements Theory.

Prediction: Performance of a redundant postural tracking task would not transfer (either positively or negatively) to the variability of coordination in the non-redundant scanning task.

3. Multistability transfer hypothesis: The HKB model has been used to explain the existence of stable in-phase and antiphase coordination modes in postural coordination (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2006, 2009). However, the HKB model was created with reference to coordination dynamics in non-redundant (e.g., bimanual coordination), but not redundant, coordination tasks such as the postural tracking task used in postural coordination studies. Therefore, the applicability of the intrinsic dynamics found in a non-redundant coordination task in a redundant task is questionable. Other discrepancies between experimental results and hypotheses based on the HKB model may be due to an

inapplicability of the HKB model to the coordination dynamics operating in the performance of redundant coordination tasks. The previous study of frequency-scaling in hip-ankle coordination examined averaged group data but not individual participant data. While group data follow predictions of the HKB model it is possible that individual data may not.

Prediction: in individual data hip-ankle coordination patterns in addition to in-phase and antiphase will be found.

1.3. Delimitations

This study was limited to no more than 11 participants per group. Experiments 1, 2, and 3 examined young adults between the ages of 18 and 29 years. Participants were screened for the exclusionary criteria of any history of neurological disorders or surgery to the legs. The data were collected in the Motor Behavior Laboratory at the Pennsylvania State University, University Park campus. Dependent variables included the Root Mean Square Error (RMSE) of participant performance in a postural tracking task. Mean relative phase was used to estimate the coordination patterns that occurred between the hip and ankle joints in all tasks. The amplitude of hip and ankle joint movement was also calculated. Information entropy was used as an estimate of variability of hip-ankle relative phase.

1.4. Limitations

1. Standing may produce fatigue effects. To counteract this, participants received a rest period between testing blocks.
2. One limitation of this study is that part of the experimental objective of Experiment 2 was supporting a null hypothesis. This was necessary as a theoretically based prediction in this experiment was the absence of transfer between two tasks. However, in the scientific method it is not possible to prove a

null hypothesis. Therefore, the objective in this experiment was not to prove the occurrence of a null effect, but rather was to provide evidence supporting the absence of transfer.

3. This study included the examination of hip and ankle joint coordination during a postural task. Participants were instructed and observed to maintain their knees in an extended position. During normal everyday usage this constraint does not exist. Therefore, the findings of this study do not necessarily generalize to everyday behavior.

CHAPTER 2. THE CONTROL OF REDUNDANT AND NON-REDUNDANT COORDINATION TASKS

2.0. Abstract

This chapter presents literature relevant to inconsistencies that have been found between the coordination dynamics of the hip-ankle and bimanual effector systems. Key issues addressed are the differences between the redundant and non-redundant coordination tasks being used in hip-ankle and bimanual coordination research. Theories of hierarchical control are discussed and how they relate to redundant and non-redundant coordination tasks. The transfer of learning is also discussed to clarify the relation between the levels of control responsible for redundant and non-redundant coordination tasks. The review concludes with a discussion of the potential for different control structures to operate with different dynamics and on different timescales of change.

2.1. Introduction

The coordination dynamics of the hip-ankle effector system reveals findings that are inconsistent with those of bimanual coordination. In an attempt to understand these inconsistencies this chapter will review fundamental aspects of coordination and control. What is sought is a theoretical basis upon which to further investigate and clarify these inconsistencies on different patterns of coordination.

A central problem in the field of motor control is how the nervous system solves the 'degrees of freedom problem' (Bernstein, 1967). This problem is how the many degrees of freedom in the human body are controlled to meet task demands within an environmental context. It has become widely accepted in the field of motor control that a control structure alternately known as a synergy, or coordinative structure, is responsible for the organization of coordinated movement (Kelso, 1995; Latash, Scholz, & Schöner, 2007; Ranganathan & Newell, 2008; Turvey, 2007). However, little research has addressed how the output of this level of control is adapted to meet task demands. The research on hip-ankle coordination dynamics has hypothesized that the same dynamics will occur in the tasks utilized in this effector system as have been found in rhythmic bimanual coordination. However, what has not been addressed is the fact that the tasks employed in the study of this effector system have included both redundant and non-redundant coordination solutions.

Non-redundant coordination tasks are those in which a specific pattern of coordination between two effectors is the task goal. Studies of bimanual coordination have typically used non-redundant coordination tasks (e.g., Kelso, 1984). Redundant coordination tasks are those in which multiple, or even an infinite number of, potential coordination solutions could potentially be used to satisfy the task goal. These tasks include actions such as throwing, locomotion and maintaining posture in the face of internal or external perturbations. The research on hip-ankle coordination dynamics has employed both redundant and non-redundant coordination tasks, hypothesizing that the results of each these types of tasks will be consonant with those found in non-redundant bimanual coordination research.

What has been neglected, to date, is that the same theoretical approach that hypothesized the existence of a synergy control structure to solve the degrees of freedom problem also hypothesized that other levels of control exist. In this theoretical framework the level of synergies pertains to the control of non-redundant coordination tasks while a higher level of control, that of space, is responsible for adapting coordinated movement patterns to external task and environmental demands. This space level of control pertains to the control of redundant coordination tasks. The dynamics of the space and synergy levels of control need not necessarily be the same. This may be the reason that inconsistencies have been found in the dynamics of non-redundant bimanual coordination and in redundant hip-ankle coordination tasks (Beek, 2000; Bernstein, 1996; Turvey, 2007).

The central focus of this chapter is to discuss the differences between redundant and non-redundant coordination tasks and the hierarchical control structures theorized to control each of these types of tasks. While previous studies have examined coordination in redundant and non-redundant coordination tasks they have not sought to distinguish the dynamics operating between the space and synergy levels of control. This chapter will focus upon basic theories of motor control and learning that will provide a principled means of distinguishing the operation of the levels of control responsible for redundant and non-redundant coordination tasks. This will lead to the experimental designs found in later chapters that seek to investigate the inconsistencies between hip-ankle and bimanual coordination dynamics.

2.2. Redundant and Non-redundant Coordination Tasks

A substantial body of literature has examined human coordination in redundant tasks which do not specify a coordination pattern (Newell & McDonald, 1994). For example, changes in coordination in learning have been studied in juggling (Haibach et al., 2004), in response to postural perturbations (Horak & Nashner, 1986) and learning a soccer kick (Anderson & Sidaway 1994). In these tasks, the coordination patterns are not specified by the task demands but emerges as a consequence of practice.

The coordination dynamics perspective has examined non-redundant coordination tasks (e.g., bimanual coordination) in which a specified coordination pattern is the task goal (Kelso, 1984; Mechsner et al., 2001; Salter et al., 2004; Treffner & Turvey, 1996). Recent research has also applied the coordination dynamics approach to the study of redundant coordination tasks, examining dynamic properties such as pattern stability, phase transitions, critical fluctuations and relaxation times (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2006, 2009). This research into the dynamics of redundant coordination tasks has produced results that conflict with the HKB and the Schöner, Haken and Kelso (SHK; 1986) models of bimanual coordination and with experimental findings regarding the dynamics of non-redundant coordination tasks.

The terms redundant and non-redundant coordination tasks are defined in terms of the spatiotemporal (kinematic) relation between the body segments. In any task, redundancy is always likely to be present at some level (e.g. the activation of motor units). For the present purposes the level of analysis to be utilized will be confined to the coordination of body segments, with the terms redundant and non-redundant tasks defined solely with respect to this kinematic criterion.

2.3. Hierarchical Control

The research on redundant coordination tasks from the synergetic perspective (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2006,2009) has not addressed the theory that different levels of control may operate in different types of tasks (Bear, Connors & Paradiso, 2001; Bernstein, 1996; Brooks, 1986; Jackson, 1932; Kandel et al., 2000; Latash, 1998; McArdle, Katch, & Katch, 1996). A longstanding theory in neurophysiology is that a hierarchical organization of control exists within the nervous system. Hughlings Jackson (1932) posited a hierarchy of control consisting of the premotor cortex, motor cortex, brain stem and spinal cord. In this framework behavioral automaticity decreases across these respective levels of control. More recent work suggests that these levels of control operate both hierarchically and in parallel (Kandel et al., 2000).

2.3.0. Bernstein's Levels of Control

Bernstein (1996) theorized four levels of hierarchical control: *tone, muscular-articular links* (or *synergies*), *space* and *action*. These theoretical levels are hierarchically organized both structurally, within the nervous system, and functionally, with evolutionarily higher levels able to lead lower levels in various tasks and environmental conditions. In Bernstein's paradigm lower brain centers control more rudimentary and autonomic functions. Higher level brain structures are hypothesized to control newer evolutionary functions. This control is considered to be hierarchical in nature because the proper functioning of 'higher' levels depends upon the proper functioning of 'lower' levels (Bernstein, 1996).

2.3.0.0. Level A: Tone. The lowest hierarchical level of control theorized by Bernstein is the level of tone. He stated that this level is used to produce smooth, slow, tonic contractions in muscles and predominantly uses the primitive chemical, rather than electrical, method of excitation transmission. This level also controls the excitation and inhibition of spinal cells and the resulting degree of muscular contraction they stimulate. In this way, the level of tone provides a background level of contraction in the musculature upon which higher levels operate. He stated that the level of tone almost never leads movement, except in rare circumstances such as when the body is momentarily more or less free from gravity (such as during freefall). The red nuclei brain structures are the executive neural centers for the level of tone and also act as a relay, transferring impulses from the level of synergies to motor neurons.

2.3.0.1. Level B: Synergies. The level of control hierarchically above tone is that of muscular-articular links, or synergies. Bernstein related this level of control to the structural brain area of the pallidum in the deep regions of the brain. The motor output of this level projects downward to the red nuclei of the level of tone before being relayed on to the musculature. Central to the operation of this level is the thalamus, which receives a large amount of direct sensory information. This direct sensory information comes from all peripheral exteroceptors and proprioceptors. This rich supply of sensory information regarding the state of the body makes the thalamus especially well suited to perform sensory corrections of movement and ideal for participation in the organization of movement synergies. While areas adjacent to the thalamus also receive visual, auditory, and olfactory information as well as information from internal organs, the synergy level of control largely does not receive or utilize visual or auditory information.

Bernstein considered that through the process of encephalization, that is of new brain structures evolving and taking over functions that had previously been controlled by lower, older brain structures, the localization of his levels of control are in the process of migrating upward within the nervous system. The process of encephalization has made the thalamus less directly involved with the senses of vision and audition. This has caused the level of synergies to play less of a leading role in many actions, with encephalization moving the leading level of control for these actions to the level of either space or actions in higher brain structures. The large amount of proprioceptive information received by the thalamus, and the level of synergies in general, makes this level especially fit to provide internal consistency to movements. By typically playing a background role in movement this level oftentimes operates without conscious control and at least partially involuntarily. However, Bernstein stated that conscious control is capable of intervening in this level more than in the level of tone.

The internal consistency created by the synergy level of control makes the movements produced by this level look coherent and harmonious. Its functioning is not inborn but requires experience to build up the repertoire of synergies available for use. However, due to its relative lack of visual and auditory information, the synergy level requires higher level control to adapt it to environmental and task demands (Turvey & Carello, 1996). In the present study the operation of the synergy level was examined with regard to its control of a non-redundant postural coordination task. While some have considered synergies to be adaptive to environmental conditions (Latash, 2008) Bernstein hypothesized that this level of control was adapted to task and environmental demands by a separate level of control.

2.3.0.2. Level C: Space. Bernstein stated that the space level of control dates to the evolutionary origin of striated muscles or a skeleton with joints and that this level became needed when animals developed teleceptors and the ability to move in space. This level provides the basis for many athletic movements (gymnastics, track and field etc.). Bernstein considered this level to be in the middle of encephalization and to be leaving the extrapyramidal motor system, including the striatum and pallidum, and to be migrating to the pyramidal motor system, including the frontal central cortex, to become part of the cortical motor system. In this way the space level of control is in the evolutionary process of becoming cortical and pyramidal. At present this level uses both pyramidal and extrapyramidal motor system brain structures and also extensively utilizes the primary motor and sensory cortices. Movements by this level are typically aimed or purposive transferring movements. This is different than the movements controlled by the level of synergies, which are not 'purposive'. These purposive movements of the level of space are of the type typically found in redundant coordination tasks. In the present study this level will be examined with regard to its control of a redundant postural coordination task.

2.3.0.3. Level D: Actions. Bernstein's highest level of control is that of actions. This level is only seen in the highest mammals (e.g., horses, dogs, humans), but the operation of this level is so limited in other mammals that this level might be called the 'human level'. This level of control concerns the ability to create a chain structure across movements and to produce adaptive variability within behavior. For example, while a chicken won't go around a fence to get food (except by chance), a dog will. A monkey is also able to use a tool to pull the food to itself. These adaptive features of behavior indicate the operation of the action level of control.

2.3.1. Leading Level of Control

Within his hierarchical framework, Bernstein (1996) denoted a level of synergies, or muscular-articular links, as solving the problem of organizing the redundant degrees of freedom of the body into consistent spatio-temporal movement patterns. He hypothesized a level of space that is capable of leading the level of synergies so as to meet the demands of external conditions in the execution of a given task. Levels of tone and action are hierarchically located below and above, respectively, the levels of synergies and space. The levels of synergies, space or action may lead a movement depending upon the type of task and environmental conditions. Bernstein (1996) also proposed that the level to which attention is directed will lead in the control of movement.

According to Bernstein, consciousness resides at the level of control that is leading a movement, and by fixing consciousness on a background level (e.g., synergies) that level is brought to be the leading level of the movement. By attending to the movements of the body, rather than to a task goal, one brings the level of synergies to be the leading level of the movement. He said that while this may be valuable for instances of re-learning it can also have negative long-term consequences. He wrote an amusing story of a centipede that was unable to walk after a toad directed the centipede's attention to his legs. Bernstein's point was that when attending to the movements of the body the level of synergies is brought to the forefront of movement control. This is likely what oftentimes occurs in non-redundant coordination tasks when attention is directed to the task goal of producing a specific phase relation between body segments. This also is likely to occur in redundant coordination tasks when attention is directed to the body segments.

Prior research that may reflect the difference between whether the synergy or space level leads a movement is the constrained action hypothesis (McNevin & Wulf, 2002; Wulf, Lauterbach, & Toole, 1999; Wulf & Prinz, 2001). This hypothesis holds that attending to one's own body or movements, as opposed to external movement effects, may interfere with the self-organizing process responsible for functional movement production. Recent evidence suggests, however, that this phenomenon may be somewhat more complex than originally proposed (Perkins-Ceccato, Passmore, & Lee, 2003; Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002). The act of attending to one's body or movements is what Bernstein described as causing the level of synergies to lead movement. The interference with task performance described by the constrained action hypothesis when an internal focus of attention is used during performance may be due to the synergy level, rather than the space level, leading movement and may support Bernstein's conception of a hierarchical relation between these levels.

In prior research by Bardy and Faugloire the possibility of different levels of control operating within different types of tasks has not been addressed. Neither has the possibility been acknowledged that the dynamics pertaining to different levels of control (e.g., synergies and space) might differ from each other. The goal of this project is to ascertain the nature of the relation between these two levels of control in postural coordination.

2.4. Order and Control Parameters

The synergetic approach to the study of dynamic systems (Haken, 1977, 1984) utilizes the identification of an order parameter that describes a consistent and coherent organization of the components of a system. Control parameters, that need not be specific to the order parameter, lead the system through its possible states as described by the order parameter (Kelso, 1995). In bimanual coordination the relative phase between body segments has been identified as an order parameter and movement frequency as a control parameter (Kelso, 1981, 1984). In the study of hip-ankle coordination it has been found that the relative phase of hip and ankle segments is an order parameter (Bardy et al., 1999) and that movement frequency, height of center of mass, effective foot length and movement amplitude are all control parameters (Bardy et al., 1999, 2002).

Research by Bardy and colleagues has applied the synergetic approach to the study of coordination in the hip-ankle system (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2006, 2009). Their research has examined the production of hip-ankle coordination patterns both in non-redundant coordination tasks in which the explicit task goal is to produce a specified coordination pattern and also in a redundant coordination task in which a coordination solution emerges spontaneously from multiple potential solutions. The Bardy group hypothesized (Bardy et al., 2002; Faugloire et al., 2005, 2006) that the same dynamics previously found to operate in bimanual coordination will be found in the hip-ankle system. These researchers also hypothesized that the same coordination dynamics found when a specific coordination pattern is the task goal will similarly operate when coordination patterns spontaneously emerge in a redundant coordination task using the same effector system.

2.5. Hip-Ankle Coordination Dynamics

Bardy and colleagues (1999) began their study of hip-ankle coordination dynamics by determining the order and control parameters for this effector system. They found that two relative phase patterns typically occurred in a redundant postural tracking task in which the objective was to track a target on a visual display that oscillated toward and away from the participant. This task is redundant in that the task goal is to move the head and body synchronously with an oscillating target with the coordination between effectors left unspecified. The consistent coordination patterns were an approximately in-phase pattern (≈ 20°) and an antiphase pattern (≈ 180°). In terms of the synergetic approach these consistent patterns supported the consideration of relative phase as the order parameter of the system.

By manipulating the independent variables of movement amplitude and movement frequency Bardy and colleagues determined that these variables operated as control parameters that drove the hip-ankle system between in-phase and antiphase order parameter values. At low movement frequencies and amplitudes the in-phase coordination pattern was produced while the antiphase pattern was produced at higher movement frequencies and amplitudes. The height of the center of mass was also manipulated and was either raised approximately 5 cm by adding a 10 kg weight at the level of the neck or lowered approximately 9 cm by adding the same weight at the level of the knees. Lowering the body's center of mass increased the likelihood of an in-phase pattern being produced while raising the center of mass increased the occurrence of the antiphase pattern. The antero-posterior base of support, which Bardy et al. termed effective foot length, was also manipulated by having participants stand on a narrow antero-posterior support surface (short effective foot length) or by strapping them into boots that were rigidly connected to the floor (long effective foot length). They found that short effective foot length increased the occurrence of the antiphase pattern while long effective foot length increased the occurrence of the in-phase pattern.

Bardy et al. (2002) further examined the order-control parameter relation by reproducing the fundamental frequency scaling experiment that has been used in bimanual coordination (Kelso, 1984). They had participants perform the redundant postural tracking task across frequencies that increased or decreased from 0.05 Hz to 0.80 Hz in stepwise fashion. They found that as movement frequency increased a phase transition occurred from in-phase to antiphase. A transition from antiphase to in-phase also occurred as movement frequency was scaled down. The presence of phase transitions supported the view of this effector system as a dynamical system, as phase transitions are a property associated with dynamic systems. However, these findings differed from those of bimanual coordination in that the phase transitions occurred both from antiphase to in-phase as well as the reverse, while in bimanual coordination these transitions only occur from antiphase to in-phase. Also, in bimanual coordination the transition from antiphase to in-phase occurs as movement frequency is scaled up, while in the postural task the transition from antiphase to in-phase occurred as movement frequency was scaled down. A limitation of this study is that the finding of only two coordination patterns was based on the analysis of grouped data. Individual data were not examined to determine the number of coordination patterns present.

The Bardy group continued their research on hip-ankle coordination dynamics by examining the intrinsic dynamics of this system (Faugloire et al., 2005). This was done by applying the non-redundant scanning protocol used in bimanual coordination (Maslovat et al., 2005; Zanone & Kelso, 1992). In this protocol participants attempt to produce a range of coordination patterns ranging from 0° to either 180° or 360° with the effector system being examined. This task is non-redundant because the task goal is to move the effectors with a specified phase relation. In bimanual coordination it has been found that only the in-phase and antiphase patterns can typically be produced without additional practice (Zanone & Kelso, 1992, 1997). In the hip-ankle effector system Faugloire et al. (2005) found that the anthiphase, but not the in-phase, pattern could be produced in this non-redundant task. This is in contrast not only to bimanual coordination but also to the redundant postural tracking task in which both antiphase and in-phase (≈ 20°) patterns occurred. It is not clear why the number of stable coordination patterns is different in these redundant and non-redundant postural tasks.

Another study by these authors examined the ability to learn a new hip-ankle relative phase pattern and the influence of the pre-existing intrinsic dynamics on this process. Faugloire et al. (2006) had participants perform a postural tracking task at 0.25 and 0.65 Hz. At the slower frequency the in-phase hip-ankle coordination pattern was produced and the antiphase pattern at the faster movement frequency. Participants then practiced a 135° relative phase pattern with the hips and ankles. It was found that learning this pattern caused a shift of the in-phase and antiphase patterns toward the learned 135° relative phase pattern. This effect is consistent with the HKB model of bimanual coordination (Kelso, 1984; Schöner & Kelso, 1988). It was also found that the pre–existing stability of the intrinsic in-phase and antiphase patterns did not affect the ability to learn the new coordination pattern. These findings indicate transfer from the non-redundant coordination pattern that was learned to the redundant tracking task. However, no transfer occurred from the stability properties of the in-phase and antiphase patterns in the redundant task to the learning of the non-redundant task. This unidirectional transfer could potentially indicate a hierarchical relation between the control structures for these redundant and non-redundant coordination tasks, with the redundant task dependent up the non-redundant task. Such a hierarchical relation could be responsible for this directional effect in transfer.

The finding that the stability properties of the intrinsic dynamics did not affect the learning of a new coordination pattern is in contrast to both theory and experimental findings of bimanual coordination (Tallet, Kostrubiec, & Zanone, 2008; Zanone & Kelso, 1994). However, in bimanual coordination it is the stability properties of intrinsic patterns in the non-redundant task that have been found to affect the ability to learn a new coordination pattern (Tallet et al., 2008; Zanone & Kelso, 1994). Faugloire et al. (2006) estimated the stability of intrinsic patterns in the redundant task. It is not known why the stability of intrinsic patterns influences the learning of a new coordination pattern in bimanual but not in hip-ankle coordination. However, this difference in the task used to estimate intrinsic pattern stability in these studies could play a role in this inconsistent finding.

Faugloire et al. (2009) have also examined transfer of learning in the hip-ankle effector system. Participants performed a pre-test scan of the intrinsic dynamics landscape, then practiced a non-redundant 90° relative phase pattern with the hip and ankle for 3 days. Post- and retention test scans of the intrinsic dynamics were performed after the third day of practice and 1 week later, respectively. The learning of this new coordination pattern positively transferred across the intrinsic dynamics landscape, causing stable coordination patterns to be produced across the entire 0° ↔ 360° range. This is counter to both theory and experiment regarding bimanual coordination. In bimanual coordination, after learning a new coordination pattern other patterns decrease in instability, at least temporarily (Fontaine, Lee, & Swinnen, 1997; Kelso & Zanone, 2002; Lee, Swinnen, & Verschueren, 1995; Zanone & Kelso, 1992, 1994, 1997).

2.6. Analysis of Intrinsic Dynamics

As mentioned above a scanning protocol has been developed to characterize the stability properties of the underlying intrinsic dynamics of an effector system (Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992). In this method a participant attempts to produce a series of relative phase patterns that span the range of all potential patterns (0° ↔ 360°) with the body segments of interest. The stability, or lack thereof, and bias of the produced phasing relation between limbs are used to infer the layout of attractors in the intrinsic dynamics landscape. This scanning method has been developed (Yamanishi et al., 1980), studied (Maslovat, Bredin, Chua, & Franks, 2005), and applied in both the research on bimanual coordination (Zanone & Kelso, 1992, 1997; Kelso & Zanone, 2002) and studies of coordination in the hip-ankle effector system (Faugloire et al., 2005, 2006, 2009).

Refinements in the scanning protocol used to characterize the intrinsic dynamics of an effector system have occurred over the years. Some earlier studies (Tuller & Kelso, 1989; Zanone & Kelso, 1992, 1997) presented relative phase conditions in an ordered fashion (e.g. from 0° to 180° or 360° in continuously increasing increments) during the scanning protocol. However, a randomized ordering of relative phase conditions has also been employed (Kelso & Zanone, 2002; Faugloire et al., 2005; Yamanishi et al., 1980). This use of a randomized ordering of phase conditions counteracts the occurrence of order effects across subjects.

The use of a Lissajous figure has become common in both scanning and learning protocols. A Lissajous figure is an angle-angle plot with the angular positions of two joints plotted on the x- and y- axes. Maslovat et al. (2005) found that the use of a Lissajous figure with pacing information provided a more robust detection of changed intrinsic dynamics after learning than did a visual metronome. In a related study, Kovacs, Buchanan and Shea (2008) found that learning a novel relative phase coordination pattern occurred much more quickly with an unpaced, rather than a paced, form of Lissajous feedback. Each of these studies indicate that the form of perceptual information provided during the performance of novel coordination patterns can produce different learning results. It may be that the use of an unpaced Lissajous form of feedback may provide a more sensitive indication of the capacity of change within the intrinsic dynamics.

The maintenance of posture in the face of perturbations has previously been considered to consist of the use of either hip or ankle strategies, depending upon factors such as the properties of the support surface (Horak & MacPherson, 1996; Horak & Nashner, 1986; Horak, Nashner, & Diener, 1990; Massion, 1994; McCollum & Leen, 1989; Nashner, Shupert, Horak, & Black, 1989). However, in the hip and ankle strategies during postural perturbations both of these joints exhibit movement (Horak & Nashner, 1986; Horak et al., 1990; Nashner & McCollum, 1985). More recent research has also found that in these previously considered hip and ankle strategies the movement of these two body segments is actually coordinated (Bardy et al., 1999, 2002). These findings indicate that a complete understanding of postural maintenance should include an examination of the coordination between hip and ankle joints (Bardy et al., 1999).

The in-phase and antiphase coordination patterns have been found to be intrinsically stable in bimanual coordination (Fontaine et al., 1997; Kelso, 1984). In hip-ankle coordination these two patterns have also been found to be intrinsically stable when the level of space is leading in action (i.e., in a redundant task in which a coordination solution is not specified). However, only the antiphase pattern has been found to be inherently stable when the level of synergies is leading movement (i.e., when producing a specific coordination pattern is the task goal; Faugloire et al., 2005, 2006, 2009). Thus, only one coordination pattern is intrinsically stable within the intrinsic dynamics (as traditionally estimated by the scanning protocol) while two patterns are producible in a stable fashion in a redundant coordination task using the same effectors. This indicates that intrinsic dynamics, which are identified through the use of a scanning protocol utilizing a non-redundant coordination task, do not necessarily operate in the same way in the performance of a redundant coordination task with the same effectors. A limitation of the prior studies that found only the in-phase and antiphase patterns to be stable in redundant postural coordination is that the analysis was performed on averaged group data. Individual participant data were not examined to determine the number of stable coordination patterns occurring.

2.7. Transfer

Transfer occurs when the performance of one activity affects another (Adams, 1987). Studies of transfer have found this phenomenon can be positive, negative, neutral, retroactive or proactive and that factors such as task difficulty and the amount of original and interpolated learning affect the amount of transfer that occurs (Barcy & Lewis, 1954; Lewis, McAllister, & Adams, 1951; McAllister & Lewis, 1951).

Theoretical accounts of transfer, such as the Identical Elements Theory (Thorndike & Woodworth, 1901) have hypothesized that aspects of the tasks involved and their similarity may determine the type and amount of transfer that occurs. The Identical Elements Theory predicts that positive transfer occurs due to the separateness or similarity of functions involved in tasks. This theory holds that transfer between tasks occurs from either task to the other, in a bidirectional manner. Therefore, according to the Identical Elements Theory transfer should be of the same type (e.g., positive) whether the test of transfer is from a non-redundant to a redundant task, or vice versa. In contrast, from a hierarchical control perspective transfer might be unidirectional between two tasks controlled by a higher, and a lower, level of control, due to the hierarchical relation between these levels of control.

From this theoretical perspective elements that constitute the similarities between tasks include structural and surface characteristics (Holyoak, 1985). Structural elements are those that are causally related to the attainment of the task goal. Surface elements are those that contain no such relationship but that cause performers to perceive a similarity between tasks. Transfer has been hypothesized to result from even the perception of similarity between tasks. A perceived similarity between tasks will trigger memory retrieval and cause the learner to attempt transfer. Whether transfer is positive or negative will be determined by the features of each task (Gick & Holyoak, 1987). The amount of transfer is a function of perceived similarity between tasks while the direction of transfer is a function of structural similarity (Holyoak, 1985).

Subsequent work from the perspective of the Identical Elements Theory has hypothesized that the similarity between stimulus and response requirements produces transfer (Ellis, 1965; Osgood, 1949; Schmidt & Young, 1987). A theoretical transfer surface has been hypothesized that can be biased toward positive or negative transfer depending upon the similarity of stimulus and response in two tasks (Osgood, 1949). When responses in a second task are identical or similar to those in an original learning task the transfer surface is biased in the positive direction with the highest point equating to the sharing of identical responses. When stimuli remain the same but the responses differ the surface is tipped downward in the negative direction, due to interference. Much of this theoretical transfer surface is flat, equating to the occurrence of no transfer.

The performance of each task can involve common or distinctive processing functions and these have been considered to potentially affect transfer between tasks. Positive transfer has been considered more likely when performers process tasks in a similar way (Bransford & Franks, 1976; Bransford, Franks, Morris, & Stein, 1979; Lung & Dominowski, 1985; Morris, Bransford, & Franks, 1977). Learning a task that requires the combination of a new response with a stimulus from a previously learned task will result in negative transfer (Siipola, 1941).

While transfer has typically been measured in terms of task outcome, it is also possible to measure change that occurs due to interpolated learning in terms other than the task outcome (Whiting, 1984). In a redundant coordination task, for example, changes in the coordination pattern, rather than in task performance, could be measured before and after a bout of interpolated learning. A change in the coordination pattern, either in terms of the phase relation between body segments or the coordination pattern's stability properties, is not inherently positive or negative as such changes could result in either better or worse performance of the task goal.

Short and long term retention of motor skills have been studied extensively (Adams & Dijkstra, 1966; Hill, Rejall, & Thorndike, 1913; Hollingworth, 1909), however, the occurrence of transfer between motor skills has not typically been studied over a long enough time period to determine the duration of positive or negative transfer effects (see Adams, 1987 for a review). Many traditional studies of transfer have not performed more than one almost immediate post-test. However, several studies of bimanual coordination dynamics have examined the permanence, or lack thereof, of interference (i.e., negative transfer) effects. These studies have found conflicting evidence regarding whether retroactive interference from a learned bimanual coordination pattern to intrinsically stable bimanual patterns is permanent or transitory.

In the dynamical approach to studying coordinated behavior, existing models of bimanual coordination (Haken et al., 1985; Schöner et al., 1986) indicate that the number and stability properties of behavioral attractors affect the learning of a new coordination pattern. Experimental evidence has been found supporting this prediction (Schöner et al., 1992; Zanone & Kelso, 1992). The HKB and SHK models also predict that the learning of a new coordination pattern will produce a lasting destabilization of existing behavioral attractors (Zanone & Kelso, 1994). This prediction has received mixed support from experimental evidence, with some studies supporting this (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1994, 1997) while others show only a transient destabilization of existing behavioral attractors after learning a new coordination pattern (Fontaine et al., 1997; Lee et al., 1995). It is relevant that the behavior captured by the HKB model pertains to movements being led by the level of synergies, as the task goal is to produce an internally consistent movement pattern rather than to adapt a movement pattern to meet external task demands.

While studies of bimanual coordination have found that the learning of a new coordination pattern results in the attraction of nearby patterns toward the learned pattern (Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1994, 1997), quite a different phenomenon has been found in the study of hip-ankle coordination. In this effector system it was found that the learning of a new relative phase pattern led to positive transfer in all other coordination patterns with these effectors (Faugloire et al., 2009). Learning a novel hip-ankle non-redundant coordination pattern has also been found to modify the intrinsically stable in-phase and antiphase patterns in the direction of the learned coordination pattern as these intrinsically stable patterns emerge spontaneously in a tracking task (Faugloire et al., 2006). This was interpreted as an attraction of these stable patterns toward the learned pattern, as is consistent with the HKB model of bimanual coordination.

However, this finding of modified intrinsic dynamics after learning (Faugloire et al., 2006) pertains to movement with the level of space leading while the HKB model has generally been investigated only with regard to movements in which the level of synergies is leading (i.e. in non-redundant coordination tasks). The HKB model and associated predictions may be valid with regard to Bernstein's (1996) hypothesized level of synergies, but may not necessarily hold across levels of control (i.e., in redundant coordination tasks). Also, the finding of modified intrinsic patterns after learning by Faugloire et al. (2006) was only verified at two control parameter (movement frequency) values. The possibility remains that the examination of a range of movement frequencies would indicate that another process is responsible for this effect.

2.8. Timescales of Change

Another issue relevant to the study of learning and transfer is that different processes can be involved in the process of motor learning such as warm-up decrement (Adams, 1952), consolidation (Press, Casement, Pascual-Leone, & Robertson, 2005), and fatigue (Carron, 1969). It has also been found that different timescales can exist within the adaptive and persistent processes of learning (Mayer-Kress, Newell, & Liu, 2009; Newell et al., 2001; Smith, Ghazizadeh, & Shadmehr, 2006; Stratton et al. 2007). In the process of learning a novel bimanual coordination pattern three different timescales of change have been found (Wenderoth & Bock, 2001). It has also been theorized that different systems and subsystems within the nervous system may operate with different characteristic timescales (Newell et al., 2001). It remains a possibility that different characteristic timescales may exist for Bernstein's theoretical levels of control, such as space and synergies.

2.9. Summary

Recent research has begun to examine the dynamics of coordination in the hip-ankle effector system while engaging in a postural task (Bardy et al., 1999, 2002; Faugloire et al., 2005, 2006, 2009). Basing hypotheses upon prior theoretical and experimental study of bimanual coordination (Haken et al., 1985; Kelso, 1984; Kelso & Zanone, 2002; Schöner et al., 1986), this research has found mixed evidence for the application of existing theory (HKB and SHK models), with both predicted and unexpected changes in coordination patterns occurring. Much remains unclear regarding the dynamics operating in non-redundant coordination tasks that specify a particular coordination pattern and those operating in redundant coordination tasks in which coordination patterns are unspecified and emerge spontaneously.

The recent research on hip-ankle coordination dynamics has not specifically addressed, in theoretical terms, the fact that different dynamics may exist in redundant coordination tasks and those in which a specific coordination pattern is the task goal (as is typically the case in bimanual coordination protocols). The work of Bernstein (1996) may provide a theoretical base for advancing our understanding of the dynamics operating in these two types of coordination tasks. Bernstein hypothesized hierarchical levels of control within the nervous system, with the level of synergies producing internally consistent spatio-temporal movement patterns and the level of space adapting these synergies to meet task demands within an environmental context. The type of task and the focus of attention can determine which level of control is leading a movement. The space level of control typically leads in movements involving an external task goal, such as typically exist in redundant coordination tasks. The synergy level of control typically leads movements in which attention is directed to body segments, such as may occur in non-redundant coordination tasks.

This project utilized prior theoretical perspectives that hypothesizes the existence of different control structures that pertain to: a) the organization of coordinated movement patterns; and b) the adaptation of these patterns to environmental and task demands (Bear et al., 2001; Bernstein, 1996; Latash, 1998; McArdle et al., 1996) as a theoretical guide for studying coordination dynamics in the hip-ankle effector system. Our goal was to clarify the ways in which existing coordination dynamics theory may or may not apply to redundant coordination tasks. The project also sought to explain discrepancies between existing theory and prior experimental results and to more closely examine the accuracy of prior conclusions regarding coordination dynamics.

CHAPTER 3. EXPERIMENTS 1 AND 2

3.0. Abstract

Prior studies of postural coordination have shown phenomena such as bidirectional phase transitions and transfer of learning that are inconsistent with those of bimanual coordination. These inconsistencies were investigated by testing the hypothesis that there are different hierarchical control structures for redundant and non-redundant coordination tasks (Bernstein, 1996). The transfer between a non-redundant postural tracking task and a redundant scanning task consisting of 16 hip-ankle relative phase patterns from 0° ↔ 337.5° was investigated. The results showed that the transfer between the tasks was transitory, negative and occurred only from the non-redundant to the redundant task. This finding supports the hypothesis that inconsistencies between hip-ankle and bimanual coordination dynamics are due to different hierarchical control structures in the performance of these tasks.

3.1. Introduction

The findings on hip-ankle coordination dynamics in postural control have been both consistent and inconsistent with the Haken, Kelso and Bunz (HKB) model (1985) and empirical data on bimanual coordination. In the performance of a supra-postural tracking task both in-phase and antiphase patterns have been found in hip-ankle coordination (Bardy, Marin, Stoffregen, & Bootsma, 1999), which is consistent with a core tenet of the HKB model of bimanual coordination (Kelso, 1984; Lee, Swinnen, & Verschueren, 1995; Post, Peper, Daffertshofer, & Beek, 2000). The phenomena of phase transitions and hysteresis have also been found in hip-ankle coordination (Bardy, Oullier, Bootsma, & Stoffregen, 2002). Furthermore, learning a new hip-ankle coordination pattern leads to the intrinsically stable coordination patterns (in-phase and antiphase) being modified in the direction of the learned pattern (Faugloire, Bardy, & Stoffregen, 2006). These findings are all consistent with the HKB model (Haken et al., 1985; Schöner, Haken, & Kelso, 1986; Schöner & Kelso, 1988).

Inconsistencies between findings on hip-ankle and bimanual coordination dynamics include the directional nature of phase transitions. In bimanual coordination phase transitions only occur from antiphase to in-phase as movement frequency is scaled up (Kelso, 1984). In the supra-postural tracking task utilized to study hip-ankle coordination, transitions have been found to occur both from in-phase to antiphase and vice versa (Bardy et al., 2002). Also, the transition from antiphase to in-phase in the postural tracking task occurs as movement frequency is scaled down, rather than up as in bimanual coordination.

It has also been shown that while both the antiphase and in-phase coordination patterns are produced spontaneously in the postural tracking task only the antiphase pattern can typically be produced intentionally with the hip and ankle (Faugloire, Bardy, Merhi, & Stoffregen, 2005). In bimanual coordination, however, both of these patterns can be produced intentionally. Another discrepancy between bimanual and hip-ankle coordination is that in the latter the learning of a single new coordination pattern has been found to transfer positively across the entire intrinsic dynamics landscape (Faugloire, Bardy, & Stoffregen, 2009). This type of transfer effect has not been found in bimanual coordination dynamics.

A theory-based approach may be useful in clarifying the empirical discrepancies between bimanual and hip-ankle coordination. The theory of hierarchical control structures of the nervous system (Bernstein, 1996; Jackson, 1932; Kandel, Schwartz, & Jessup, 2000) provides a framework to begin examining differences in the coordination dynamics operating in different types of tasks. Bernstein (1996) proposed hierarchical control levels of *action*, *space*, *muscular-articular links* and *tone*. Within this hierarchy the level of muscular-articular links (also known as synergies) organizes internally consistent spatio-temporal coordination patterns while the next higher level of space adapts the output of the synergy level to an environmental and task context (Turvey, 2007; Turvey & Carello, 1996).

The level of space is capable of leading the level of synergies so as to meet the demands of external conditions in the execution of a given task. Levels of tone and action are hierarchically located below and above, respectively, the levels of synergies and space. The levels of synergies, space or action may lead a movement depending upon the type of task and environmental conditions. Bernstein (1996) hypothesized that the level to which attention is directed will lead in the control of movement. In his hypothesis consciousness resides at the level of control that is leading a movement, and by fixing consciousness on a background level (e.g., synergies) that level is brought to be the leading level of the movement. By attending to the movements of the body, rather than to a task goal, the level of synergies becomes the leading level of movement. It is proposed that this is what occurs in non-redundant coordination tasks when attention is directed to the task goal of producing a specific phase relation between body segments. This also applies to redundant coordination tasks when attention is directed to the body segments. According to this hypothesis the HKB model pertains to movements being led by the level of synergies, as the task goal is principally to produce an internally consistent movement pattern rather than to adapt a movement pattern to meet external task demands.

Another experimental approach that can be used to investigate the organization of control within the nervous system is the study of transfer effects. Transfer refers to the effects of performing one task upon the performance of another (Adams, 1987; Holyoak, 1985; Osgood, 1949; Thorndike & Woodworth, 1901). These effects may be positive, negative, or neutral and can affect tasks already learned (retroactive transfer) or the learning of new tasks (proactive transfer). The type (e.g., negative) and direction (e.g., from one task to another, but not vice versa) of transfer that occurs between two tasks may indicate the organization of the control structures used in the tasks under consideration.

Dynamic systems theory accounts for transfer effects as the incorporation of new behavioral patterns into an existing intrinsic dynamics landscape. From this theoretical perspective, transfer occurs as the result of the cooperation or competition of behavioral information with a preexisting intrinsic dynamics landscape (Von Holst, 1937/1973; Zanone & Kelso, 1994). For example, in the HKB model (Schöner & Kelso, 1988) learning a new relative phase pattern produces changes across the intrinsic dynamics landscape, such as the creation of a stable symmetrical coordination pattern (e.g., stabilization of the 270° relative phase pattern after learning the 90° pattern).

The HKB model predicts that the stability of the intrinsic dynamics will affect the ability to learn a new relative phase pattern (Zanone & Kelso, 1994). In the hip-ankle effector system preliminary experimental findings have indicated that this is not the case (Faugloire et al., 2006). One potential explanation for this inconsistency is that different control structures are involved in the hip-ankle and bimanual tasks and that the HKB model does not capture the dynamics associated with the control structures for each of these tasks.

In the study by Faugloire et al. (2006) the tasks performed were: a) a redundant coordination task that involved tracking an oscillating target with the head and body, and b) a non-redundant coordination task of producing specific coordination patterns with the hip-ankle effector system. A potential explanation for the finding that the stability of intrinsic patterns is not affected by the learning of a new pattern is that the HKB model may only capture the dynamics of the control structure for the production of the non-redundant coordination task. It may not capture the dynamics of the structure for performance of the redundant tracking task.

Non-redundant coordination tasks such as are generally used in studies of bimanual coordination map to Bernstein's (1996) description of internally-consistent movement patterns that are controlled by the level of synergies. Redundant coordination tasks (such as the tracking task employed by Faugloire et al., 2006) map to Bernstein's description of tasks controlled by the level of space. This is the level that adapts the internally consistent movement patterns produced by the level of synergies to an environmental and task context. It is hypothesized here that the control structure that is captured by the HKB model may lead movement in non-redundant hip-ankle coordination and bimanual coordination tasks but that a different control structure, such as Bernstein's level of space, may lead movement in the performance of the redundant tracking task utilized by Bardy et al. (2002). Different dynamics may govern the operation of each level of control, thereby leading to inconsistent findings when comparing the dynamics arising in redundant and non-redundant tasks.

It has been shown that learning a novel coordination pattern increases the stability of the intrinsic dynamics in the hip-ankle effector system (Faugloire et al., 2009). In the present study we investigate the hypothesis that: a) the repeated performance of a range of relative phase patterns, all of which are likely to be novel patterns except for antiphase (Faugloire et al., 2005), will produce an increase in the stability of the intrinsic dynamics in the hip-ankle effector system. If in redundant coordination tasks a higher level control structure utilizes lower level control output to meet task demands (Bernstein, 1996) a change (e.g., a stabilization) in the lower level of control may require an adaptive reorganization before the higher level of control can effectively utilize the altered lower level output to meet task demands. Therefore, if the performance of novel coordination patterns causes a stabilization of hip-ankle intrinsic dynamics this may cause interference with higher level task performance. However, a change in the higher level of control need not require a re-organization in its coupling with a lower level because of the hierarchical relation between these levels. Based upon this hierarchical dependence of the higher space level of control upon the lower synergy level it was also hypothesized that: a) the performance of novel hip-ankle coordination patterns would negatively transfer to the tracking task; and b) the performance of the tracking task would not transfer to the performance of novel coordination patterns.

3.2. Experiment 1

In Experiment 1 the hypothesis was tested that transitory negative interference would occur from a non-redundant relative phase scanning task to a redundant postural tracking task involving the hip and ankle effector system. If the control structure for the redundant task is hierarchically above, and dependent upon, the control structure for the non-redundant task a reorganization in the lower level may interfere with performance on the redundant task.

3.2.0. Methods

3.2.0.0. Participants. Volunteer participants (N= 27, 13 males, 14 females; *M* = 21.78, *SD* = 2.19 years) were recruited from The Pennsylvania State University student body. The participants signed informed consent forms approved by the University Institutional Review Board committee and were compensated for their time. All reported normal or corrected-to-normal vision and no history of neurological disorder or surgery to the legs. They were not informed about the topic of study. Their mean height was 1.71 (*SD* = 0.09) m and their mean mass was 69.65 (*SD* = 11.66) kg.

All participants performed pre- and post-tests of a postural tracking task. Those randomly assigned to the experimental scanning group also performed a hip-ankle scanning task between tests on the tracking task. 12 participants from the experimental scanning (n = 6) and sway control (n = 6) groups were randomly selected to perform an additional 24 hr retention test consisting of two blocks of the tracking task.

3.2.0.1. Apparatus. A Celesco (Chatsworth, CA) SP2-50 string-potentiometer was attached to the back of a hat worn by participants to measure antero-posterior displacement of the head. Two Celesco electrogoniometers (models XM110 and XM180) with an accuracy of +/- 1° were fixed to participants' right hip and ankle joints using adhesive tape.

An InFocus (Wilsonville, OR) projector was used to project concurrent visual feedback onto the wall in front of participants. Data from the potentiometer and goniometers were collected at 100 Hz and subsequently filtered with a recursive, lowpass Butterworth filter with a cutoff frequency of 2 Hz. This cutoff frequency was used as high frequency movement characteristics are not captured by the point estimate used to calculate relative phase (Faugloire et al., 2006).

3.2.0.2. Procedures. Participants were randomly assigned to one of 3 groups; an experimental scanning group (n=11), a sway control group (n=11) and a rest control group (n=5). Tasks were performed in a standing position and included tracking a visually projected oscillating target with the head and a scanning protocol in which specific hip-ankle coordination patterns were produced. The experimental design followed an A:B:A format. Task A was the tracking task and Task B was either the scanning task (performed by the scanning group), simple postural swaying movements (performed by the sway control group) or seated rest (performed by the rest control group). The scanning group performed the tracking task, then the scanning task followed by a second performance of the tracking task. The rest control group performed the tracking task, followed by seated rest for the same duration of time as required to complete the scanning task, followed by a second performance of the tracking task. The sway control group performed the tracking task, then performed oscillating body movements at a self-selected frequency and amplitude that were similar to those performed in both the tracking and scanning tasks. The same number of cycles of the sway control movements were performed by the sway control group as was performed in the scanning task by the experimental scanning group.

To test the persistence of learning effects 12 participants in the scanning (n = 6) and sway control (n = 6) groups performed a 24 hr retention test of the tracking task. The sway control group was selected to perform this retention test rather than the rest control group as it was determined on the initial day of testing that the sway control group performed more similarly to the scanning group. In this way the sway control group provided a more conservative approach for retention testing.

The protocol was designed to test if negative transfer occurs from a non-redundant to a redundant coordination task involving the same effector system (hips and ankles) in each task. The redundant coordination task utilized was a tracking task in which a visually projected oscillating target was tracked by moving the head and body in an antero-posterior direction with the coordination of hip and ankle joints left unspecified. Visually projected concurrent feedback provided information regarding the discrepancy between the participant's head and the oscillating target. This visual feedback consisted of two dots, that moved vertically, projected onto the wall directly in front of the participant. One dot pertained to a target that oscillated vertically at a specified frequency and the second dot depicted the participant's head position, thereby providing feedback regarding tracking task performance. The previous studies of postural coordination have provided a visual display of a moving target during the postural tracking task but not concurrent visual feedback regarding task performance (Bardy et al., 2002; Faugloire et al., 2006; Faugloire et al., 2009). In previous studies (Faugloire et al., 2005, 2006, 2009) concurrent visual feedback regarding error in scanning task performance was provided. As the purpose of the present study was to compare possible transfer effects in each task it was necessary to provide concurrent visual feedback regarding task error during the performance of each task.

A head movement of 10 cm was necessary to match the movement of the oscillating target. All visual feedback was projected a distance of 2.5 m from the participants with the target moving through a visual angle of 7°. The tracking task was performed at two different target oscillation frequencies: 0.15 and 0.75 Hz. In each test (pre-test, post-test, 1st and 2nd retention tests) participants performed 1 block of 5 trials at each frequency. Each trial was of 1 min duration at each frequency and 1 min of rest was given between trials and 3 min rest between tasks. The order of tracking task frequency presentation was counterbalanced across participants and all participants were given 3 min to familiarize themselves with the performance of each task.

The non-redundant coordination task employed was a scanning task in which participants performed hip-ankle coordination patterns spanning the range of 0° → 337.5° in 22.5° increments. This protocol has previously been utilized to characterize the intrinsic dynamics of effector systems (Zanone & Kelso, 1992; Faugloire et al., 2009). This task was only performed by the scanning group between the pre- and post-tests of the tracking task. One trial was performed at each required relative phase condition with 33 movement cycles performed in each trial. The order of relative phase condition presentation was randomized for each participant. Participants were instructed to keep their knees extended, their feet flat on the floor, and to cross their arms across their chest at all times during the performance of each task.

During performance of the scanning task concurrent visual feedback depicting hip and ankle position was projected onto the wall in front of participants. This feedback consisted of a Lissajous plot of hip and ankle positions (on the *x*- and *y*- axes, respectively) in conjunction with a target pattern pertaining to specific relative phase patterns of the hip and ankle that participants were to reproduce by appropriately moving these joints. An example of this feedback is represented in Figure 3.1.

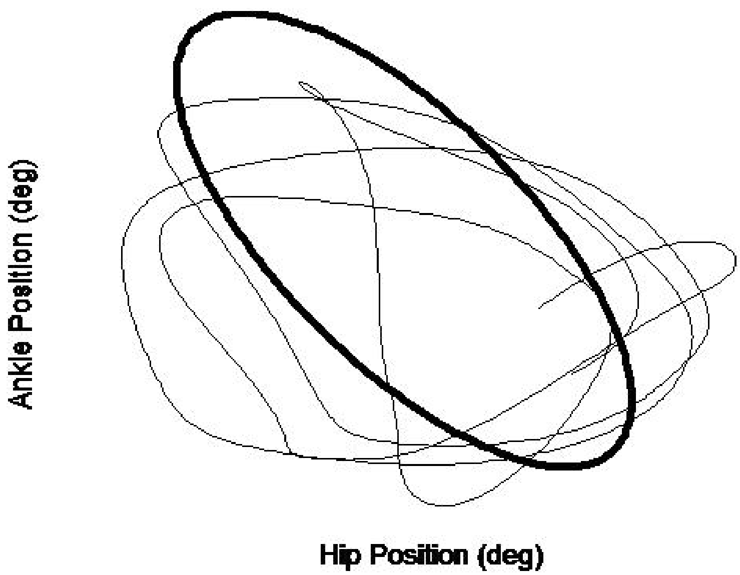

Figure 3.1. Representation of the visual feedback provided to participants depicting relative phase target (bold line) and feedback of participant movement (fine line).

3.2.0.3. Data analyses. The root mean square error (RMSE) between head and target position was used to operationalize tracking task performance. The RMSE of the last 3 out of 5 trials in each tracking task condition was averaged and used in subsequent inferential statistical analyses. The first 2 trials in each test were discarded to eliminate the possible inclusion of warm-up effects during these trials. An example of head and target data in the 0.75 Hz condition is shown in Figure 3.2a.

In keeping with prior studies (Faugloire et al., 2006, 2009) a point estimate of relative phase was used to estimate the relative phase of hip and ankle joints with both

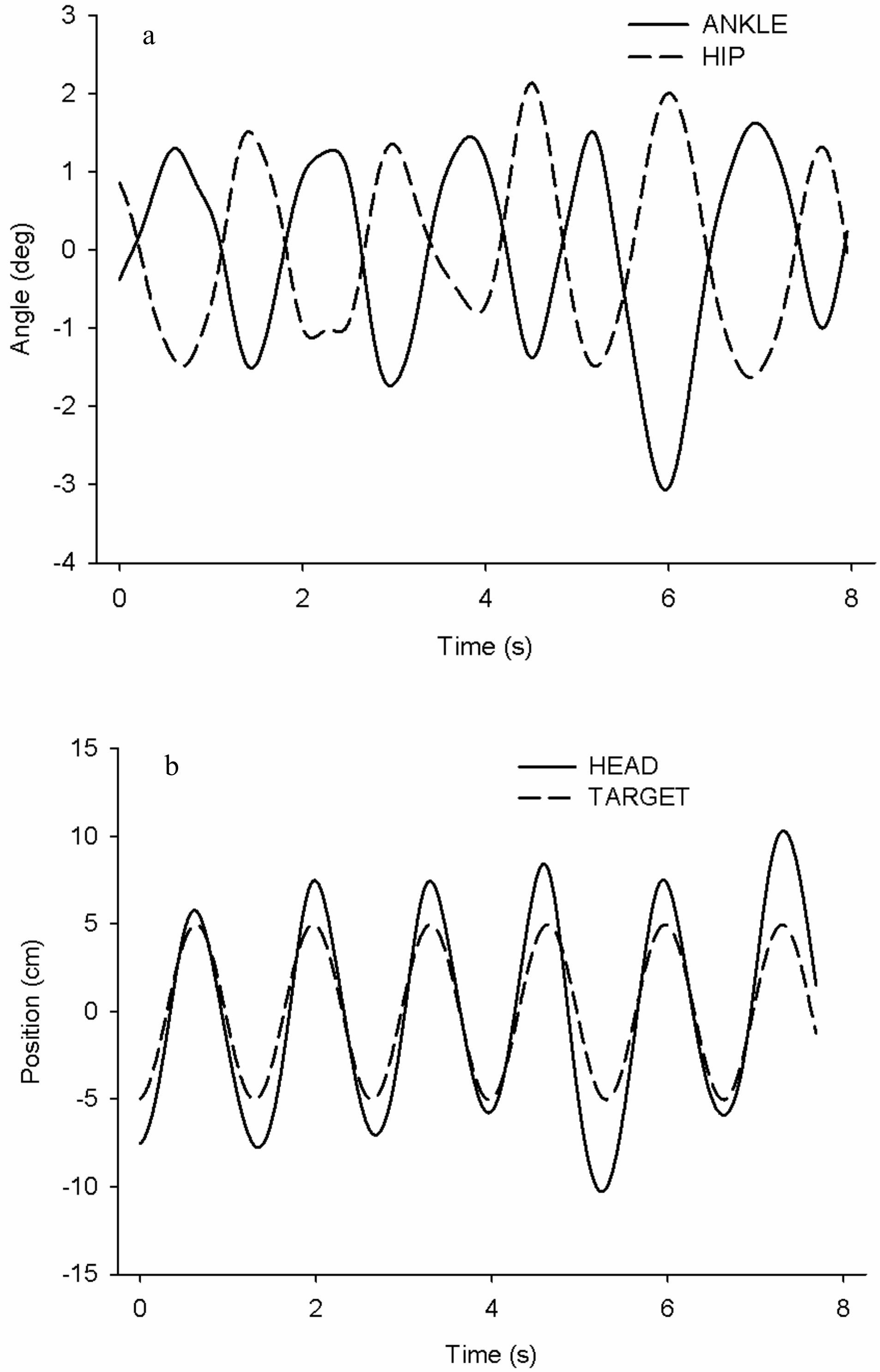

Figure 3.2. Exemplar data of a) head and ankle displacement, and b) hip and ankle displacement in the 0.75 Hz frequency condition.

endpoints of movement (maximum flexion and extension) included in this calculation. For the calculation of relative phase in the tracking task, the first movement cycle was eliminated from analysis to remove possible transient fluctuations. The point relative phase values for the following 6 (for the 0.15 Hz task frequency condition), or 33 (for the 0.75 Hz task frequency condition), movement cycles were calculated for both points or maximum flexion and extension of joint movement. The 12 (for 0.15 Hz), or 66 (for 0.75 Hz), point relative phase values from each of the final 3 trials at each frequency were combined and analyzed to determine mean relative phase and relative phase entropy for each participant. An example of hip and ankle displacement data in the 0.75 Hz condition is represented in Figure 3.2b.

In the scanning task a total of 33 movement cycles were performed in each relative phase condition. The first 3 movement cycles were eliminated from analysis to remove possible transient fluctuations. The point relative phase values for the following 30 movement cycles were calculated for both points of maximum flexion and extension of joint movements. These 60 point relative phase values were analyzed to determine the mean relative phase and relative phase entropy for each participant in each relative phase condition.

Standard circular statistics (Batschelet, 1981) were used to estimate the mean relative phase of point relative phase values in both scanning and tracking task trials. The Rayleigh uniformity test (Batschelet, 1981) was used to determine if relative phase distributions could be distinguished from a uniform distribution with 95% confidence. For relative phase time series that were statistically distinguishable from a uniform distribution the mean relative phase and inter-participant *SD* were calculated.

The information entropy of relative phase was used to estimate the variability of relative phase time series. The equation for information entropy is (Williams, 1997):

$$I_w = -\sum_{i=1}^{N} P_i \log P_i \qquad (1)$$

where I_w is information entropy, i is each of a total of N data values and P is the probability of data occurring in each bin. A bin size of 5° was used to determine the probability of relative phase occurrences across the 0° ↔ 360° range. Relative phase entropy was used as an estimate of variability because it does not depend upon the assumption of a von Mises distribution (the circular counterpart to the Gaussian distribution), as does the use of the circular *SD*. Because of this, relative phase entropy allowed an estimation of variability even in experimental trials that could not be distinguished from a uniform distribution with 95% confidence.

RMSE and relative phase entropy were each analyzed using a 3 (Group) × 2 (Test) × 2 (Frequency) repeated measures ANOVA for the 1-day testing and a 2 (Group) × 4 (Test) × 2 (Frequency) ANOVA for the 2 groups that performed the 24 hr retention testing. The calculation of all dependent variables was performed with coded MATLAB (Mathworks, Natick, MA) programs. Inferential statistical analyses were performed using the SPSS software package and circular statistical analyses were performed with Oriana (Anglesey, Wales) software. All pairwise comparisons were conducted using the LSD (Lease Significant Difference) method.

In this experiment the main interest was to detect if transitory negative transfer occurred from the scanning task to the tracking task. Data were examined to determine if performance of the scanning task caused: a) a decrement in tracking task performance (RMSE) across testing sessions compared to the control group, and b) a change in the variability (relative phase entropy) of hip-ankle coordination patterns during the performance of the tracking task. Hypothesis a) would be supported by a significant Test × Group interaction in RMSE, with the scanning group not improving as much as the rest and sway control groups. Hypothesis b) would be supported by a significant Test × Group interaction in relative phase entropy with a different pattern of change occurring in the scanning group than in the control groups. Descriptive statistics of hip and ankle movement amplitude and relative phase for all tasks are also included, though not used to test experimental hypotheses.

3.2.1. Results

3.2.1.0. Root mean square error. Support for the first experimental hypothesis was found in the 1-day testing groups given a significant Test × Group interaction in RMSE, $F(2,24) = 6.72$, $p < 0.01$. As can be seen in Figure 3.3a the general trend was greater improvement in task performance (lower RMSE) in the control groups than in the scanning group. This supports the experimental hypothesis that performance of the scanning task would have a negative effect on the tracking task in the scanning group. *Post hoc* testing determined that the post-test RMSE was lower than the pre-test in the scanning ($p < 0.05$), sway control ($p < 0.001$) and rest control ($p < 0.001$) groups. In neither pre-test nor post-test were there any significant differences between groups (all $p > 0.05$).

As depicted in Figure 3.3b there was a significant Test × Group interaction in the 24 hr retention groups, $F(3,30) = 4.72$, $p < 0.01$. *Post hoc* analysis determined that the scanning group had no significant improvement in RMSE from the pre-test to the post-test ($p > 0.05$). However, there was a significant improvement in the scanning group after 24 hrs as both retention tests were lower than either the pre-test or post-test (all $p < 0.001$).

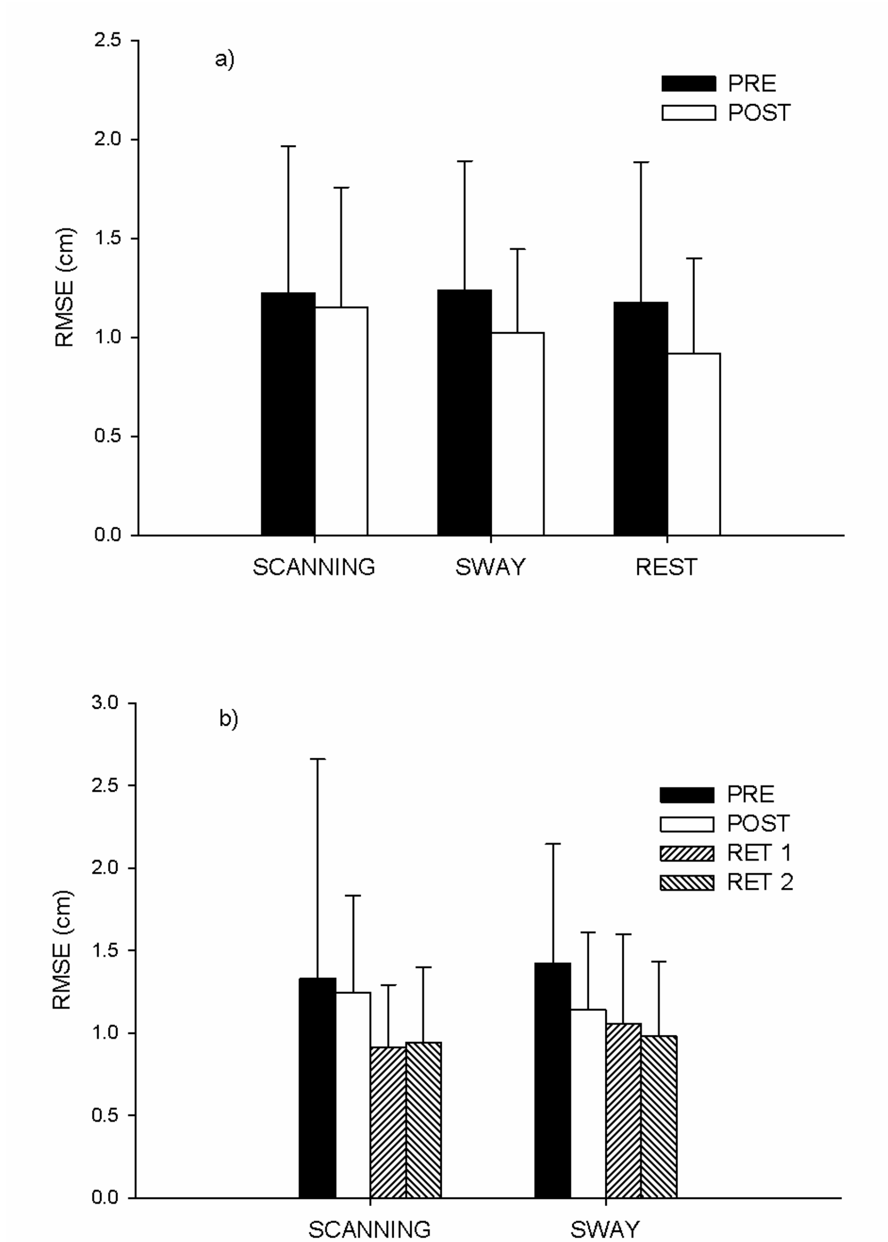

Figure 3.3. Root mean square error as a function of group and test for a) the 1-day groups, and b) the 24 hr groups. PRE = pre-test, POST = post-test, RET 1 = first retention test, RET 2 = second retention test. SCANNING = experimental scanning group, SWAY = sway control group, REST = rest control group. Standard error bars are shown.

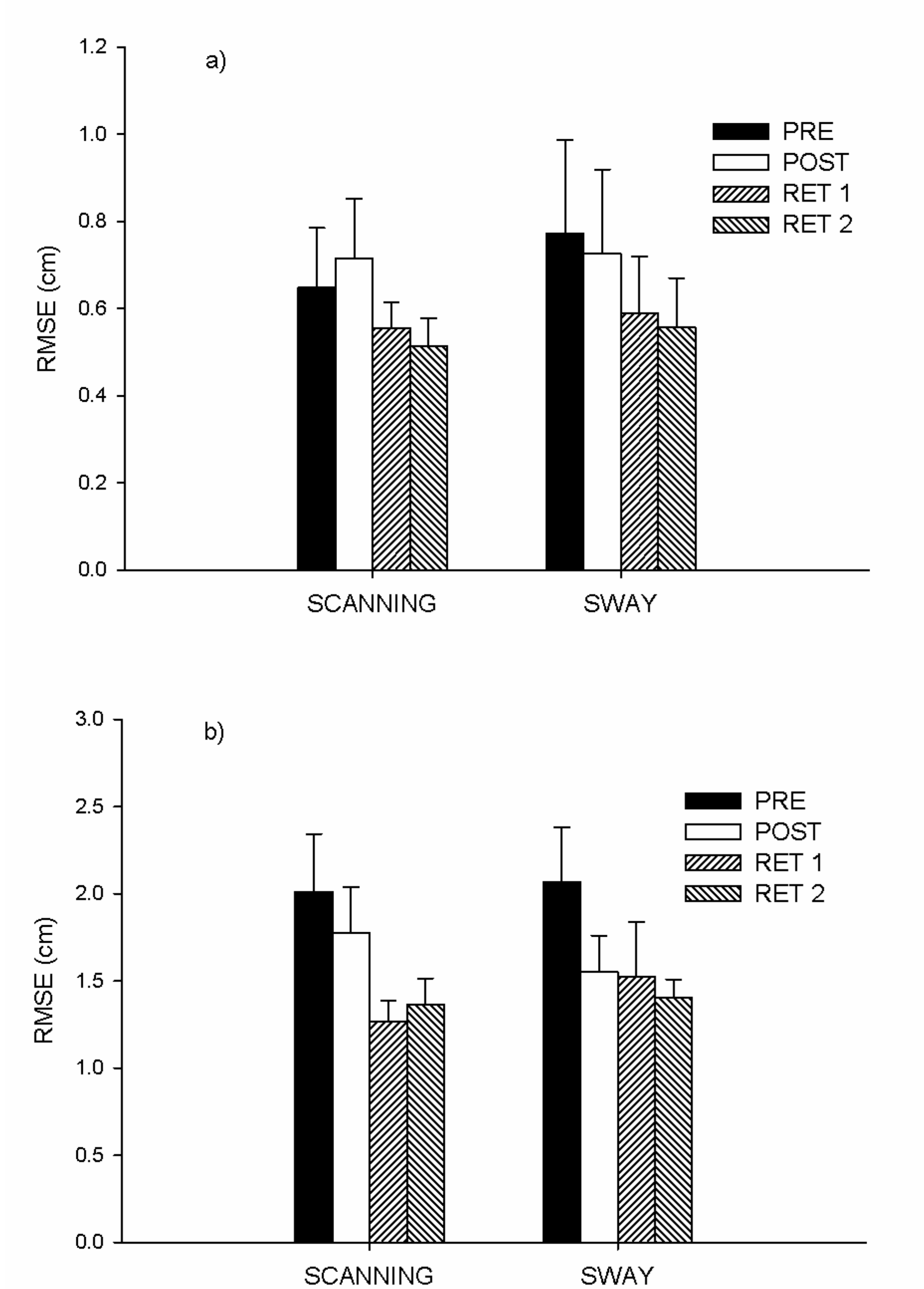

Figure 3.4. Root mean square error a function of group, test and frequency for the 24 hr retention groups. A) 0.15 Hz RMSE, b) 0.75 Hz RMSE. PRE = Pre-test, POST = post-test, RET 1 = first retention test, RET 2 = second retention test. SCANNING = experimental scanning group, SWAY = sway control group. Standard deviation is shown by error bars.

The sway control group improved significantly from the pre-test to the post-test as well as from the pre-test to each retention test (all $p < 0.001$) and from the post-test to the second retention test ($p < 0.05$). As found in the 1-day testing groups, these results demonstrate that there was an immediate improvement in task performance (lower RMSE) in the control groups while this improvement was delayed in the scanning group. This supports the first experimental hypothesis that transitory negative transfer would occur from the scanning task to the tracking task.

In the 24 hr groups there was a main effect for Test on RMSE with the post-test significantly lower than the pre-test, $F(3,30) = 60.49$, $p < 0.001$. A significant main effect for Frequency occurred with the 0.15 Hz task significantly lower than that of the 0.75 Hz task, $F\ (1,10) = 215.78$; $p < 0.001$. There was no difference between groups, $F(1,10) = 0.41$, $p > 0.05$, and the Frequency × Group interaction was not significant, $F(1,10) = 0.02$, $p > 0.05$.

In the 24 hr testing groups there was also a significant Test × Frequency × Group interaction, $F(3,30) = 3.06$, $p < 0.05$. *Post hoc* tests showed that improvement in tracking task performance from the pre-test to post-test occurred in the sway control group in the 0.75 Hz task frequency condition ($p = 0.001$) but not in the scanning group (see Figure 3.4b). This shows that the negative transfer from the scanning task to the tracking task was specifically in the 0.75 Hz task condition. There was no improvement in the 0.15 Hz task in either group (all $p > 0.05$).

<u>3.2.1.1. Relative phase entropy.</u> Relative phase entropy was examined to determine the changes in the emergent hip and ankle coordination patterns that accompanied the above changes in tracking task performance (RMSE). It was found that the scanning task caused a transitory decrease in hip-ankle coordination variability, thereby supporting the second

experimental hypothesis. In the 1-day groups a significant Test effect occurred, indicating an overall decrease in variability from the pre-test to the post-test, $F(1,24) = 21.66$, $p < 0.001$. Represented in Figure 3.5 is the significant Test × Group interaction, $F(2,24) = 3.88$, $p < 0.05$, with *post hoc* analysis showing that the post-test entropy was lower than the pre-test only in the scanning group ($p < 0.001$). There were no significant differences between testing sessions in either the sway or rest control groups (both $p > 0.05$). Also, in the post-test the scanning group had significantly lower entropy than the sway control group ($p < 0.05$; see Figure 3.5).

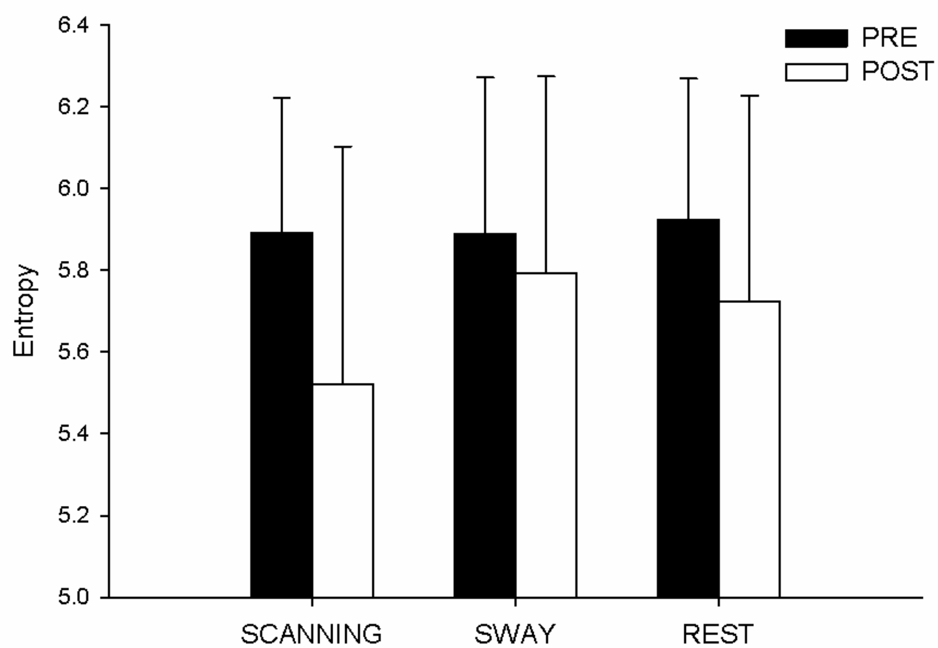

Figure 3.5. Relative Phase entropy as a function of group and test in the 1-day testing groups on the tracking task. PRE = pre-test, POST = post-test, SCANNING = scanning experimental group, SWAY = sway control group, REST = rest control group. Standard deviation bars are shown.

These results indicate that performance of the scanning task led to a significant decrease in relative phase entropy from the pre-test to the post-test that did not occur in either of the control groups. The 1-day groups showed a significant Frequency effect, $F(1,24) = 47.87$, $p < 0.001$, with lower entropy in the 0.75 Hz condition. There was no significant Group effect, $F(2,24) = 1.16$, $p > 0.05$, Frequency × Group, $F(1,24) = 1.06$, $p > 0.05$, or Test × Frequency × Group interaction, $F(2,25) = 2.96$, $p > 0.05$.

Similar test effects were also present in the 24 hr test conditions, $F(3,30) = 8.27$, $p = 0.001$. *Post hoc* analysis showed that post-test entropy was significantly lower than the pre-test ($p < 0.05$), and both the first ($p < .01$) and second ($p = 0.001$) retention tests (see Figure 3.7.). As shown in Figure 3.6 there was a significant Test × Group interaction, $F(3,30) = 3.35$, $p < 0.05$. *Post hoc* analysis showed that the only differences between testing periods were within the scanning group. In this group the post-test entropy was lower than the pre-test ($p < 0.01$; see Figure 3.6). This supports the hypothesis that the scanning task leads to a change in the relative phase entropy in the scanning group. *Post hoc* testing also showed that this change in entropy was only transitory, as entropy returned to a significantly higher level in the first ($p = 0.001$) and second ($p < 0.001$) retention tests and with no significant differences between the pre-test and either of the retention tests.

On the post-test the 24-hr scanning group had significantly lower entropy than the sway control group ($p < 0.01$). This lower entropy in the post-test by the scanning group also contributed to a significant Group effect, $F(1,10) = 5.53$, $p < 0.05$, in which the scanning group entropy was lower than that of the sway group. These changes within the scanning group across testing sessions are in contrast to the sway group, in which no significant differences between testing sessions occurred (all $p > 0.05$).

As shown in Figure 3.6 there was also a significant Test × Frequency × Group interaction, $F(3,30) = 3.13$, $p < 0.05$. *Post hoc* analysis showed that at post-test within the 0.75 Hz frequency condition the scanning group had lower entropy than the sway group ($p < 0.01$). Also, in the scanning group during the 0.15 Hz frequency task condition the post-test entropy was lower than in both the first ($p < 0.05$) and second ($p < 0.01$) retention tests. In the scanning group during the 0.75 Hz frequency task condition the post-test entropy was lower than the pre-test ($p < 0.01$) and both retention tests (both $p = 0.001$). These findings support the hypothesis that the scanning task would alter the coordination variability in the scanning group.

<u>3.2.1.2. Hip and ankle joint amplitude.</u> In the 1-day groups the mean amplitude of hip movement was 3.99° (*SD* = 1.73°) and for the ankle 3.62° (*SD* = 1.60°). In the 24 hr retention groups the mean hip movement was 3.88° (*SD* = 1.81°) and for ankle 3.49° (*SD* = 1.39°). In the scanning task performed by the scanning group the mean ankle joint movement amplitude was 4.30° (*SD* = 0.51°) and for the hip 3.82° (*SD* = 0.59°).

For the sway control movements performed by the sway control group the mean hip movement amplitude was 3.96° (*SD* = 1.91°) and for the ankle 3.33° (*SD* = 1.34°) in the 1-day groups. The mean sway frequency of this group was 0.76 Hz (*SD* = 0.33 Hz). In the 24 hour retention groups the mean hip movement amplitude was 4.18° (*SD* = 1.45°) and for the ankle movement 3.43° (*SD* = 1.64°). The mean sway frequency of these movements was 0.89 Hz (*SD* = 0.41 Hz).

<u>3.2.1.3. Mean relative phase.</u> The Rayleigh test of uniformity was used to determine if relative phase time series for each participant could be distinguished from a uniform distribution with 95% confidence. In general, relative phase in the 0.15 Hz frequency

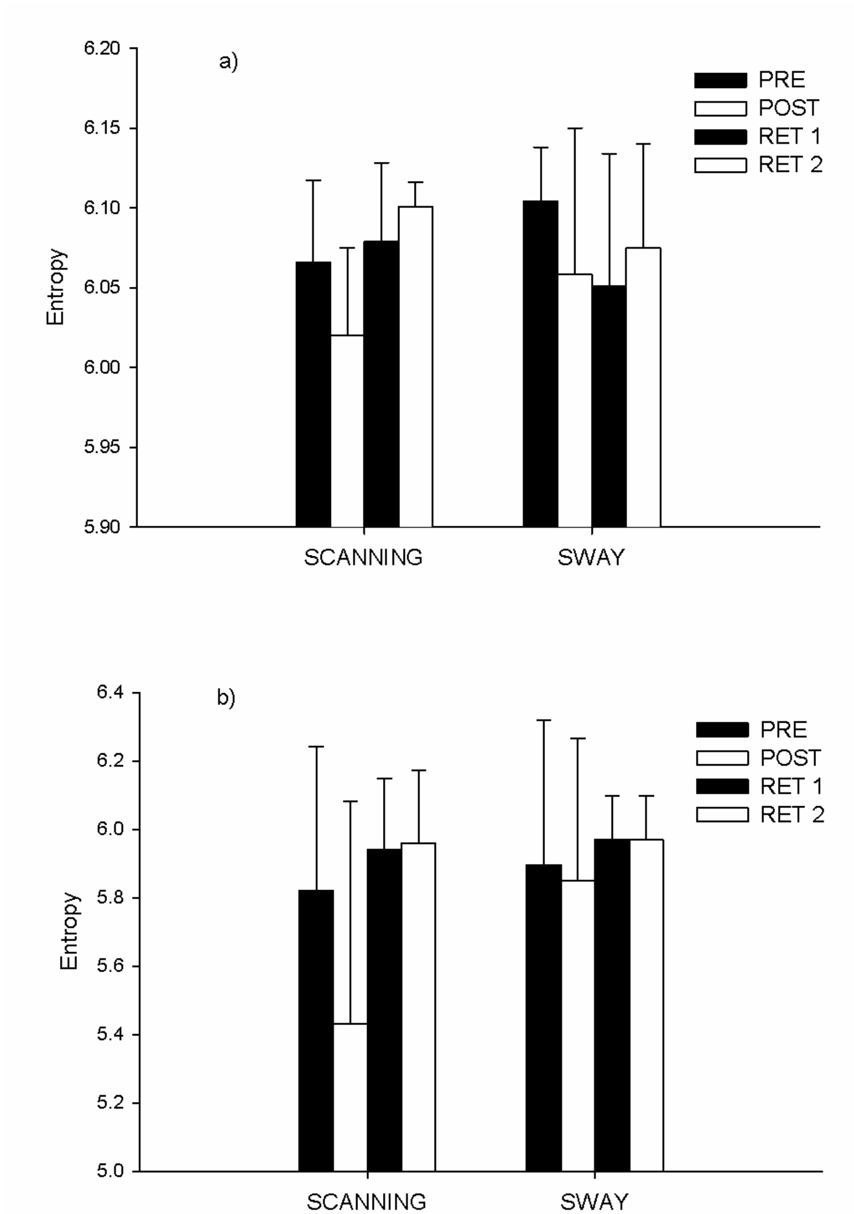

Figure 3.6. Relative phase entropy as a function of group, test and frequency in the 24 hour retention groups on the tracking task at: a) 0.15 Hz, b) 0.75 Hz. PRE = pre-test, POST = post-test, SCANNING = scanning experimental group, SWAY = sway control group. Standard deviation is shown with error bars.

condition approximately an in-phase patterns was performed and an antiphase pattern in the 0.75 Hz frequency condition. In the 1-day groups the between-participant mean relative phase in the 0.15 Hz frequency condition in the scanning group was 1.09° and 2.22° for the pre-test and post-test, respectively. In the sway control group mean relative phase was 22.08° and 89.91° (pre-test, post-test) and in the rest control group 8.70° and 24.15° (pre-test, post-test). In the 0.75 Hz frequency condition mean relative phase for the scanning group was 154.53° and 163.93° (pre-test, post-test). For the sway control group 154.48° and 183.06° (pre-test, post-test) and for the rest control group 188.20° and 163.08° (pre-test, post-test).

In the 24 hr groups the mean relative phase in the 0.15 Hz task frequency condition in the scanning group was 1.08°, -28.20°, -42.08° and 172.18° (pre-test, post-test, 1st retention test, 2nd retention test). In the sway control group the mean relative phase was 43.01°, 96.15°, 117.41° and 152.98° (pre-test, post-test, 1st retention test, 2nd retention test). In the 0.75 Hz frequency condition mean relative phase for the scanning group was 158.66°, 166.48°, 112.29° and 117.00° (pre-test, post-test, 1st retention test, 2nd retention test). For the sway control group 177.40°, 200.81°, 57.4° and 185.86° (pre-test, post-test, 1st retention test, 2nd retention test).

3.2.2. Discussion

It was found that the scanning task led to an immediate decrement in accuracy on the tracking task and to a decrease in the variability of coordination patterns during this task. These effects disappeared by the 24 hr retention tests. This shows that negative transfer occurred from the scanning to the tracking task and supported the experimental hypotheses.

These results also support the hypothesis that the control structure for the redundant tracking task is dependent upon, or utilizes, the control structure that organizes the non-redundant coordination patterns.

Bernstein (1996) theorized a hierarchy of control in which a level of synergies organizes internally consistent coordination patterns. A higher level of control, that of space, adapts the output of the lower synergy level to meet environmental and task demands. The present findings support Bernstein's theoretical framework in that the use of the control structure for the level of space depended upon the use of the level of synergies. When the level of synergies was altered by the performance of the scanning task the output of the level of space decreased in its ability to meet tracking task demands. However, this disruption was only temporary in nature as tracking task performance by the scanning group returned to the level of control group participants after 24 hrs.

One possible mechanism for the observed decrement in the output of the level of space (i.e., tracking task performance) may have been the need for a reorganization of the coupling between the space and synergy levels, due to the increased stabilization that occurred in the intrinsic dynamics that are controlled by the level of synergies. It may be that the increased stability in the level of synergies temporarily interfered with the ability of the level of space to adapt the lower synergy level to meet redundant task demands. Also, the decreased ability of the level of space to meet task demands indicates that the functioning of the level of space depends upon the use of the synergy control structure. Experiment 2 examines whether the operation of the level of synergies depends upon the use of the level of space.

3.3. Experiment 2

3.3.0. Introduction

In Experiment 1 it was found that transitory negative transfer occurred from the scanning task to the tracking task. This effect is consistent with a hierarchical relation between the control structures for the redundant and non-redundant tasks. However, if transfer also occurs from the tracking to the scanning task the relation between these levels could potentially be parallel. If transfer does not occur from the tracking to the scanning task this would support the hypothesis that the relation between these levels is hierarchical, with the control structure for the redundant tracking task hierarchically above, and dependent upon, the structure for the non-redundant scanning task. In Experiment 2 it was hypothesized that transfer would not occur from the tracking to the scanning task. A limitation of this hypothesis is that it is, in effect, seeking to confirm the null hypothesis. This hypothesis was necessary to test for the absence of transfer. The second hypothesis tested was that a stabilization of the intrinsic dynamics would occur over the three repeated performances of the scanning task.

3.3.1. Methods

3.3.1.0. Participants. There were 14 volunteer participants (7 males, 7 females; *M* = 19.57,years *SD* = 0.76 years) recruited from The Pennsylvania State University student body. The participants signed informed consent forms approved by the University Institutional Review Board committee and were compensated for their time. All reported normal or corrected-to-normal vision and no history of neurological disorder or surgery to the legs. They were not informed about the topic of study. Their mean height was 1.70 (*SD* = 0.09) m and their mean weight was 70.10 (*SD* = 12.11) kg. None of the participants in Experiment 1 were recruited for Experiment 2. The same apparatus and data analysis procedures were used as in Experiment 1.

3.3.1.1. Procedures. Participants were randomly assigned to one of 2 groups: an experimental tracking group (n = 7) or a rest control group (n = 7). The tasks were the same as those used in Experiment 1. Both groups performed a pre-test, post-test and a 24 hr retention test of the scanning task. Between the pre-test and post-test participants in the tracking group also performed the tracking task. The rest group rested in a chair instead of performing the tracking task.

In Experiment 1 it was found that during the post-test the difference between the rest control and scanning groups was greater than between the sway and scanning groups. The greater difference between the scanning and rest control groups indicated a trend of greater transfer between these groups. Therefore, as it was hypothesized in this experiment that no transfer would occur from the tracking to the scanning task the rest condition was chosen for the control group as being a conservative approach in which transfer was more likely to be found, if present. The experimental design followed an A:B:A format with task A pertaining to the scanning task and task B pertaining to either the tracking task (performed by the tracking group) or to rest (performed by the rest control group). The protocol was designed to test if negative transfer would occur from a redundant to a non-redundant coordination task. The non-redundant and redundant coordination tasks were the scanning and tracking tasks, respectively.

In the scanning task, 1 trial of 24 movement cycles was performed in each of the 16 relative phase pattern conditions. The relative phase patterns were randomized for each participant and presented in the same order in each testing session. Between the pre- and post-tests 4 blocks of 5 trials of the tracking task were performed by the tracking group. 2 blocks each of the 0.15 Hz and 0.75 Hz tracking task frequencies were performed alternately with 1 min of rest between trials. The order of tracking task frequency was counterbalanced across participants. The same visual feedback was provided in the scanning and tracking tasks as in Experiment 1.

3.3.1.2. Data analyses. The information entropy of relative phase was used to estimate the variability of relative phase time series and was calculated in the same manner as in Experiment 1. For the RMSE in the tracking task a 2 (Test) × 2 (Frequency) repeated measures ANOVA was performed to determine if the performance on this task improved across blocks.

To minimize the number of relative phase conditions to be analyzed in the scanning task the change in entropy from pre-test to post-test and from post-test to retention test were used in statistical analysis. A *one-sample t-test* of means was performed to determine if the change in entropy in the tracking and rest groups differed significantly from zero. The 95% confidence intervals were calculated for each condition to determine whether these overlapped. Change in entropy was analyzed using a 2 (Group) × 2 (Test) × 16 (Relative Phase) repeated measures ANOVA.

As in Experiment 1 the point relative phase method was used to estimate the relative phase between the hip and ankle joints with both endpoints of movement (maximum flexion and extension) included in this calculation. For the scanning task, in each relative phase condition the first 4 movement cycles were eliminated from analysis to remove possible transient fluctuations. The point relative phase values for the following 20 movement cycles were calculated for points of maximum flexion and extension of joint movement. These 40 point relative phase values for each trial were analyzed to determine the mean relative phase and relative phase entropy for each participant in each relative phase condition. For the calculation of relative phase in the tracking task, the first movement cycle was eliminated from analysis to remove possible transient fluctuations. The point relative phase values for the following 6 (for the 0.15 Hz task frequency condition), or 33 (for the 0.75 Hz task frequency condition), movement cycles were calculated for points or maximum flexion and extension of joint movement. The 12 (for 0.15 Hz), or 66 (for 0.75 Hz), point relative phase values from the final 3 trials at each frequency were combined and analyzed to determine mean relative phase and relative phase entropy for each participant.

Standard circular statistics (Batschelet, 1981) were used to analyze relative phase data. Rayleigh uniformity tests were conducted to determine if relative phase distributions could be distinguished from a uniform distribution with 95% confidence. For relative phase time series that were statistically distinguishable from a uniform distribution the mean relative phase and inter-subject *SD* were calculated. The calculation of all dependent variables was performed with coded MATLAB (Mathworks, Natick, MA) programs. Inferential statistical analyses were performed using the SPSS software package and circular statistical analyses were performed with Oriana (Anglesey, Wales) software. All pairwise comparisons were conducted using the LSD (Lease Significant Difference) method. Descriptive statistics (Mean and *SD*) of hip and ankle joint movement amplitude and mean relative phase for all tasks are also reported though not used to test the experimental hypotheses.

3.3.2. Results

3.3.2.0. Relative phase entropy. A *one-sample t-test* of means showed that the change in entropy in the scanning task for both groups in each test was significantly greater than zero (both $p < 0.001$). The *one-sample t-test* of means for the testing intervals within each group showed that all four means were significantly greater than zero (all $p < 0.001$). These outcomes demonstrate that the mean entropy change in both groups and across testing sessions was significantly greater than zero. This supports the hypothesis that the scanning task causes a stabilization of the intrinsic dynamics.

The 95% confidence intervals for the tracking group were 0.02 ↔ 0.07 and 0.02 ↔ 0.06 for the rest group. The 95% confidence interval for the first change in entropy was 0.03 ↔ 0.08 for the tracking group and 0.02 ↔ 0.07 for the rest group. For the second change in entropy the 95% confidence interval for the tracking group was 0 ↔ 0.07 and 0 ↔ 0.07 for the rest group. The finding that all of the tracking and rest group confidence intervals overlap supports the hypothesis that no difference existed between groups and that transfer did not occur in the tracking group.

For the ANOVA of change in relative phase entropy in the scanning task no significant differences occurred in the main effects for Test, $F(1,12) = 1.38$, $p > 0.05$, Relative Phase, $F(15,180) = 1.29$, $p > 0.05$, or Group, $F(1,12) = 0.19$, $p > 0.05$. No Significant Test × Group, $F(1,12) = 0.05$, $p > 0.05$, Test × Relative Phase, $F(15,180) = 1.63$, $p > 0.05$, Relative Phase × Group, $F(15,180) = 1.52$, $p > 0.05$, or Test × Relative Phase × Group, $F(15,180) = 0.65$, $p > 0.05$, interactions occurred. A representation of entropy values in all conditions is shown in Figure 3.7. In the tracking task performed by the tracking group the mean relative phase entropy was 6.01 ($SD = 0.09$) in the 0.15 Hz frequency condition and 5.34 ($SD = 0.41$) in the 0.75 Hz frequency condition.

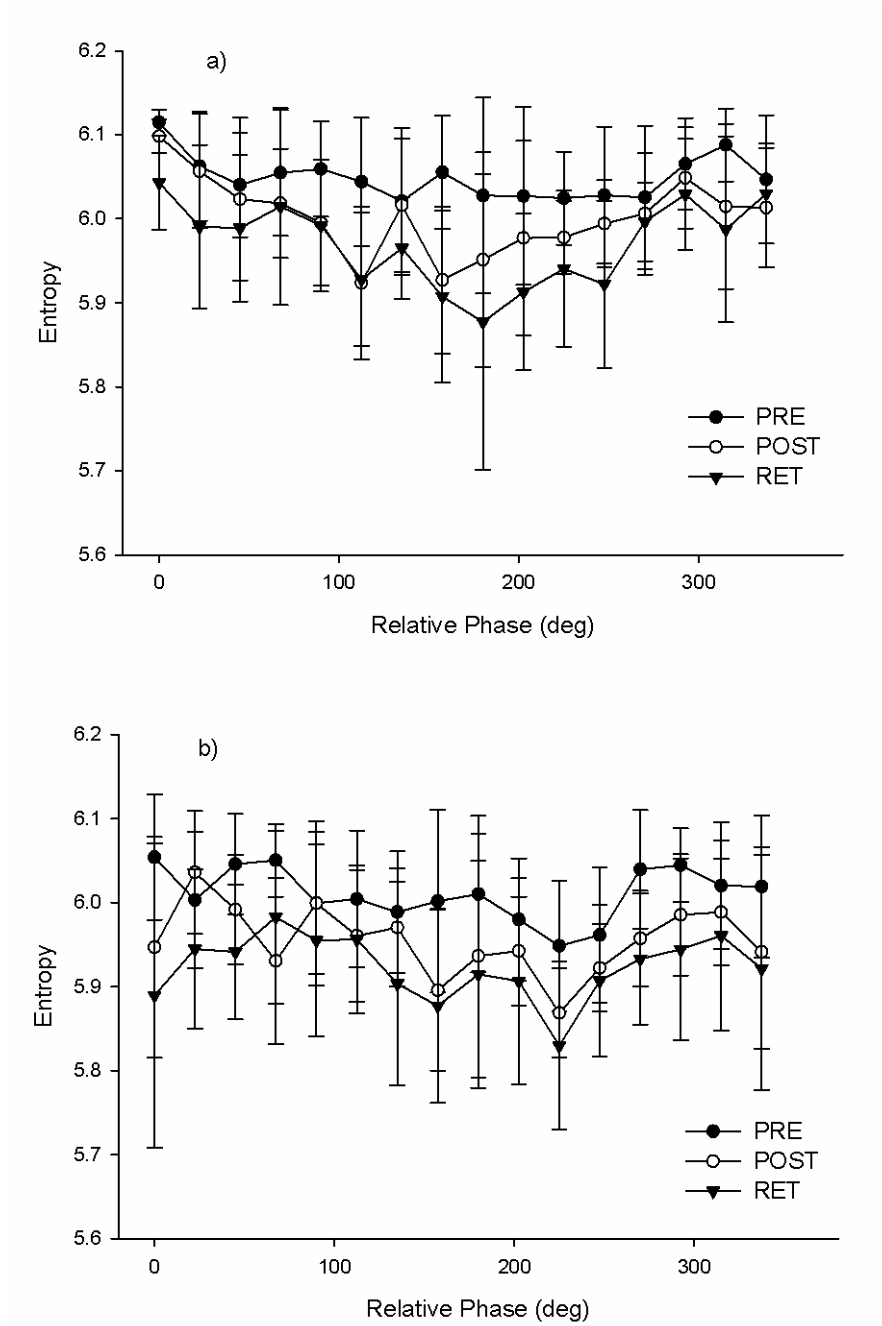

Figure 3.7. Relative Phase entropy in Experiment 2 on the scanning task as a function of Relative Phase, Test and Group. a) = experimental tracking group, b) = rest control group. PRE = pre-test, POST = post-test, RET = 24 hr retention test. Standard deviation is shown with error bars.

3.3.2.1. Joint movement amplitude. In the scanning task the mean hip joint movement amplitude across all participants was 6.19° (*SD* = 1.61°). At the ankle the mean amplitude was 6.69° (*SD* = 1.07°). In the tracking task performed by the tracking group the mean hip movement amplitude was 3.30° (*SD* = 1.87°) and the mean ankle amplitude was 3.08° (*SD* = 1.65°).

3.3.2.2. Mean relative phase. The mean relative phase of tracking and rest groups in each relative phase condition are shown in Table 3.6. A trend was observed that the produced relative phase was biased away from the required relative phase toward the antiphase pattern. This is consistent with the HKB model of bimanual coordination that is interpreted as a competition of behavioral information and intrinsically stable patterns (Zanone & Kelso, 1994). In the tracking task performed by the tracking group in the 0.15 Hz frequency condition there were two subgroups of mean relative phase found. One group (n = 3) produced the in-phase pattern (*M* = 14.54°; *SD* = 67.89°) and the other group (n = 4) approximately the antiphase pattern (*M* = 169.41°; *SD* = 19.36°). In the 0.75 Hz frequency condition the mean relative phase was 171.10° (*SD* = 8.51°).

3.3.2.3. Root mean square error. In the tracking task, performed by the tracking group between the first and second blocks of the scanning task, a significant Test effect occurred, condition, $F(1,6) = 124.13$, $p < 0.001$. The Test × Frequency interaction was not significant, $F(1,6) = 3.85$, $p > 0.05$.

3.3.3 Discussion

The hypothesis that no transfer would occur from the tracking task to the scanning task was supported. This is consistent with a hierarchical organization of control in which

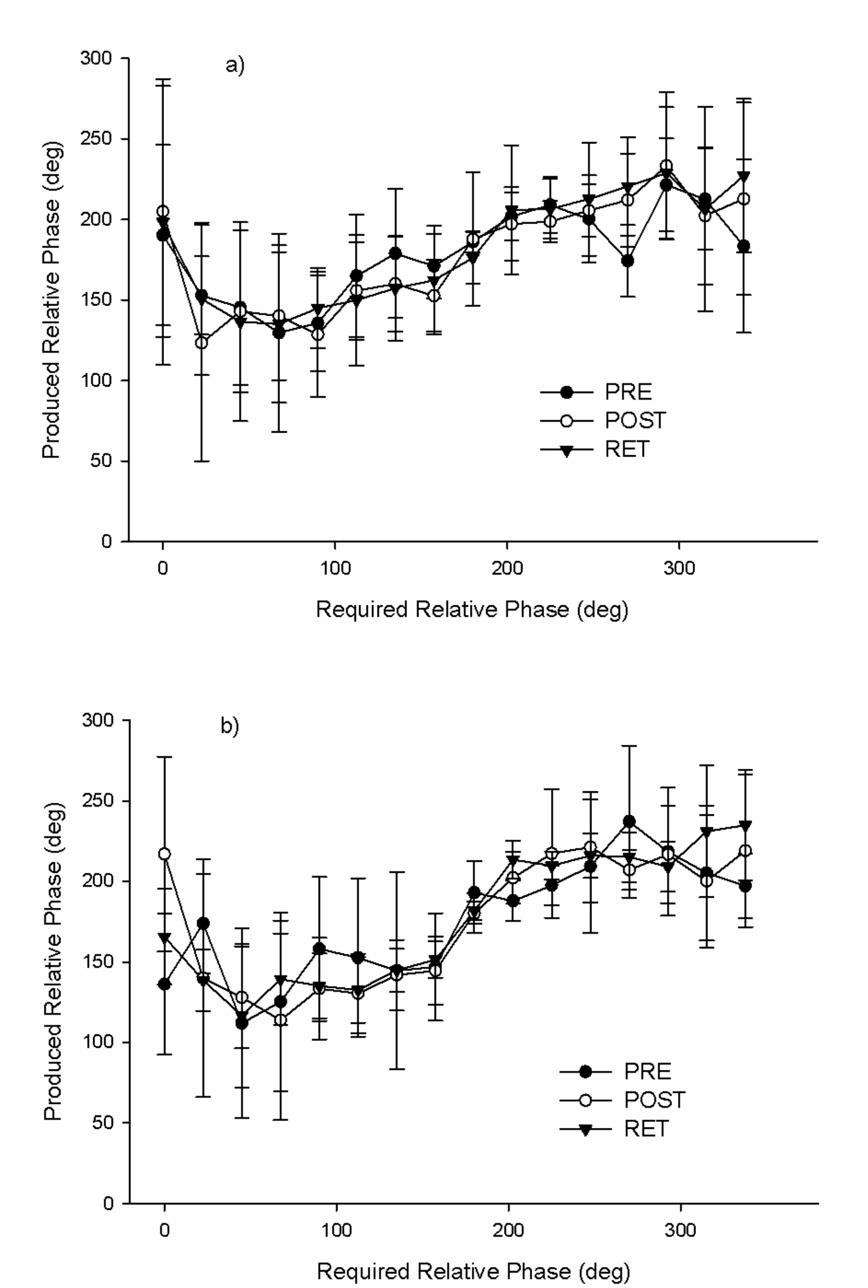

Figure 3.8. Mean relative phase in the scanning task as a function of relative phase condition for a) the experimental tracking group, and b) the rest control group. PRE = pre-test, POST = post-test, RET = 24 hr retention test.

the control structure that organizes the non-redundant scanning task (i.e., the synergy level) is not dependent upon the control structure for the organization of the redundant coordination task (i.e., the space level). The finding that the variability of hip-ankle coordination decreased across performances of the scanning task supported the hypothesis that the overall intrinsic dynamics of this effector system were stabilized with practice, with the second testing block significantly lower than the first block, $F(1,6) = 6.09$, $p < 0.05$.

The scanning task employed in this study has been used to characterize the intrinsic dynamics of various effector systems (Faugloire et al., 2005; Maslovat, Bredin, Chua, & Franks, 2005; Zanone & Kelso, 1992). While several studies have indicated that learning a novel coordination pattern causes a destabilization within the intrinsic dynamics, a recent study of the hip-ankle effector system demonstrated that learning a novel coordination pattern causes a transfer of stability across the entire intrinsic dynamics landscape (Faugloire et al., 2009). The present finding of decreased coordination variability across the intrinsic dynamics landscape after the performance of 16 relative phase patterns in the scanning task is consistent with the finding by Faugloire et al. (2009).

3.4. General Discussion

The present study investigated differences between redundant and non-redundant coordination tasks within the longstanding theory of hierarchical control of the nervous system (Bernstein, 1996; Jackson, 1932; Kandel et al., 2000). In Bernstein's (1996) theoretical hierarchy a lower level of control, termed synergies (or muscular-articular links), is responsible for the organization of internally consistent movement patterns. This level of control leads movement when attention is directed to the movement of body segments. It was hypothesized here that in this way the synergy level of control takes a leading role in non-redundant bimanual coordination tasks in which the task goal is to produce an internally consistent movement pattern. In Bernstein's hierarchy a higher level, termed space, adapts the lower level of control to meet environmental and task demands. This level takes a leading role in control when attention is directed to the external effects of movement (Bernstein, 1996). It was hypothesized here that in this way the space level of control takes a leading role in redundant coordination tasks in which attention is directed to the achievement of a task goal while the coordination of effectors emerges spontaneously.

In Experiment 1 the hypothesis that tracking task performance would temporarily interfere with the scanning task was supported. The temporary decrease in coordination variability that accompanied this decrement in performance also supported the hypothesis that this transfer was only transitory in nature. These findings are consistent with the hypothesis of hierarchical control, with the control structure for the production of redundant coordination tasks dependent upon the structure for non-redundant tasks. In Experiment 2 the tracking task did not cause a significant change in coordination variability in the scanning task, a finding that is consistent with an hierarchical organization of motor control.

The finding of unidirectional transfer between the redundant and non-redundant coordination tasks in these two experiments supports the hypothesis of hierarchical control of the nervous system, with the control of redundant tasks organized at a higher level than that of non-redundant tasks. This is consistent with Bernstein's hierarchy of control in which the synergy level organizes internally consistent movement patterns without respect to environmental or task demands. The level of space adapts the lower synergy level output to meet task demands. In this way the space level is dependent upon the synergy level, but not necessarily vice versa (Bernstein, 1996).

In Experiment 2, the finding that the relative phase patterns in the scanning task decreased in variability, even on the second trial, indicated the immediate onset of stabilization in these patterns. As the variability of relative phase patterns within the scanning protocol has been used to characterize the stability properties of the intrinsic dynamics this indicates that this task caused a general stabilization of the intrinsic dynamics. This is consistent with the finding of Faugloire et al. (2009) that learning a novel non-redundant coordination pattern transferred to greater stability across the entire range of possible relative phase patterns. It remains unknown as to why this effect occurs in the hip-ankle effector system when it has not been found in bimanual coordination (Wenderoth & Bock, Wenderoth, Bock, & Krohn, 2002; Fontaine et al., 1997; Zanone & Kelso, 1997).

The present results also demonstrate that different timescales of change operate between and within the space and synergy levels of control. In Experiment 2 stabilization of intrinsic dynamics was found to occur within the ½ hour between the performances of the pre- and post-tests of the scanning task. Also, in Experiment 1 performance on the tracking task occurred immediately in the control groups. These findings indicate that change within the synergy and space levels of control occurred on a relatively fast timescale of less than ½ hour.

However, the decreased coordination variability and decrement in tracking task performance caused by the scanning task in Experiment 1 took up to 24 hrs to return to the level of control groups. This shows that a reorganization of the coupling relation between the synergy and space levels was necessary and that this change operated on a slower timescale of up to 24 hrs. The finding of two distinct timescales is consistent with prior work indicating multiple timescales in learning (Mayer-Kress, Newell, & Liu, 2009; Newell, Liu, & Mayer-Kress, 2001; Wenderoth & Bock, 2001). In the present study, as the faster timescale was found to occur in repeated performances of the same task this may reflect a rapid adaptation to task demands. The changes that occurred on a slower timescale were due to the influence of one task on the other. These changes may reflect a process of learning that has previously been found to occur on a relatively slow timescale (Newell et al., 2001).

The combined findings of these experiments indicate that the dynamics operating in the synergy and space control structures, and the respective timescales on which they operate, are not the same. It appears that it may be inappropriate to assume that the dynamics describing one level of control, such as that pertaining to the HKB model, necessarily operate at a different level of control. This may explain some apparent inconsistencies in the hip-ankle and bimanual coordination literature. For example, the redundant postural tracking task used in the present experiments, and other similar tasks, may be organized by a different level of control than that which organizes non-redundant coordination tasks such as bimanual coordination.

The operation of different dynamics in redundant and non-redundant coordination tasks might explain the inconsistency of unidirectional phase transitions in bimanual coordination and bidirectional phase transitions in hip-ankle coordination. Bidirectional phase transitions in the hip-ankle effector system occur during the performance of a redundant tracking task (Bardy et al., 1999). It is suggested here that this task may be controlled by a different structure, with different dynamics, than that which controls non-redundant coordination tasks such as bimanual coordination, in which unidirectional phase transitions have been found.

In bimanual coordination the stability of intrinsic patterns has also been found to affect the ability to learn a new coordination pattern (Zanone & Kelso, 1994), but not in hip-ankle coordination (Faugloire et al., 2006). However, in this hip-ankle study the stability properties of intrinsic patterns were estimated in a redundant coordination task (postural tracking) while the learning of a novel coordination pattern was a non-redundant task. The present findings suggest that the inconsistency between this study and prior research on bimanual coordination (Zanone & Kelso, 1994) could be due to the fact that the hip-ankle study involved an interaction between both the space and synergy levels of control while the bimanual study only pertained to one level of control (the synergy level).

The present conclusion of distinct, hierarchically organized control structures also calls into question the prior interpretation of intrinsically stable hip-ankle coordination patterns being attracted toward a newly learned pattern (Faugloire et al., 2006). While this interpretation is consistent with the HKB model, in the protocol in which this was found both redundant and non-redundant coordination tasks were involved. The learning of a novel hip-ankle coordination pattern in Faugloire et al. (2006) was a non-redundant task while the altered intrinsically stable patterns were observed in a redundant coordination task. Hence, this finding might involve an interaction of two different levels of control rather than a simple attraction effect as occurs at the synergy level of control in the HKB model. It is questionable whether the same dynamics operating in each of these tasks, and their associated levels of control, are the same as those operating in bimanual control.

While higher level structures may utilize lower level structures this does not necessarily imply a strictly unidirectional relation. Rather, interactions may potentially occur between levels. For example, control structures within the nervous system have been found to operate both in parallel as well as in a hierarchical fashion (Kandel et al., 2000). Also, within Bernstein's theoretical hierarchy each level can potentially take the lead in movement depending upon task, environmental and attentional factors. In other theoretical accounts of organization within the nervous system a coupling between multiple systems and subsystems has been suggested, each with distinct timescales (Newell et al., 2001).

In summary, the present study sought to clarify previously found inconsistencies in the dynamics of hip-ankle (Bardy et al., 2002; Faugloire et al., 2005, 2009) and bimanual (Kelso, 1984; Zanone & Kelso, 1994; Wenderoth et al., 2002) coordination. The theoretical paradigm of hierarchical control of the nervous system was used as a means of potentially mediating these inconsistencies (Bernstein, 1996). In this hierarchical framework of control a lower synergy level assembles internally consistent movement patterns while these are adapted to meet task demands by a higher space level of control. The synergy level of control is associated with non-redundant coordination tasks and the space level of control with redundant coordination tasks. It was found that transitory negative transfer occurred from the non-redundant task to the redundant task, but not vice versa. Change within both the synergy and space levels of control occurred on a relatively short timescale while the coupling between these levels reorganized on slower timescale of up to 24 hrs.

CHAPTER 4. EXPERIMENT 3

4.0. Abstract

In-phase and antiphase hip-ankle coordination patterns have previously been identified in a frequency-scaled postural tracking task. However, the identification of these patterns was based on an analysis of group-averaged data that spanned only 5-6 movement frequencies. In the present study participants (N = 16) performed a frequency-scaled postural tracking task in increasing and decreasing directions at 20 frequencies ranging from 0.05 Hz to 1 Hz in increments of .05 Hz. Both group-averaged and individual data were analyzed to determine the number of distinct and uniform coordination patterns produced. Group averaged data showed the existence of in-phase and antiphase patterns before and after phase transitions. However, individual data revealed that the majority of participants produced more than two coordination patterns as well as uniform coordination distributions. Given that prior research has found that only the antiphase pattern can be produced in non-redundant coordination these results indicate that a one-to-one mapping from non-redundant to redundant coordination dynamics does not occur.

4.1. Introduction

In bimanual coordination the in-phase and antiphase modes have been found to be stable and phase transitions commonly occur from the latter to the former as movement frequency is scaled up (Kelso, 1984). These two coordination modes have also been found in the hip-ankle effector system during performance of a postural tracking task (Bardy, Marin, Stoffregen, & Bootsma, 1999; Faugloire, Bardy, Merhi, & Stoffregen, 2005). However, phase transitions from in-phase to antiphase occur in this task as movement frequency is scaled up and also as frequency is scaled down (Bardy, Oullier, Bootsma, & Stoffregen, 2002). The conclusion has been reached that the Haken, Kelso and Bunz (HKB) model (1985) that captures the dynamics of bimanual coordination also reflects the dynamics operating in the hip-ankle effector system during this postural tracking task (Bardy et al., 1999; 2002).

While similarities between postural and bimanual coordination have been identified a number of differences in the dynamics of these two types of coordination tasks also exist. In the non-redundant task of producing specific coordination patterns with the hip and ankle only the antiphase pattern is typically performed (Faugloire et al., 2005), while the in-phase pattern can also be performed in bimanual tasks. Phase transitions in postural coordination have been found to be bidirectional (Bardy et al., 2002), rather than unidirectional as in bimanual coordination (Kelso, 1984). In the postural tracking task these phase transitions occur in the opposite direction than in bimanual coordination, namely from in-phase to antiphase as movement frequency is scaled up. Also, in hip-ankle coordination uniform relative phase distributions have been found to occur (Bardy et al., 2002; Faugloire, Bardy, &

Stoffregen, 2006). These differences between bimanual and hip-ankle coordination indicate that different dynamics operate in each type of task.

One potential reason for the difference in postural and bimanual coordination dynamics may be the redundancy of the tasks involved. Typical studies of bimanual coordination involve a non-redundant coordination task in which a specified coordination pattern is the task goal. The HKB model was created to capture the dynamics of these non-redundant coordination tasks (Haken et al., 1985). However, the task in which in-phase and antiphase postural coordination patterns have been found is redundant. That is, multiple coordination solutions exist that can potentially meet the task demands. This difference in the nature of bimanual and postural tracking tasks is a potential reason why the HKB model may not be applicable to redundant postural dynamics.

The redundant nature of the postural tracking task previously studied may contribute to the empirical inconsistencies between bimanual and hip-ankle findings. Thus, the differences that exist in the dynamics of bimanual and postural tasks may not be due simply to the different effector systems used but may pertain to the redundancy of the tasks involved. A complex mapping may exist from the intrinsic dynamics of an effector system, as measured by a non-redundant coordination protocol (Zanone & Kelso, 1992), to the coordination dynamics that operate in redundant coordination tasks.

There have also been methodological limitations in prior studies of hip-ankle coordination that may have confounded conclusions regarding similarities between hip-ankle and bimanual coordination dynamics. One such limitation is that in some cases hip-ankle relative phase data have been averaged across participants. For example, the identification of in-phase and antiphase hip-ankle coordination patterns in a frequency-scaled postural tracking protocol was determined with group data that were averaged across individuals (Bardy et al., 2002). An analysis of individual hip-ankle relative phase data was not performed to determine the number of distinct coordination patterns produced by individual participants. In another study Bardy et al. (1999) averaged group data with no test to determine if differences in coordination patterns occurred between individuals or experimental conditions (target amplitude, height of center-of-mass and effective foot length). The results showed relatively large between participant standard deviations that might potentially reflect different coordination patterns being produced by different individuals.

In another study only two movement frequency conditions were used, thereby excluding the possibility of finding more than two coordination patterns produced by individual participants (Faugloire et al., 2006). As movement frequency has been identified as a control parameter in postural coordination, a complete understanding of postural coordination dynamics requires an analysis of a broad range of movement frequencies. Also, in the prior study of a frequency-scaled hip-ankle protocol only 5-6 frequency steps per participant were included in analysis (Bardy et al., 2002). Analysis of a broader range of frequencies may be needed to capture the full range of coordination modes. Another limitation has been that data not distinguishable from a uniform distribution have been eliminated from analysis and theoretical consideration (e.g., Faugloire et al., 2006). The use of a uniform hip-ankle relative phase distribution is a viable strategy that needs to be accounted for in a theory of the dynamics of hip-ankle coordination.

The present study sought to verify the presence of only two patterns, in-phase and antiphase, in hip-ankle coordination in a postural tracking task through the analysis of individual relative phase data over a wide range of movement frequencies. The number of uniform distributions was also examined on an individual basis. An analysis of group averaged data, similar to that performed in prior hip-ankle postural coordination dynamics, was also performed for comparison. The objective was to investigate potential differences between the redundant hip-ankle coordination task and prior findings on non-redundant bimanual tasks. These differences are relevant to a theoretical understanding of the coordination dynamics in redundant and non-redundant coordination tasks.

4.2. Methods

4.2.0. Participants

Healthy young adult participants (N = 16; 8 males, 8 females) with a mean age of 22.56 (*SD* = 4.80) years and height 1.64 m (*SD* = 0.08 m) were recruited from The Pennsylvania State University student body. The participants signed informed consent forms approved by the University Institutional Review Board committee and were compensated for their time. All reported normal or corrected-to-normal vision and no history of neurological disorder or surgery to the legs. They were not informed about the topic of study.

4.2.1. Apparatus

A Celesco (Chatsworth, CA) SP2-50 string-potentiometer was attached to the back of a hat worn by participants to measure anteroposterior displacement of the head. Two Celesco electrogoniometers (models XM110 and XM180) with an accuracy of +/- 1° were fixed to participants' right hip and ankle joints using adhesive tape. An InFocus (Wilsonville, OR) projector was used to project a visual display onto a screen 1.5 m in front of participants. Data from the potentiometer and goniometers were collected at 100 Hz.

4.2.2. Procedures

Participants performed a frequency-scaled postural tracking task in both increasing and decreasing frequency directions. The task consisted of tracking an oscillating target with the head in the antero-posterior direction at frequencies continuously scaled between 0.05 Hz and 1.0 Hz in 0.05 Hz increments. Participants performed 1 trial in each of the upward and downward frequency directions with 10 movement cycles performed at each frequency. During task performance a visual target was projected onto a screen 1.5 m in front of participants. This target consisted of a rectangular box of dimensions 47 cm × 64 cm (height × width).

The target appeared to oscillate at an amplitude of 10 cm toward and away from the participant who tracked the movement of this box by moving his or her head and body in the antero-posterior direction. The order of the frequency scaling direction was counterbalanced across participants. Participants wore a CPB Donjoy brace on each knee that locked the joint in a fixed position. They were furthermore instructed to keep their feet flat on the floor, and to cross their arms across their chest at all times during the performance of each task. It was predicted that the examination of individual participant data would reveal coordination patterns in addition to in-phase and antiphase.

4.2.3. Data Analyses

In keeping with prior studies (Bardy et al., 1999, 2002; Faugloire et al., 2006; Faugloire, Bardy, & Stoffregen, 2009; Kelso, 1984; Zanone & Kelso, 1992) a point estimate of relative phase was used to estimate the relative phase of the head-target and hip-ankle. The first and last movement cycles at each movement frequency step were eliminated from analysis to remove possible transient fluctuations. The point relative phase values were calculated for points of both maximum and minimum displacement for each of the remaining 8 movement cycles at each frequency step. Standard circular statistics (Batschelet, 1981) were used to calculate the mean and *SD* of point relative phase values when statistically distinguishable from a uniform distribution.

An initial statistical test that needs to be performed with circular data is to determine whether these differ from a uniform distribution. Once it has been determined that data are significantly clustered around a mean value inferential circular statistics can be performed. The Rayleigh uniformity test (Batschelet, 1981) was used to determine if relative phase distributions could be distinguished from a uniform distribution with 95% confidence. As all head-target relative phase distributions differed significantly from a uniform distribution the mean relative phase and intra-individual *SD* were calculated. Movement frequencies that participants were not able to produce were eliminated from subsequent analysis. These were identified as those frequency steps at which the *SD* of head-target relative phase exceeded 30°. The mean of non-uniform hip-ankle relative phase data was calculated for each participant at each frequency step. The number of hip-ankle relative phase distributions that could not be distinguished from a uniform distribution was also determined.

The Watson-Williams *F* test determines if the means of circular distributions differ significantly from each other. This test was used to determine the number of distinct relative phase patterns produced by each participant by comparing hip-ankle relative phase distributions across frequency steps. A type-I error of 0.05 was used with a Bonferroni correction made to correct for the total number of pairwise comparisons made on each variable.

The occurrence of a phase transition was defined as a change between two such statistically distinguishable relative phase patterns. The Watson-Williams *F* test was also used to compare the group averaged mean hip-ankle relative phase before and after phase transitions. As in prior research (Bardy et al., 2002) the group data were aligned so that the movement frequencies at which phase transitions occurred overlapped and with data above and below the transition frequency separately averaged. Also reported in the results are descriptive statistics of hip and ankle movement amplitude, though they were not used to test experimental hypotheses.

Data from the frequency-scaled task were filtered at each frequency step with a recursive, 4^{th} order lowpass Butterworth filter with a cutoff frequency of the frequency step plus 0.05 Hz (Bardy et al., 2002). The calculation of dependent variables was performed with coded MATLAB (Mathworks, Natick, MA) programs. Inferential statistical analyses were performed using the SPSS software package and circular statistical analyses were performed with Oriana (Anglesey, Wales) software.

4.3. Results

For the upward frequency direction the mean ankle movement amplitude was 3.39° (*SD* = 0.43°) and for the hip joint 3.86° (*SD* = 0.32°). In the downward frequency direction ankle amplitude was 3.36° (*SD* = 0.47°) and for the hip 3.47° (*SD* = 0.36°). The Rayleigh test showed that 100% of head-target relative phase time series differed significantly from a uniform distribution. The mean head-target relative phase was 355.48° (*SD* = 9.75°), indicating that the head, on average, lagged slightly behind the target.

Phase transitions were found to occur in hip-ankle coordination. However, this did not necessarily indicate that there were only two (i.e., pre- and post-transition) coordination patterns present. 9 participants showed a phase transition in the upward frequency direction and 8 in the downward direction. 14 participants showed a phase transition in at least one frequency direction.

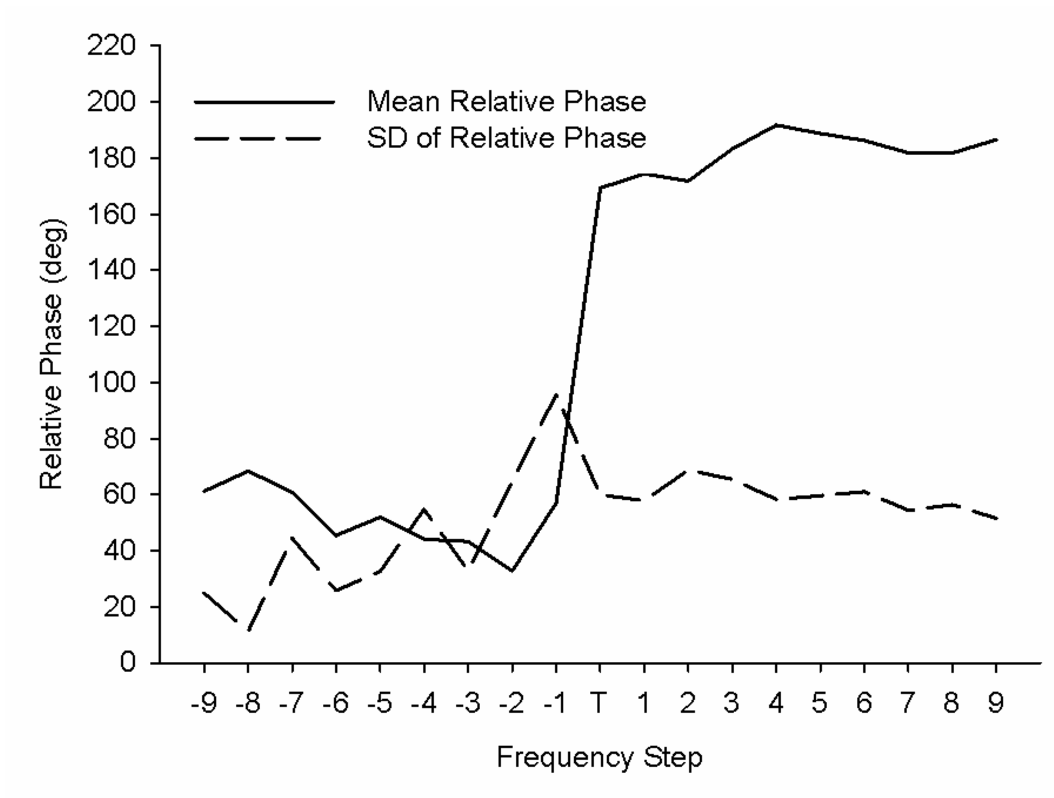

Figure 4.1. Group averaged relative phase before and after a phase transition as a function of frequency step. T = the frequency at which the phase transition occurred for each participant. The *x*-axis depicts the number of 0.05 Hz steps before and after the phase transition.

When the hip-ankle relative phase data above and below the phase transition were separately averaged across participants the Watson-Williams F test showed that the below- and above-transition data differed significantly, $F(1,1790) = 1095.09$, $p < 0.001$. The mean below-transition relative phase was 50.14° with a 95% confidence interval of 44.04° - 56.24°. The mean above-transition relative phase was 181.81° with a 95% confidence interval of

178.52° - 185.09°. The group averaged relative phase above and below phase transitions is represented in Figure 4.1.

The Rayleigh test showed that at least one uniform hip-ankle relative phase frequency step occurred in 15 out of 16 participants (93.75%). In the upward frequency direction the mean number of uniform frequency steps per participant was 6.38 (*SD* = 7.2) while in the downward direction the mean was 7.88 (*SD* = 6.66). The minimum number of uniform frequency steps in a single frequency direction per participant was 0 while the maximum was 19.

In the analysis of individual participant relative phase data the pairwise Watson-Williams *F* tests showed that 9 out of 16 participants (56.25%) produced more than 2 identifiable relative phase patterns in either the upward or downward frequency direction. There was 1 participant that produced 5 distinct coordination patterns and 1 participant that produced 4 patterns. 7 participants produced 3 distinct coordination patterns, 5 participants produced 2 patterns and 2 participants produced only 1 coordination pattern. Exemplars of individual hip-ankle relative phase data are shown in Figure 4.2.

4.4. Discussion

Previous research has demonstrated the existence of two stable hip-ankle coordination patterns in a redundant postural tracking task with phase transitions occurring between these patterns as movement frequency is scaled up or down (Bardy et al., 2002). It was concluded that an in-phase pattern tends to be produced at lower movement frequencies and an antiphse pattern at higher frequencies. This experiment investigated whether this conclusion is confounded by the analysis of group data over a limited number of movement frequencies.

The group-averaged data showed the occurrence of phase transitions as movement frequency was scaled up or down, together with the production of an in-phase coordination pattern at low movement frequencies and an antiphase pattern at higher frequencies. The 95% confidence interval for the in-phase pattern was slightly higher than and did not include 0° while the antiphase pattern included 180° within the 95% confidence interval. These

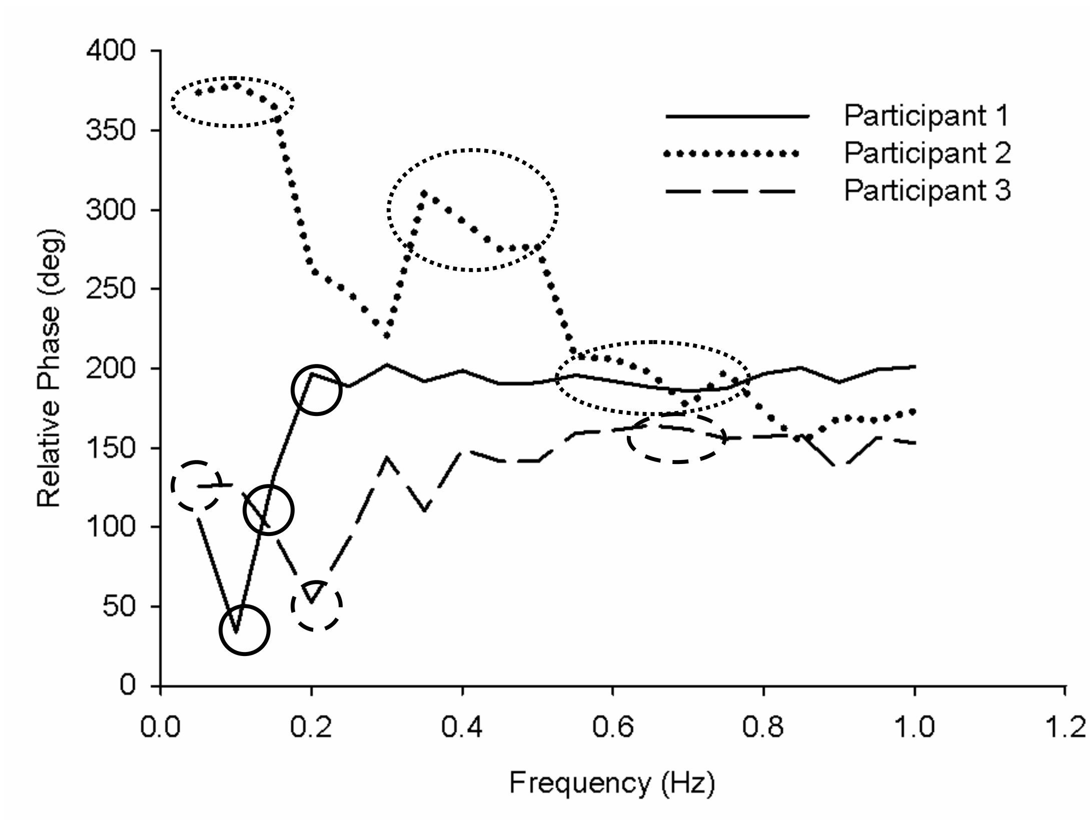

Figure 4.2. Exemplars of individual mean relative phase data as a function of movement frequency. Participant 1: The 34° pattern (0.1 Hz) is significantly different than the 133° pattern (0.15 Hz) which differs from the 191°-203° patterns (0.3 Hz → 0.6 Hz, 0.8 Hz → 1 Hz) which also differs from the 34° pattern. Participant 2: The 367° → 369° (0.05 Hz → 0.15 Hz) patterns are significantly different than the 168° → 206° patterns (0.6 Hz → 0.8 Hz, 0.9 Hz, 1 Hz) which differ from the 276° → 312° patterns (0.35 Hz, 0.4 Hz, 0.5 Hz) which differ from the 367° → 369° patterns. Participant 3: The 53° (0.2 Hz) pattern is significantly different than the 125° (0.05 Hz) pattern, which differs from the 161° → 165° (0.65 Hz → 0.7 Hz) patterns which are in turn different than the 53° pattern. Participant 2 data were plotted > 360° to reflect the continuity in the data. Distinct coordination patterns within participants are circled.

findings replicate those of Bardy et al. (2002) in which group data before and after phase transitions were averaged.

However, the present study demonstrated that while these two patterns were observed in group averaged data a different pattern of findings occurred in individual participants. When individual data were analyzed more than two distinct coordination patterns were observed in the majority (56.25%) of participants. It was also found that uniform in hip-ankle coordination distributions commonly occur in redundant postural coordination. Almost all participants (93.75%) produced coordination distributions that were not statistically distinguishable from a uniform distribution. Whereas prior research has excluded such uniform relative phase distributions from analysis the occurrence of this type of coordination pattern is not uncommon and should be considered in a theory of coordination dynamics.

In prior research it has been shown that in a non-redundant hip-ankle coordination task only the antiphase coordination pattern can typically be produced (Faugloire et al., 2005). Prior research (Bardy et al., 2002) as well as the present study have shown that coordination patterns in addition to the antiphase pattern spontaneously emerge in a redundant coordination task. These findings indicate that a simple one-to-one mapping does not exist between non-redundant intrinsic dynamics and the dynamics of redundant coordination tasks. Rather, a more complex process of organization appears to operate in which multiple distinct coordination patterns as well as uniform coordination solutions emerge from the intrinsic dynamics that contains fewer intrinsically stable coordination solutions.

The present findings provide a rationale for a reinterpretation for the results of Bardy et al. (2002). These authors found that only two coordination patterns were stable across a range of movement frequencies. However, this determination was based upon the analysis of group averaged data while an analysis of the number of distinct hip-ankle relative phase patterns within individual participants was not performed. This may have led to a failure to identify patterns within individual data that differed from the group average. It has previously been shown that the averaging of data across individuals can result in a group averaged function that does not reflect the output of any single individual (Newell et al., 2001). Also, in Bardy et al. (2002) only data from 5-6 movement frequencies were included in analyses that were centered on the phase transition frequency. The analysis of this limited range of movement frequencies may have led to a failure to identify other stable coordination patterns that occurred at movement frequencies outside of this range. The finding of distinct results in individual and group averaged data reaffirms the theoretical perspective that individual intrinsic dynamics need to be examined to determine the principles operating in the dynamics of coordinated movement (Kelso, 1995).

The present study showed the consistent presence of uniform coordination patterns in this postural tracking task. Uniform coordination solutions are viable strategies to meet the task demands of redundant coordination tasks. It is concluded that the emergence of uniform as well as specific coordination solutions should be accounted for in a theory of coordination dynamics in redundant tasks and that uniform patterns should not be removed from consideration in empirical studies.

The findings of the present study indicate that while the HKB model captures the dynamics associated with non-redundant coordination tasks, such as bimanual coordination, it does not necessarily capture those that emerge in redundant tasks. The organization of redundant coordination tasks may be governed by dynamics that utilize, but are separate from, the intrinsic dynamics captured by the HKB model. This distinction between redundant and non-redundant coordination tasks and the possible operation of different dynamics within each type of task provides a potential explanation for the discrepancies previously found between hip-ankle and bimanual coordination.

CHAPTER 5. GENERAL DISCUSSION

This thesis was conducted to investigate the dynamics of coordination in a postural tracking task and why these dynamics may differ from those previously identified in bimanual coordination. The redundant and non-redundant nature of coordination tasks and the theory of an hierarchical organization of control were examined as an account of the empirical differences previously found between postural and bimanual coordination. Experiment 1 investigated transfer from a non-redundant to a redundant postural tracking task. Experiment 2 studied transfer from a redundant to a non-redundant postural task using the same tasks as Experiment 1. Experiment 3 investigated the coordination patterns produced in a frequency-scaled redundant postural tracking task to determine the relation between the intrinsic dynamics that operate at the non-redundant level and those at the redundant level. The findings from these experiments provide empirical and theoretical support for hierarchical control with different dynamics operating within hierarchical levels of control than operate in redundant and non-redundant postural coordination tasks. The importance of analyzing individual coordination patterns as opposed to averaging across participants was reaffirmed.

5.1. Hierarchical Control Levels

The theoretical framework of hierarchical control (Bernstein, 1996; Jackson, 1932; Kandel et al., 2000) was invoked to investigate previously found inconsistencies between hip-ankle and bimanual coordination dynamics. In Bernstein's (1996) hierarchical organization a lower level of control, termed synergies (or muscular-articular links), organizes internally consistent movement patterns. It was hypothesized that this level of control pertains to non-redundant coordination tasks (e.g., typical bimanual coordination tasks) in which the task goal is to produce an internally consistent movement pattern. In Bernstein's hierarchy a higher level, termed space, adapts the lower level of control to meet task demands. It was hypothesized that this level of control pertains to the performance of redundant coordination tasks in which attention is directed to the achievement of a task goal while the coordination of effectors emerges spontaneously.

A general hypothesis of the present study was that redundant coordination tasks are controlled by a higher level within the nervous system that depends upon the proper functioning of a lower level control structure (Bernstein, 1996). The first two experiments were designed to specifically test this theoretical dependence across levels of control. The third experiment was designed to investigate the mapping between levels of control. Individual participant data were analyzed in Experiment 3 to determine the number of distinct coordination patterns produced in the redundant postural tracking task across a range of movement frequencies.

In Experiment 1 possible transfer from a non-redundant hip-ankle scanning task to a redundant postural tracking task was investigated. In Experiment 2 possible transfer from the same redundant postural task to the non-redundant task was tested.
The results of Experiment 1 showed that the scanning task led to transitory negative transfer in the postural tracking task. The effect on the tracking task was a temporary decrease in accuracy on the tracking task and a temporary decrease in hip-ankle coordination variability. In Experiment 2 transfer did not occur from the tracking to the scanning task. In Experiment 1 the control group immediately improved on the tracking task and in Experiment 2 a decrease in coordination variability in the scanning task also occurred immediately. These results show a process of change occurring within the synergy (Experiment 1) and space

(Experiment 2) levels of control on a fast, almost immediate, timescale. However, a delayed effect, taking up to 24 hours, was found for the dissipation of the negative transfer that occurred from the scanning task to the tracking task in Experiment 1. This showed that the adaptation between the levels of space and synergies operated on a slower timescale, taking up to 24 hrs. The results of the first two experiments supported the theoretical view that there are different hierarchical control structures for the performance of redundant and non-redundant coordination tasks and that a different timescale of change occurs in the coupling between these structures. This finding of two distinct timescales is consistent with prior work indicating multiple timescales in learning (Mayer-Kress, Newell, & Liu, 2009; Newell, Liu, & Mayer-Kress, 2001; Stratton, Liu, Hong, Mayer-Kress, & Newell, 2007; Wenderoth & Bock, 2001).

The hypothesis of hierarchical organization was also supported by the finding that transfer between the two tasks employed was unidirectional, occurring from the non-redundant scanning task to the postural tracking task but not vice versa. The unidirectional transfer that occurred in the first two experiments supported the view that the control structure for the tracking task is dependent upon the structure for the scanning task, but not the reverse, in a hierarchical organization.

Experiment 3 examined the number of patterns produced in redundant hip-ankle coordination. As it has previously been found that only the antiphase pattern can be produced in non-redundant postural coordination the findings of this experiment provide an indication of the nature of the mapping between the redundant and non-redundant control structures. Multiple distinct coordination patterns as well as uniform patterns were found in the redundant tracking task. This finding provides a reinterpretation for the results of Bardy et al. (2002). These authors found that only two coordination patterns were stable across a range of movement frequencies. However, this determination was made through the analysis of group averaged data. An analysis of the number of distinct hip-ankle relative phase patterns within individual participants was not performed by these authors. Also, only 5-6 movement frequencies centered on the movement frequency at which phase transitions occurred were included in analyses. The analysis of this limited range of movement frequencies may have missed other stable coordination patterns that occurred at other frequencies.

In Experiment 3 the dynamics that operate in hip-ankle coordination during the postural tracking task were found to be different than those that typically operate in non-redundant coordination. Namely, while only the antiphase coordination pattern can be produced in a non-redundant hip-ankle task (Faugloire et al., 2005) multiple coordination patterns were found across a range of movement frequencies in the redundant task. This indicates the operation of different dynamics in the redundant task and supports the hypothesis of a separate control structure for this type of task. This finding also indicates that the relation between the synergy and space levels does not follow a simple one-to-one mapping and supports the hypothesis that the output of the synergy control structure is adapted to meet task and environmental demands (Bernstein, 1996).

The combined findings of these experiments indicate that the dynamics operating in each of these tasks and levels of control, and the respective timescales at which they operate, are not the same. It appears that it may be inappropriate to assume that the dynamics describing one level of control, such as that pertaining to the HKB model, necessarily operate at a different level of control. Rather, a more complex relation appears to exist with multiple solutions emerging at the space level from the existence of a single stable attractor within the intrinsic dynamics at the synergy level.

However, while higher levels of control may utilize lower level control structures this does not necessarily imply strictly one-way control. Rather, interactions may potentially occur between levels. For example, control structures within the nervous system have been found to operate both in parallel as well as in a hierarchical fashion (Kandel et al., 2000). Also, within Bernstein's (1996) theoretical hierarchy each level can potentially take the leading level in different behaviors. In other theoretical accounts of organization within the nervous system a coupling between multiple systems and subsystems has been suggested, each with distinct timescales (Newell, Liu, & Mayer-Kress, 2001).

5.2. Hip-Ankle and Bimanual Coordination

An objective of the experiments was to investigate the previously found inconsistencies between bimanual and hip-ankle coordination dynamics (Bardy et al., 2002; Faugloire et al., 2006; Kelso, 1984; Zanone & Kelso, 1994). Two coordination modes can typically be produced in a non-redundant bimanual task while only one pattern can be produced in a non-redundant hip-ankle task (Faugloire et al., 2005). Also, in hip-ankle coordination it has been found that learning of a new non-redundant pattern increases the stability of all relative phase patterns (Faugloire et al., 2009). In bimanual coordination this type of transfer does not occur (Zanone & Kelso, 1992). Bidirectional phase transitions occur in hip-ankle coordination (Bardy et al., 2002) while in bimanual coordination only unidirectional phase transitions, from antiphase to in-phase, occur. Another inconsistency is that while the stability of intrinsic patterns has been shown to affect how well a new bimanual coordination pattern is learned (Zanone & Kelso, 1994) this is not be the case in hip-ankle coordination (Faugloire et al., 2006).

The results of the present experiments support the hypothesis that inconsistencies in the hip-ankle and bimanual coordination literature may be due to the involvement of two levels of control (synergy and space) in the redundant hip-ankle task while typical bimanual tasks only involve one level of control (synergy). The redundant postural tracking task used in the hip-ankle experiments (Bardy et al., 1999, 2002; Faugloire et al., 2005) may be organized by a different level of control than that which organizes non-redundant coordination tasks such as bimanual coordination, the dynamics of which are captured by the HKB model. The results of the present experiments support the hypothesis that the dynamics in the redundant postural task, and the associated levels of control, differ from those of non-redundant bimanual coordination tasks.

The operation of different control structures could explain the inconsistency of unidirectional phase transitions in bimanual coordination and bidirectional phase transitions in hip-ankle coordination. The bidirectional phase transitions in the hip-ankle effector system were found during the performance of a redundant tracking task. It is suggested here that this task may be controlled by a different structure, with different dynamics, than that which controls non-redundant coordination tasks such as bimanual coordination.

The present findings also support the hypothesis that an understanding of coordination dynamics requires that data be examined on an individual basis (Kelso, 1995), rather than relying upon the analysis of group averaged data (Bardy et al., 2002; Faugloire et al., 2006). Also demonstrated in the present study is how uniform coordination patterns are potential solutions to redundant coordination tasks. The finding in Experiment 3 of uniform coordination patterns is consistent with the finding in Experiment 1 of a decrement in tracking task performance occurring in conjunction with a decrease in hip-ankle coordination variability. These findings indicate that high variability in postural coordination may be beneficial in the postural tracking task. This indicates that a uniform distribution of hip-ankle coordination is a viable strategy to meet task demands and should not be eliminated from analysis and theoretical consideration, as has occurred in prior studies (Bardy et al., 2002; Faugloire et al., 2006). The emergence of uniform as well as distinct coordination solutions must be accounted for in a theory of coordination dynamics in redundant tasks.

These overall conclusions indicate that while the HKB model captures the dynamics associated with non-redundant coordination tasks it does not necessarily capture those that emerge in redundant tasks. Another higher level of control appears to operate in redundant coordination tasks the dynamics of which utilize, but are separate from, the intrinsic dynamics that operate in non-redundant coordination. The operation of different levels of control provides a potential explanation for the discrepancies previously found between hip-ankle and bimanual coordination as being due to the operation of different dynamics in redundant and non-redundant tasks. Discrepancies would be expected to exist between tasks that are controlled by different hierarchical levels that operate with different dynamics.

5.3. Future Directions

Future directions of study include further investigation of the mapping of non-redundant intrinsic dynamics to the level of redundant task performance. The principles governing the assembly of multiple coordination solutions from fewer stable patterns within dynamics at the non-redundant level of control are not fully understood. Experiment 3 was limited by the production of only 10 movement cycles at each frequency. The collection of larger amounts of data would allow analyses to more clearly distinguish the total number of redundant coordination patterns performed by individuals as well as the relation of these to the non-redundant intrinsic dynamics.

Future research could also determine the degree to which emergent hip-ankle coordination are consistently produced at specific movement frequencies. To date no research has examined the consistency of the relation between individual coordination patterns and the movement frequencies at which they occur. It remains to be determined how the learning of a new non-redundant coordination pattern affects the emergence of multiple coordination patterns across multiple movement frequencies. To date the learning of a new coordination pattern has only been examined in relation to the coordination patterns produced at two movement frequencies.

A complete understanding of the effects of learning of a new non-redundant coordination pattern on the redundant coordination dynamics will require an examination of multiple movement frequencies across the entire range of frequencies that can be performed. Future research could also extend the work by Bardy et al. (1999) by investigating what hip-ankle coordination patterns are produced at multiple combinations of height of center of mass and movement frequency.

5.4. General Conclusion

Three experiments were conducted investigating the relation between the organization of hip-ankle coordination in postural tasks. Several general conclusions were reached from these studies. 1) A hierarchical relation exists between the control structures for the organization of redundant and non-redundant postural coordination, with transfer occurring from the non-redundant task to the redundant, but not vice versa. 2) The timescales of change exist within and between the dynamics that organize redundant and non-redundant coordination tasks. Change in the organization of each type of task operated on a short (almost immediate) timescale. Adaptation between the control structures for these two types of tasks operated on a slower timescale of up to 24 hrs. 3) Different dynamics operate in redundant and non-redundant coordination tasks even using the same effectors.

REFERENCES

Adams, J.A. (1961). The second facet of forgetting: A review of warm-up decrement. *Psychological Bulletin, 58,* 257-273.

Adams, J.A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101*, 41/74.

Anderson, D.I., & Sidaway, B. Coordination changes associated with practice of a soccer kick. *Research quarterly for Exercise and Sport, 65*, 93-99.

Barch, A.M., & Lewis, D. (1954). The effect of task difficulty and amount of practice on proactive transfer. Journal *of Experimental Psychology, 48*, 134-142.

Bardy, B.G., Marin, L., Stoffregen, T.A., & Bootsma, R.J. (1999). Postural coordination modes considered as emergent phenomena. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1284-1301.

Bardy, B.G., Ouillier, O., Bootsma, R.J., & Stoffregen, T.A. (2002). Dynamics of human postural transitions. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 499-514.

Batschelet, E. (1981). *Circular statistics in biology*. New York: Academic Press

Beek, P.J., (2000). Toward a theory of implicit learning in the perceptual-motor domain. *International Journal of Sports Psychology, 31,* 547-554.

Beilock, S.L., & Carr, T.H. (2001). On the fragility of skilled performance: what governs choking under pressure?. *Journal of Experimental Psychology. General*, 130, 701-725.

Beilock, S.L., Carr, T.H., MacMahon, C., & Starkes, J.L. (2002). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experience performance of sensorimotor skills. *Journal of Experimental Psychology. Applied, 8*, 6-16.

Bernstein, N. (1967). *The coordination and regulation of movements.* Oxford: Pergamon Press.

Bernstein, N.A. (1996). On dexterity and its development. In M. Latash & M.T. Turvey (Eds.), *Dexterity and its development* (pp. 3-244). Mahwah, NJ: Lawrence Erlbaum.

Bransford, J.D., & Franks, J.J. (1976). Toward a framework for understanding learning. In G.H. Bower, (Ed.), *The psychology of learning and motivation, Vol. 10,* New York: Academic Press.

Bransford, J.D., Franks, J.J., Morris, C.D., & Stein, B.S. (1979). Some general constraints on learning and memory research. In L.S. Cermack and F.I.M. Craik, (Eds)., *Levels of processing in human memory*. Hilldale, N.J.: Erlbaum.

Brashers-Krug, T., Shadmehr, R., & Bizzi, E. (1996). Consolidation in human motor memory. *Nature, 382,* 252-255.

Carron, A.V. (1969). Physical fatigue and motor learning. *Research Quarterly for Exercise and Sport, 40,* 682-686.

Ellis, H.C. (1965). *Transfer of learning.* New York: Macmillan

Faugloire, E., Bardy, B.G., Merhi, O., & Stoffregen, T.A. (2005). Exploring coordination dynamics of the postural system with real-time visual feedback. *Neuroscience Letters, 374*, 136-141.

Faugloire, E., Bardy, B.G., & Stoffregen, T.A. (2006). Dynamics of learning new postural patterns: Influence of preexisting spontaneous behaviors. *Journal of Motor Behavior, 38*, 299-312.

Faugloire, E., Bardy, B.G., & Stoffregen, T.A. (2009). (De)Stabilization of required and spontaneous postural dynamics with learning. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 170-187.

Fontaine, R.J., Lee, T.D., & Swinnen, S.P. (1997). Learning a new bimanual coordination pattern: reciprocal influences of intrinsic and to-be-learned patterns. *Canadian Journal of Experimental Psychology, 51,* 1-9.

Gick, M.L., & Holyoak, K.J. (1987). The cognitive basis of knowledge transfer. In S.M. Cormier and J.D. Hagman, (Eds.), *Transfer of learning: Contemporary research and applications.* San Diego, CA: Academic Press.

Haibach, P.S., Daniels, G.L., & Newell, K.M. (2004). Coordination changes in the early stages of learning to cascade juggle. *Human Movement Science, 23*, 185-206.

Haken, H. (1977). Synergetics: an introduction: nonequilibrium phase transitions and self-organization in physics, chemistry, and biology. New York, NY: Springer-Verlag.

Haken, H. (1984). The science of structure: synergetics.. New York, NY: Van Nostrand Reinhold.

Haken, H. Kelso, J.A.S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51*, 347-356.

Holyoak, K.J. (1985). The pragmatic of analogical transfer. In G.H. Bower (Ed.), *The psychology of learning and motivation, Vol. 19.* New York: Academic Press.

Horak, F.B., & MacPherson, J.M. (1996). Postural orientation and equilibrium. In L.B.

Rowell & J.T. Shepherd (Eds.), *Handbook of physiology* (pp. 255-292). New York: Oxford University Press.

Horak, F.B., & Nashner, L.M. (1986). Central programming of postural movements: Adaptation to altered support-surface configurations. Journal *of Neurophysiology, 55*, 1369-1381.

Horak, F.B., Nashner, L.M., & Diener, H.C. (1990). Postural strategies associated with somatosensory and vestibular loss. *Experimental Brain Research, 82*, 167-177.

Jackson, J.H. (1932). *Selected writings of John Hughlings Jackson*, in J. Taylor (Ed.), Hodder and Staughton: London

Kandel, E.R., Schwartz, J.H., & Jessel, T.M. (2000). *Principles of neural science 4th edition,* McGraw-Hill Publishing Co.; London.

Kelso, J.A.S. (1981). On the oscillatory basis of movement. *Bulletin of Psychonomic Society, 18*, 63.

Kelso, J.A.S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology, 15,* R1000-R1004.

Kelso, J.A.S. (1995). *Dynamic patterns*. Cambridge, MA: MIT Press.

Kelso, J.A., & Zanone, P.G. (2002). Coordination dynamics of learning and transfer across different effector systems. *Journal of Experimental Psychology. Human Perception and Performance, 28*, 776-797.

Ko. Y.G., Challis, J.H., & Newell, K.M. (2001). Postural coordination patterns as a function of dynamics of the support surface. Human Movement Science, 20, 737-764.

Ko, Y.G., Challis, J.H., Stitt, J.P., & Newell, K.M. (2003). Organization of compensatory postural coordination patterns. Journal of Motor Behavior, 35,325-342.

Kugler, P.N., & Turvey, M.T. (1987). *Information, natural law, and the self-assembly of rhythmic movement.* Hillsdale, NJ: Erlbaum.

Latash, M.L. (2008). *Synergy*. New York: Oxford University Press.

Latash, M.L., Krishnamoorthy, V., Scholz, J.P., & Zatsiorsky, V.M. (2005). Postural synergies and their development. *Neural Plasticity, 12*, 119-130.

Lee, T.D., Swinnen, S.P., & Verschueren, S. (1995). Relative phase alterations during bimanual skill acquisition. *Journal of Motor Behavior, 27*, 263-274.

Lewis, D., McAllister, D.E., & Adams, J.A. (1951). Facilitation and interference in performance on the Modified Mashburn Apparatus: I. The effects of varying the amount of original learning. *Journal of Experimental Psychology, 41*, 247-260.

Lung, C.T., & Dominowski, R. (1985). Effects of strategy instructions and practice on nine-dot problem solving. *Journal of Experimental Psychology, Learning, Memory, and Cognition,* 11, 804-811.

Maslovat, D., Bredin, S.S., Chua, R., & Franks, I.M. (2005). Evaluation of a scanning methodology in bimanual coordination. *Motor Control, 9*, 312-331.

Massion, J. (1994). Postural control system. *Current Opinion in Neurobiology, 4*, 877-877.

Mayer-Kress, G., Newell, K.M., & Liu, Y.T. (2009). Nonlinear dynamics of motor learning. *Nonlinear Dynamics, Psychology and Life Sciences, 13,* 3-26.

McAllister, D.E., & Lewis, D. (1951). Facilitation and interference in performance on the Modified Mashburn Apparatus: II. The effects of varying the amount of interpolated learning. *Journal of Experimental Psychology, 41,* 356-363.

McCollum, G., & Leen, T.K. (1989). Form and exploration of mechanical stability limits in erect stance. *Journal of Motor Behavior, 21*, 225-244.

McNevin, N.H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science, 21*, 187-202.

Morris, C.D., Bransford, J.D., & Franks, J.J. (1977). Levels of processing versus transfer appropriate processing. *Journal of Verbal Learning and Verbal Behavior, 16,* 519-533.

Nashner, L.M., Shupert, C.L., Horak, F.B., & Black, F.O. (1989). Organization of posture control: An analysis of sensory and mechanical constraints. *Progress in Brain Research, 80*, 411-418.

Newell, K.M. (1986). Constraints on the development of coordination. In M.G. Wade and H.T.A. Whiting (Eds.). *Motor development in children: Problems of coordination and control.* Martinus Hijhoff: Dordrecht.

Newell, K.M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42*, 213-237.

Newell, K.M., Liu, Y.T., & Mayer-Kress, G. (2001). Time scales in motor learning and development. *Psychological Review, 108,* 57-82.

Osgood, C.E. (1949). The similarity paradox in human learning: a resolution. *Psychological Review, 56,* 132-143.

Perkins-Ceccato, N., Passmore, S.R., & Lee, T.D. (2003). Effects of focus of attention depend on golfers' skill. *Journal of Sports Sciences, 21*, 593-600.

Post, A.A., Peper, C.E., Daffertshofer, A., & Beek, P.J. (2000). Relative phase dynamics in perturbed interlimb coordination: stability and stochasticity. *Biological Cybernetics, 83,* 443-459.

Press, D.Z., Casement, M.D., Pascual-Leone, A., & Robertson, E.M. (2005). The time course of off-line motor sequence learning. *Brain Research. Cognitive Brain Research, 25,* 375-378.

Schmidt, R.A. & Young, D.E. (1987). Transfer of movement control in motor skill learning. In S.M. Cornier and J.D. Hagman, (Eds.), *Transfer of learning: Contemporary research and applications.* San Diego, CA: Academic Press.

Schöner, G., Haken, H., & Kelso, J.A.S. (1986). A stochastic theory of phase transitions in human hand movement. *Biological Cybernetics, 53,* 247-257.

Schöner, G., & Kelso, J.A. (1988). A synergetic theory of environmentally-specified and learned patterns of movement coordination. I. Relative phase dynamics. *Biological Cybernetics, 58*, 71-80.

Schöner, G., Zanone, P.G., & Kelso, J.A. (1992). Learning as change of coordination dynamics: theory and experiment. *Journal of Motor Behavior, 24*, 29-48.

Siipola, E.M. (1941). The relation of transfer in habit-structure. *Journal of Experimental Psychology, 28,* 233-261.

Stratton, S.M., Liu, Y.T., Hong, S.L., Mayer-Kress, G., & Newell, K.M. (2007). Snoddy (1926) revisited: time scales of motor learning. *Journal of Motor Behavior, 39,* 503-515.

Thorndike, E.L., & Woodworth, R.S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review, 8*, 247-261.

Thorndike, E.L. (1903). *Educational psychology.* New York: Lemcke and Buechner.

Tognoli, E., & Kelso, J.A. (2009). Brain coordination dynamics: true and false faces of phase synchrony and metastability. *Progress in Neurobiology, 87,* 31-40.

Treffner, P.J., & Turvey, M.T. (1996). Symmetry, broken symmetry, and handedness in bimanual coordination dynamics. *Experimental Brain Research, 107*, 463-478.

Turvey, M,.T. (2007). Action and perception at the level of synergies. *Human Movement Science, 26,* 657-697.

Turvey, M.T., & Carello, C. (1996). Dynamics of Bernstein's level of synergies. In M.L. Latash & M.T. Turvey (Eds.) *Dexterity and its development*. Mahwah, New Jersey: Lawrence Erlbaum.

Turvey, M.T., Shaw, R.E., & Mace, W. (1978). Issues in a theory of action: degrees of freedom, coordinative structures, and coalitions. In: Requin J (ed.) *Attention and performance VII*. Erlbaum: NJ, pp 557-598.

Von Holst, E. (1937/1973). *The behavioral physiology of animals and man.* Coral Gables, FL: University of Miami Press.

Wenderoth, N., & Bock, O. (2001). Learning of a new bimanual coordination pattern is governed by three distinct processes. *Motor Control, 5,* 23-35.

Wenderoth, N., Bock, O., & Krohn, R. (2002). Learning a new bimanual coordination pattern is influenced by existing attractors. *Motor Control, 6,* 166-182.

Whiting, H.T.A. (1984). The concepts of 'adaptation' and 'attunement' in skill learning. In *Adaptive control of ill-defined systems*. O.G. Selfridge, E.L. Rissland, and M.A. Arbib, (Eds). (pp. 177-186). New York: Plenum Press

Williams, G.P. (1997). *Chaos theory tamed.* Washington, D.C.: Joseph Henry Press.

Wixted, J.T. (2004). The psychology and neuroscience of forgetting. *Annual Review of Psychology, 55,* 235-269.

Wulf, G., Lauterbach, B., & Toole, T. (1999). The learning advantages of an external focus of attention in golf. *Research Quarterly for Exercise and Sport, 70*, 120-126.

Wulf, G., & Prinz, W. (2001). Direction attention to movement effects enhances learning: a review. *Psychonomic Bulletin & Review, 8*, 648-660.

Yamanishi, J., Kawato, M., & Suzuki, R. (1980). Two coupled oscillators as a model for the coordinated finger tapping by both hands. *Biological Cybernetics, 37*, 219-225.

Zanone, P.G., & Kelso, J.A. (1992). Evolution of behavior attractors with learning: nonequilibrium phase transitions. *Journal of Experimental Psychology. Human Perception and Performance, 18*, 403-421.

Zanone, P.G., & Kelso, J.A. (1994). The coordination dynamics of learning. In S. Swinnen, H. Heuer, J. Massion, & P. Casaer (Eds.). *Interlimb coordination, neural, dynamical, and cognitive constraints* (pp. 461-488). San Diego: Academic Press.

Zanone, P.G., & Kelso, J.A. (1997). Coordination dynamics of learning and transfer: Collective and component levels. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1454-1480.

APPENDIX A. THE PENNSYLVANIA STATE UNIVERSITY INFORMED CONSENT FORMS

PENNSTATE 1855

Insert starting on a new page

Informed Consent Form for Biomedical Research
The Pennsylvania State University

ORP USE ONLY: IRB**#26876 Doc#1**
The Pennsylvania State University
Office for Research Protections
Approval Date: 12/12/07 JKG
Expiration Date: 11/06/08 JKG
Biomedical Institutional Review Board

Title of Project: *Relation Between Task Performance, Spontaneous Coordination and Intrinsic Dynamics*

Principal Investigator: Karl M. Newell, Ph.D.
275 Recreation Building
814-863-1163

Other Investigator(s): Eric G. James, M.S.

1. Purpose of the study: The purpose of this research is to study how the movements you make while standing naturally are coordinated. We are interested in how people perform a swaying task and how they intentionally produce specific movements while standing.

2. Procedures to be followed: You will be asked to participate in 1 testing session performing each of the following tasks:

a. Perform a small swaying movement forward and backward while standing in place. On different trials you will be asked to perform this swaying task at 2 different speeds while you are tracking a target on a visual display. A marker showing the position of your head will also be shown on the display and your task will keep the marker for your head position as close as possible to the target marker.

b. Perform specific coordination patterns of your hips and ankles. You will see a visual display showing how you are moving your ankles and hips and you will be asked to attempt to match the movements of these parts of your body to a target pattern shown on the display. You will be asked to perform 16 of these different movement patterns.

While performing these tasks you will have small plastic devices that will measure your leg movements attached to your right hip and ankle. You will also have a string attached to the back of your head with a comfortable strap that will be used to measure your head movement.

3. Discomforts and risks: As with all forms of physical activity involving full body movements, slight muscular discomfort related to fatigue is possible, depending on your fitness level.

4. Benefits: The benefits to you include personal contribution to the research community and potential social benefits from interacting with investigators. The benefits to society include increased understanding of postural dynamics, possibly contributing to enhanced balance treatment interventions.

5. Duration/time of the procedures and study: You will be requested to participate in one session of approximately 1 hour in length.

6. Statement of confidentiality: This signed consent form will be kept in a locked file cabinet in a locked office. In the event of publication of this research, no personally identifying information will be disclosed. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Department of Health and Human Services, the Biomedical Institutional Review Board and the PSU Office for Research Protections. Data will be kept on hard discs and other forms of computer media will be kept in the locked laboratory of Dr. Newell. Once the manuscript is published, the data will be transferred and kept in a locked cabinet in the laboratory for at least 5 years.

7. Right to ask questions: Please contact Dr. Karl Newell at 814-863-1163 with questions, complaints or concerns about the research. You can also call this number if you feel this study has harmed you. Questions about your rights as a research participant may be directed to Penn State University's Office for Research Protections at (814) 865-1775. You may also call this number if you cannot reach the research team or wish to talk to someone else.

8. Payment for participation: You will receive $15.00 for participating in this testing session. Should you choose to leave the session prior to the completion of all tasks, your pay will be pro-rated based on the percentage of the session that you have completed.

9. Voluntary participation: Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

10. Injury Clause: In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to take part in this research study.

If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

_______________________________________ ____________________
Participant Signature Date

_______________________________________ ____________________
Person Obtaining Consent Date

Informed Consent Form for Biomedical Research
The Pennsylvania State University

Title of Project: *Relation Between Task Performance, Spontaneous Coordination and Intrinsic Dynamics*

Principal Investigator: Karl M. Newell, Ph.D.
275 Recreation Building
814-863-1163

Other Investigator(s): Eric G. James, M.S.

1. Purpose of the study: The purpose of this research is to study how the movements you make while standing naturally are coordinated. We are interested in how people perform a swaying task and how they intentionally produce specific movements while standing.

2. Procedures to be followed: You will be asked to participate in 2 testing sessions performing each of the following tasks:

a. Perform a small swaying movement forward and backward while standing in place. On different trials you will be asked to perform this swaying task at 2 different speeds while you are tracking a target on a visual display. A marker showing the position of your head will also be shown on the display and your task will keep the marker for your head position as close as possible to the target marker.

b. Perform specific coordination patterns of your hips and ankles. You will see a visual display showing how you are moving your ankles and hips and you will be asked to attempt to match the movements of these parts of your body to a target pattern shown on the display. You will be asked to perform 16 of these different movement patterns.

While performing these tasks you will have small plastic devices that will measure your leg movements attached to your right hip and ankle. You will also have a string attached to the back of your head with a comfortable strap that will be used to measure your head movement.

3. Discomforts and risks: As with all forms of physical activity involving full body movements, slight muscular discomfort related to fatigue is possible, depending on your fitness level. Additionally, the movements you will be asked to do are in the standing position, therefore a slight risk of falling exists.

4. Benefits: The benefits to you include personal contribution to the research community and potential social benefits from interacting with investigators. The benefits to society include increased understanding of postural dynamics, possibly contributing to enhanced balance treatment interventions.

5. Duration/time of the procedures and study: You will be requested to participate in two sessions of approximately 1 hour in length each.

6. Statement of confidentiality: This signed consent form will be kept in a locked file cabinet in a locked office. In the event of publication of this research, no personally identifying information will be disclosed. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Department of Health and Human Services, the Biomedical Institutional Review Board and the PSU Office for Research Protections. Data will be kept on hard discs and other forms of computer media will be kept in the locked laboratory of Dr. Newell. Once the manuscript is published, the data will be transferred and kept in a locked cabinet in the laboratory for at least 5 years.

7. Right to ask questions: Please contact Dr. Karl Newell at 814-863-1163 with questions, complaints or concerns about the research. You can also call this number if you feel this study has harmed you. Questions about your rights as a research participant may be directed to Penn State University's Office for Research Protections at (814) 865-1775.

8. Payment for participation: You will receive a total of $15.00 for participating in these two testing sessions. Should you choose to leave the session prior to the completion of all tasks, your pay will be pro-rated based on the percentage of the session you have completed.

9. Voluntary participation: Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

10. Injury Clause: In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to take part in this research study.

If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

Participant Signature	Date
Person Obtaining Consent	Date

PENNSTATE

1855

Informed Consent Form for Biomedical Research
The Pennsylvania State University

ORP USE ONLY: IRB #: 30130
The Pennsylvania State University
Office for Research Protections
Approval Date: 01/27/09
Expiration Date: 01/19/10
Biomedical Institutional Review Board

Title of Project: *Changes in Postural Coordination After Learning a New Hip Ankle Coordination Pattern*

Principal Investigator: Karl M. Newell, Ph.D.
275 Recreation Building
814-863-1163

Other Investigator(s): Eric G. James, M.S.

1. Purpose of the study: The purpose of this research is to study how the movements you make while standing naturally are coordinated. We are interested in how people perform a swaying task and how they are able to learn a new way of making swaying postural movements.

2. Procedures to be followed: You will be randomly assigned to one of two groups. If you are assigned to group A you be asked to participate in 4 testing sessions. The first 3 days of testing will be on consecutive days and day 4 will be 1 week after day 3. If assigned to group A you will be asked to perform tasks a) and b), described below, on days 1, 2 and 3. One day 4 you will only be asked to perform task a). If you are assigned to group B you will only be tested on 3 days. You'll come in for day 1 testing, then skip a day before coming in for day 2 testing. You'll then be tested 1 week later for the third day of testing. If assigned to this group you will perform only task a). The two tasks that will be performed are:

a. Perform a small swaying movement forward and backward while standing in place. On different trials you will be asked to perform this swaying task at different speeds while you are tracking a target on a visual display. A marker showing the position of your head will also be shown on the display and your task will keep the marker for your head position as close as possible to the target marker.

b. Perform specific coordination patterns of your hips and ankles. You will see a visual display showing how you are moving your ankles and hips and you will be asked to attempt to match the movements of these parts of your body to a target pattern shown on the display.

While performing these tasks you will have small plastic devices that will measure your leg movements attached to your right hip and ankle. You will also have a string attached to the back of your head with a comfortable strap that will be used to measure your head movement.

3. Discomforts and risks: As with all forms of physical activity involving full body movements, slight muscular discomfort related to fatigue is possible, depending on your fitness level. Additionally, the movements you will be asked to do are in the standing position, therefore a slight risk of falling exists. A person will be standing alongside you to prevent falling.

4. Benefits: The benefits to you include personal contribution to the research community and potential social benefits from interacting with investigators. The benefits to society include increased understanding of postural dynamics, possibly contributing to enhanced balance treatment interventions.

5. Duration/time of the procedures and study: You will be requested to participate in four sessions of approximately 45 minutes in length each.

6. Statement of confidentiality: This signed consent form will be kept in a locked file cabinet in a locked office. No names will be collected or associated with the data collected. In the event of publication of this research, no personally identifying information will be disclosed. The following may review and copy records related to this research: The Office of Human Research Protections in the U.S. Department of Health and Human Services, the Biomedical Institutional Review Board and the PSU Office for Research Protections. Data will be kept on hard discs and other forms of computer media will be kept in the locked laboratory of Dr. Newell. Once the manuscript is published, the data will be transferred and kept in a locked cabinet in the laboratory for at least 5 years.

7. Right to ask questions: Please contact Dr. Karl Newell at 814-863-1163 with questions, complaints or concerns about the research. You can also call this number if you feel this study has harmed you. Questions about your rights as a research participant may be directed to Penn State University's Office for Research Protections at (814) 865-1775.

8. Payment for participation: You will receive a total of $50.00 for participating in these four testing sessions. Should you choose to stop participating prior to the completion of all sessions your pay will be pro-rated based on the percentage of the session you have completed.

9. Voluntary participation: Your decision to be in this research is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would receive otherwise.

10. Injury Clause: In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

You must be 18 years of age or older to take part in this research study.

If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

____ ____________________
Participant Signature Date

____ ____________________
Person Obtaining Consent Date

APPENDIX B. PARTICIPANT INCLUSION/EXCLUSION QUESTIONAIRE

Screening questions for studies:

Do you have any history of neurological disorder?

Do you have any history of cardiovascular, endocrine or neuromotor disorders?

Have you ever had surgery to either of your legs?

No screening data collections sheet will be kept. If respondents answer yes to any of these questions they will not be utilized in the study nor will any records of these individuals be kept.

APPENDIX C. DEPENDENT VARIABLES

Measures regarding the movement and coordination of the hip and ankle joints were calculated as well as an estimate of tracking task performance.

Amplitude of hip and ankle joint movements: The average angular hip and ankle displacement for movement cycles during each task.

Root Mean Square Error: The level of tracking task performance was measured by calculating the root mean square error between head and target positions.

Relative phase entropy: The information entropy of hip-ankle relative phase time series was calculated for each participant to estimate the amount of coordination variability.

Mean relative phase: The mean relative phase of hip and ankle joints was calculated using the point estimate of relative phase (Kelso, 1995) including the relative phase values associated with points of both maximum flexion and extension.

APPENDIX D. RESEARCH VOLUNTEER FLYER

MOVEMENT STUDY

Participants Wanted

Ages 18-29 years

1 hour postural movement study

Compensation provided

Contact: 863-4037
Motor Behavior Lab
Dept. of Kinesiology
23 Recreation Building
Penn State University

CURRICULUM VITAE

Eric G. James

Educational Background

B.A. May 1988. St. John Fisher College, Rochester, New York. Undergraduate major in Sociology.

M.S. May 2006. University of Houston, College of Education. University Park, Pennsylvania. Graduate major in Exercise Science, Motor Behavior under the advisement of Dr. Charles S. Layne. Research Thesis "Effects of Internal and External Focus of Attention on Relative Phase Stability in Rhythmic Bimanual Movements."

Ph.D. August 2009 (Expected graduation). Pennsylvania State University, College of Health and Human Development, University Park, Pennsylvania. Graduate major in Kinesiology, Motor Control under the advisement of Dr. Karl M. Newell. Research Dissertation "Coordination Dynamics in Redundant and Non-redundant Motor Tasks."

Publications

James, E.G., Hong, S.L., & Newell, K.M. (in press). Development of dynamic stability in children's rhythmic movement. *Developmental Psychobiology*.

Newell, K.M. & **James, E.G.** (2008) The Amount and Structure of Human Movement Variability, *Routledge Handbook of Biomechanics and Human Movement Science,* Hong, Y. & Bartlett, R. (Eds.) Routledge.

Hong, S.L., **James, E.G.**, & Newell, K.M. (2008). Coupling and irregularity in the aging motor system: Tremor and movement, *Neuroscience Letters, 433,* 119-124.

Hong, S.L., **James, E.G.**, & Newell, K.M. (2008). Age-related complexity and coupling of children's sitting posture. *Developmental Psychobiology, 50,* 502-510.

Presentations

James, E.G., & Newell, K.M. (2008). Human Coordination Variability and Postural Task Performance. *Society for Neuroscience.* Washington, D.C. November 2008. Poster Presentation

James, E.G., Hong, S.L., Newell, K.M. (2008). Aging Changes the Complexity of Low Frequency Postural Dynamic. *North American Society for the Psychology of Sport and Physical Activity.* Niagara Falls, ON: June 2008. Poster presentation

James, E.G., Hong, S.L., Newell, K.M. (2007). Distinct Time-Scale Changes in Postural Dynamics Across the Lifespan. *Society for Neuroscience.* San Diego, CA: November 2007. Poster presentation

James, E.G., Hong, S.L., Newell, K.M. (2007). Complexity of Postural Dynamics Across the Lifespan. *Gerontological Society of America.* San Francisco, CA: November 2007. Poster presentation

James, E.G., Hong, S.L., Newell, K.M. (2007). Aging Alters Coupling and Irregularity in Finger Posture and Movement. *North American Society for the Psychology of Sport and Physical Activity (NASPSPA).* San Diego, CA: June 2007. Oral presentation

James, E.G., Kurz, M.J., Layne, C.S. (2007). Frequency and Relative Phase Information in the Stability of Coordination Dynamics. *Coordination Dynamics*. Boca Raton, FL: February 2007. Poster presentation

James, EG, Layne, CS (2006). Effects of Internal and External Focus of Attention on Relative Phase Stability in Rhythmic Bimanual Movements. *Houston Society for Engineering in Medicine and Biology.* Houston, TX: February 2006. Oral presentation.

James, EG, Layne, CS (2005). Time Course of Recovery from Whole-body Vibration Induced Postural Sway. *Houston Society for Engineering in Medicine and Biology.* Houston, TX: February 2005. Poster presentation.

Professional Employment

Research Assistant	Department of Kinesiology, Penn State University Fall 2008 - graduation
Lecturer, Golf 1	Department of Kinesiology, Penn State University Summer 2008
Teaching Assistant	Department of Kinesiology, Penn State University Fall 2006 – Spring 2008
Lecturer	Department of Health and Human Performance, University of Houston Summer 2006
Teaching Assistant	Department of Health and Human Performance, University of Houston Fall 2004 – Spring 2006
Instructor	Project GRAD, University of Houston June 2005
Instructor	Feldenkrais Method of Somatic Education, private practice 1994-1999 in Montevideo, Uruguay 1999 – 2004 in Rochester, N.Y.