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MOTOR LEARNING AND FORCE OUTPUT DYNAMICS

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ABSTRACT

Motor learning is characterized by the relative persistent change of behavior over time and is a product of the dynamic changes that operate at multiple levels of analysis of the motor system. This dissertation addressed the questions of how practice influenced the ability to adaptively modulate the multiple time scale processes that support the learning of task outcomes and whether the practice environment facilitates the learning of shorter time scale mechanisms. In each of the experiments an isometric force tracking task was used that afforded the manipulation of force frequency structures.

In Experiment 1, we found task-dependent modulation of slow and fast time scale processes as a function of practice and that constant and variable practice conditions produced differential effects on the organization of force output structure. Experiment 2 showed that the time course of a rest interval modified the dynamic organization of force output structure to emphasize low frequency components that are related to sensorimotor feedback mechanisms. The results of Experiment 3 revealed that individuals differentially used shorter time scales of visual information to facilitate a reduction in tracking error that was achieved through the broadening of the spectral profile of force output trajectories as a function of practice.

Overall, the findings led to the conclusions that: (a) the practice environment differentially influences task outcome and force output structure as evident by the different time scales of change at each level of analysis; (b) the persistent and transient influence of practice is mediated across a broad bandwidth of frequency structures that generate force output dynamics; and (c) that the effects of variability of practice are differentially influenced by the variability of the pathway to be tracked.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 3

CHAPTER 4

CHAPTER 5

LIST OF TABLES

CHAPTER 5

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CHAPTER 1: INTRODUCTION

When confronted with the task of acquiring a novel motor skill an individual must learn to perform and adapt a movement pattern that successfully achieves the goal of the action. The relative persistence of behavioral change is typically achieved through the process of practice and is termed motor learning (Mazur & Hastie, 1978; A. Newell & Rosenbloom, 1981; Snoddy, 1926; Thurstone, 1919). An additional goal for the individual, however, is to develop the ability to modify the learned movement pattern to novel situations and task demands. This capacity is referred to as the generalization of motor skills and has also been used to index motor learning. The inter-related issues of motor learning, retention and generalization have important practical and theoretical implications (Schmidt & Lee, 2005). Sport coaches, rehabilitation specialists and physical education teachers attempt to design training sessions that facilitate performance within and beyond practice environments. Theoretically, the learning of a novel motor skill provides information on how an individual organizes a movement pattern to achieve the task goal.

Motor Learning

Human motor behavior exhibits the ability to adaptively modify movement patterns to a variety of changes in environmental and task constraints in large part due to the redundant degrees of freedom that can be addressed at different levels of analysis (Bernstein, 1967; K. Newell & Vaillancourt, 2001; Wolpert & Kawato, 1998). One of the core issues in motor learning theory is the characterization of the pathway of change as a function of practice or experience. Two distinct theoretical frameworks have addressed this issue. According to the information processing theory (Fitts, 1964; Schmidt, 1987), the change in information transmission as a function of time defines motor learning and proposes that changes in task outcome with practice reflect a single process of forming a representation of the movement (Adams, 1987; Fitts, 1954; Schmidt & Lee, 2005). Motor learning, however, involves changes across multiple levels of analysis that can be viewed through the framework of dynamic systems (Kelso, 1995; Mitra, Amazeen, & Turvey, 1998; K. Newell, Liu, & Mayer-Kress, 2001; Schöner, 1989). In this theoretical approach, the quantification of the nature of change (i.e., dynamics) is a central feature of motor learning that reveals how the processes of the perceptual motor system support and drive behavioral modifications.

The dynamical systems approach to motor learning has incorporated Bernstein's (1967) degrees of freedom problem to address the issue of different pathways of change across a variety of tasks. In Bernstein's view, the human body possesses a greater number of degrees of freedom than are required for a motor task and the process of skill learning is reflected in the mastery of redundant degrees of freedom. Thus, the degrees of freedom problem proposed by Bernstein (1967) captures the question of how an individual learns to coordinate and control the many redundant degrees of freedom to produce an action. Through different stages of learning an individual produces different functional organizations of the degrees of freedom that achieves the task goal.

It is well established that learning leads to a more consistent performance outcome in relation to the goal of the task (Ericsson et al., 1993); but, the role of practice on movement variability is less certain. A standard finding reported in the motor learning literature is that there are general reductions in task outcome and movement variability that are typically interpreted to be inversely related to skill level. For example, practice has been shown to reduce the variation in the movement trajectories during simple reaching patterns (Darling & Cooke, 1987). Motor skill acquisition, however, can potentially induce a variety of changes in the organization of the movement pattern and the directional change of movement variability is likely task-dependent.

The role of movement variability has traditionally been interpreted to reflect noise present within the nervous system that produces random fluctuations in task performance (Riccio, 1993; Shannon & Weaver, 1948; Slifkin & Newell, 2000). However, movement variability can also be viewed as functional in that it affords flexibility or adaptability to dynamic environments (Edelman & Gally, 2001). Additionally, variability can arise from a multitude of sources within the perceptual motor system and may be a consequence of the multiple time scale processes that generate output dynamics (Desmurget & Grafton, 2000).

Recent theoretical and empirical evidence has shown deterministic structure of movement variability that is adaptable to a variety of environmental and task constraints (Slifkin & Newell, 2000). Additionally, evidence has challenged the traditional notion of general reductions in variability (outcome or movement) as a function of learning and shown task-dependent changes in the movement pattern that meets the goal of the action (K. Newell & Vaillancourt, 2001; Sosnoff & Voudrie, 2009). The ability to adaptively use movement variability is also evident in highly skilled performers that exhibit variable movement patterns to achieve the same task goal (Arutyunyan, Gurfinkel, & Mirskii, 1969; Bootsma & van Wieringen, 1990). Furthermore, skill level has been related to the ability to produce a higher dimensional output in discrete aiming (K. Newell, Liu, &

Mayer-Kress, 1997) and a tapping task when comparing musicians and non-musicians (Pressing & Jolley-Rogers, 1997).

Analyzing the temporal structure, rather than the amount, of variability in human motor performance may provide important information relative to how the perceptual-motor system organizes the multiple degrees of freedom into lower-dimensional structures (Bernstein, 1967; Kelso, 1995; Latash, Scholz, & Schöner, 2007; Turvey, 2007). One approach is to quantify the dimension of motor output to reveal the active or dynamical degrees of freedom (i.e., dimension) of the attractor dynamic that supports the coordination and control of action (Haken, Kelso, & Bunz, 1985; Haken, 1987; K. Newell & Vaillancourt, 2001). Such an approach is an extension of the mechanical degrees of freedom proposed by Bernstein (1967) and emphasizes the pathway of change (i.e., over practice trials) of the spatial-temporal properties of the movement pattern. Thus, assessing the patterns of changes within the control space provides a distinctly different approach to address the constructs of motor learning, retention and generalization than traditional interpretations (Adams, 1971; Schmidt, 1975).

Manual tracking , such as continuous isometric force production, is a form of adaptive control that allows for the investigation of a range of sensori-motor processes (Jagacinski & Flach, 2003; Pew, 1974a; Poulton, 1974) and provides access to a broader range of frequency structures than the typical discrete movements used in most motor learning investigations. In any motor task, the organization of the perceptual-motor system consists of multiple feedforward and feedback control loops that support task performance (Desmurget & Grafton, 2000; K. Newell et al., 2001). Conceptually, each mechanism operates on a distinct time scale and thus has a unique frequency structure that contributes to the output dynamics. The ability to modulate the multiple time scales of motor output has been shown to be influenced by the confluence of environmental, task and organismic constraints (K. Newell, Studenka, & Hu, in press).

In manual control tasks, there are two theoretical interpretations regarding the change in the ability to accurately track an object as a function of practice. First, it has been proposed that the nervous system organizes motor output according to the frequency structure of the environmental and task constraints. In particular, Gallistel (1980) and Bernstein (1967) posited that a cortical oscillatory mechanism sends a signal to lower centers of the motor system with information pertaining to the period, amplitude and phase of the desired trajectory. In this viewpoint, a Fourier model may not be critically important for the lower levels of control, but it may be related to learning component frequencies that define the required movement pattern (Stanley & Franks, 1990). The other approach has been the progression-regression hypothesis of tracking behavior (Fuchs, 1962; Jagacinski & Hah, 1988) in that individuals use higher order derivatives (e.g., velocity and acceleration) of error information as a function of practice.

A limited number of investigations have examined the change of motor output dimension as a function of practice and even fewer have addressed the issue of generalization. For example, the learning of whole-body (Haken, 1996) and bimanual coordination (Mitra et al., 1998) tasks induced reductions in output dimension that is reflected in a more task-appropriate coordination pattern. In contrast, an increased force output dimension has been reported during isometric force production to fixed point dynamics (i.e., constant force level targets) tasks with practice (K. Newell, Broderick, Deutsch, & Slifkin, 2003; Sosnoff & Voudrie, 2009). Overall, the findings illustrate the adaptability of the perceptual-motor system to different task constraints and support the theoretical rationale that the potential for bi-directional changes in motor output dimension is dependent on the intrinsic dynamics of the system (Kelso, 1995) and task constraints (K. Newell & Vaillancourt, 2001).

Based on the task-dependent bi-directional perspective (K. Newell & Vaillancourt, 2001), this dissertation examined the transient and persistent effects of practice on force output dynamics in an isometric force production task and on the capacity to generalize force output to novel task constraints. Over the past decade numerous investigations have shown that the adaptive nature of force output dynamics is influenced by a variety of factors including visual intermittency, gain, force level (K. Newell et al., 2013; Sosnoff, Valantine, & Newell, 2009); however, much less is known with respect to how practice influences an individual's ability to retain and transfer slow and fast time scale processes of isometric force control.

Generalization of Motor Learning

The construct of generalization has also been used to index motor learning and relates to the corollary issue of what is being learned. Generalization can be defined as to how individuals transfer learned movement patterns in particular contexts to perform the patterns in a wide variety of situations, including those that may or may not have been previously experienced. The construct of generalization has received extensive examination over the past century (Adams, 1987; Osgood, 1949; Thorndike & Woodworth, 1901). It has been shown that the ability to generalize a motor skill is influenced by several factors including task similarity (Thorndike & Woodworth, 1901), the amount of practice (Lewis, McCallister, & Adams, 1951; McCallister, 1951) and the statistical measurement of transfer (Schmidt & Young, 1987).

The historical viewpoint of generalization has been based on the relation between stimulus and response components of an action to predict the degree of transfer between two situations. For example, repeated exposure to the same stimulus (S) that requires one particular response (R) will strengthen the S-R association and results in positive transfer. Conversely, a change in either the stimulus or response component will alter the prediction of the effect of transfer. Thus, a high degree of transfer is expected between two skills or actions that share similar elements or components (Thorndike & Woodworth, 1901).

The experimental evidence has suggested that motor skills exhibit a narrow pattern of generalization (Adams, 1987; Schmidt & Lee, 2005) and identifying the key properties of a movement pattern that allow for positive transfer has been difficult. For example, in a classic transfer study minimal transfer occurred between two similar tasks that shared a critical balance requirement (Bachman, 1961). Also, it is important to note that previous experiences can result in either positive, negative or neutral effects on performance during transfer conditions. During transfer test, the degree of learning as index by performance outcome can be quantified with a variety of manipulations (i.e., different tasks, bilateral, part-whole, etc) that differ from the practice environment. Overall, the literature on generalization supports the original notion of Thorndike and Woodworth's (1901) identical elements theory that there is a high degree of specificity of motor skills.

Previous investigations have attempted to identify invariant properties of movement outcome that promote the transfer of motor skills. Schema theory of motor learning (Schmidt, 1975) has had a strong influence on the notion of generalization. Within the schema framework, an individual uses a rule-based approach that governs a generalized motor program (i.e., a particular class of movements) and selects the appropriate movement parameters that achieve the task goal. In this view, the ability to exhibit positive transfer of learning to novel circumstances is dependent on the development of an appropriate schema. Extensive investigations have attempted to identify a critical property of invariance (e.g., relative timing or force) that facilitates the transfer of learning (Schmidt, 1975). Collectively, there has been equivocal evidence for such an invariant property of motor output that generalizes across different task variations (Heuer & Schmidt, 1988; Kwon, Zelaznik, Chiu, & Pizlo, 2011; Van Rossum, 1990).

It has also been proposed that the practice environment influences the properties of motor learning and generalization. A variety of practice schedules (e.g., random vs. blocked practice, variable vs. constant practice, temporal delay and frequency of feedback information) have been developed to examine the optimal conditions that facilitate learning and generalization of motor skills (Guadagnoli & Kohl, 2001; Wulf & Schmidt, 1989). For example, the variability of practice hypothesis (Schmidt, 1975) proposes that experiencing a range of movement patterns during practice facilitates the formation of a schema to a greater degree than constant repetitions. Although, inducing task variability can also be viewed in other terms, such as exploration through different search strategies (K. Newell, Kugler, Van Emmerik, & McDonald, 1989) or using different informational constraints to drive performance toward relevant sources of information (Bennett, Davids, & Woodcock, 1999). Currently, there lacks an overall coherent theory of the role of practice on motor skill learning and generalization.

Focus of the Dissertation

The focus of this dissertation is to examine the transient and persistent changes in the dimension of isometric force output as a function of practice and practice structure. A limited number of investigations have shown persistent changes in force output dimension over several days of practice (K. Newell et al., 2003; Sosnoff & Voudrie, 2009); therefore, the dissertation investigated the dynamics of force output structure (i.e., time- and frequency-dependent properties) within and between practice using the constructs of learning, retention and generalization. Here, we used a 1/*f* noise-like target pattern that has a strong influence on the interaction of feedforward and feedback control processes of force output. It was hypothesized that such a target pattern would induce an increase in motor output dimension as a function of practice. Also, to examine the influence of the structure of practice on the force output dynamics we independently manipulated the visual information of the target pattern and of the feedback information of force output trajectory.

In addition to the effect of practice, we also examined the pattern of generalization of force output dynamics to novel task constraints. The standard proposition is that motor skills exhibit a narrow bandwidth of generalization over novel variations of the task or context, particularly when extrapolating beyond situations previously experienced (Schmidt & Lee, 2005). Furthermore, the structure of practice has been proposed to facilitate the ability to generalize motor skills; however, this viewpoint has primarily emphasized task outcome levels (i.e., performance scores).

Here, we examined whether the proposed benefits of the variability of practice hypothesis (Schmidt, 1975) extend to the multiple time scale processes that generate force output dynamics.

From this viewpoint, we address three questions in the dissertation: (a) how does movement variability (i.e., target signal trajectory) influence the multiple time scale processes of force output as a function of learning and generalization?; (b) does variable practice enhance the properties of learning, retention and generalization of slow and fast time scale processes?; and (c) how does the manipulation of visual feedback information influence the persistence of task performance and force output structure as a function of practice?

The task was isometric force production where participants had to exert an abduction force against a load cell to match a target pattern. The task goal was to reduce error as a function of practice. Task performance in the isometric force paradigm is assessed at two different levels of the behavior –outcome and force output structure. The task outcome indicates an individual's performance level (i.e., root mean square error) and the structure (i.e., spectral analysis and approximate entropy) of the force output captures the dynamical organization (i.e., time- and frequency-dependent properties) of the output that supports performance. The analyses focused on the dynamics (i.e., over practice trials) of changes at both levels of analysis relative to the constructs of motor learning, retention and generalization.

In the viewpoint of bi-directional changes in motor output (K. Newell & Vaillancourt, 2001), there are (at least) two different pathways of change that lead to an increase of force output dimension in the isometric force protocol. In one situation the mapping of the task goal drives the motor output to a higher dimension than that of the target dimension. For example, low performance error in a fixed point attractor task (i.e., constant force level) is achieved through a highly irregular (high dimension) force output structure. The other situation occurs when the task goal exhibits a higher dimension than that of the intrinsic dynamics of the system (Kelso, 1995). Thus, in order to achieve the task goal there must be an increased motor output dimension as a function of practice. The irregularity of a $1/f$ noise-like pattern meets the latter case and as previously mentioned examining the change in force output structure to such a target pattern can be conceptually linked to the ability to modulate slow and fast time scale processes of force output (Sosnoff & Newell, 2005; Sosnoff et al., 2009). Furthermore, the target pattern can be manipulated in a principled manner that affords particular predictions associated with the variability of practice hypothesis (Schmidt, 1975).

In Experiment 1, we examined the influence of practice conditions on the change of performance accuracy and the force output structure as a function of learning. The main question was whether task-induced variability at the execution level (i.e., movement trajectory) differentially influenced task performance and the use of the multiple time scales of force output. Additionally, practice included two consecutive days of force production to examine the persistent effect of practice over a longer time scale of learning.

In Experiment 2, we examined whether variable practice provides a greater benefit than constant practice on the learning, retention and generalization of the multiple time scale processes of force output. In particular, we were interested in the detailed analysis of small (4 Hz windows), consecutive frequency bandwidths to examine the transient and persistent properties of practice on the slow (i.e., feedback mechanisms) and fast (i.e., feedforward mechanisms) time scales of isometric force output.

In Experiment 3, we investigated the persistence (i.e., learning) of the interactive effects of practice and visual scaling of shorter time scale processes on the learning of an isometric force target. Three groups of participants practiced under either a fixed gain condition, intermediate frequency scaling, or high frequency scaling conditions. It was hypothesized that augmented information of shorter time scale processes (i.e., 4 – 12 Hz) of force output would facilitate a broadening of frequency properties as a function of practice.

CHAPTER 2. LITERATURE REVIEW

The constructs motor learning, retention and generalization have been addressed through several different theoretical interpretations. The first part of the literature review will address the change in task performance and movement outcome as a function of practice. The second part of the literature discusses the theoretical interpretations of the generalization of motor skills. The third and final part of the literature examines the role of the practice conditions on the properties of motor learning.

Part 1: Dynamics of Motor Learning

The process of practice typically leads toward an increasing realization of the task goal that is also accompanied by a variety of changes in the movement organization. In general, the persistent change of task outcome provides an index of motor learning and the classic power law function (A. Newell & Rosenbloom, 1981) has been used to characterize the change in performance as a function of learning. Despite the notion of this "ubiquitous" process of learning, there have been a number of different functions (e.g., exponential, s-shaped, etc) reported in the motor learning literature. Also, practice induces behavioral changes at multiple levels of analysis (i.e., movement organization, muscle firing pattern, neural changes) of the system and the organization of a movement pattern is influenced by the distinct time scales of change of these subsystems (K. Newell, Liu, & Mayer-Kress, 2001).

Motor learning functions

Motor learning is typically quantified through inferences drawn from the repeated observation of an individual's performance of a motor task over time. There has been extensive examination of learning curves (i.e., change performance over time) that reflect the key properties of motor learning and numerous models have been developed to characterize the systematic changes in performance as a function of practice (Heathcote, Brown, & Mewhort, 2000; A. Newell & Rosenbloom, 1981; K. Newell, Liu, & Mayer-Kress, 2001). Overall, the main goal of this approach has been to identify the persistent trend over practice; however, more recent theoretical modeling has characterized both transient and persistent time scales of change (K. Newell, Mayer-Kress, Hong, & Liu, 2009, 2010).

The observed changes in the organization of motor output with practice are less known and have been primarily examined within two distinct theoretical frameworks. In one view, the information processing framework emphasizes the change over time in information transmission from input to output stages of processing (Fitts, 1964; Schmidt, 1987). In this perspective, individuals move through various qualitative states that are reflected in increased levels of performance and can be described by different stages of learning (Fitts, 1964). In contrast, the dynamical systems framework emphasizes the change in movement patterns and its outcome as a function of motor learning (Kelso, 1995; Mitra, Amazeen, & Turvey, 1998; Newell, Kugler, Van Emmerik, & McDonald, 1989; Newell et al., 2001; Schöner, 1989). One of the core issues in this viewpoint relates the Bernstein's (1967) degrees of freedom problem.

Motor learning and the degrees of freedom problem

The process of skill learning as proposed by Bernstein (1967) is reflected in the mastery of redundant, joint-space degrees of freedom. In most motor tasks, there is an infinite number of possible redundant solutions that achieve the task goal and Bernstein's approach to motor skill acquisition is reflected in how the perceptual-motor system modifies the organization of the degrees of freedom with practice. Bernstein proposed that practice results in a change in the functional organization of the redundant degrees of freedom that involves a process of freezing, freeing and exploiting the multiple degrees of freedom (Bernstein, 1967; Newell, 1985). Overall, there has been limited empirical evidence for the stage formation of the dynamics of motor learning (cf. K. Newell, 1996); however, the approach underscores the notion that changes outcome at multiple levels of analysis of the system and that there are particular directional changes in movement organization occur with learning.

The traditional degrees of freedom problem focused on the peripheral, joint-space motion of a movement patterns, but other levels of analysis (i.e., joints, muscles, motor units, neurons, etc) also exhibit redundancy. For example, the dynamic properties of behavior in a state space (Haken et al., 1985) captures the active or dynamical degrees of freedom (also known as dimension) that are distinct from the joint-space degrees of freedom. The examination of the dynamics of the dimension of motor output with practice is a central feature of the dynamical systems approach to motor learning (Kelso, 1995; Mitra, Amazeen, & Turvey, 1998; Newell, Kugler, Van Emmerik, & McDonald, 1989; Newell et al., 2001; Schöner, 1989). The dimension of motor output reveals the state of the organization of the system dynamics and is reflected in the attractor dynamics (i.e., movement solution) that supports and drives the coordination and control of the motor outcome. Furthermore, there several advantages to the dimensional analysis approach, including a non-integer value, and there is not necessarily a direct or isomorphic relation between the physical and active degrees of freedom.

The dimension of motor output has been examined in a variety of tasks including posture (Newell, Van Emmerik, Lee, & Sprague, 1993), whole-body coordination (Haken, 1996), finger oscillations (Kay, 1988) and tremor (Morrison & Newell, 1996). A general viewpoint is that the dimension of the movement solution (i.e., attractor dynamics) is lower than that of the periphery degrees of freedom in the joint space (Kay, 1988) and a solution to the degrees of freedom problem is addressed through formation of low dimensional control structures (i.e., synergies or coordinative structures). With respect to motor learning, a limited number of investigations have examined the change in dimension over practice. For example, Haken (1996) showed reductions to a single dimension of limb and torso motion during the learning of a whole-body pedalo task over practice. In a single-limb coordination task, Mitra et al. (1998) also reported reduced dimensionality of limb coordination as a function of practice. Overall, the findings support the general notion that movement variability is reduced with motor learning.

Directional changes of motor output dimension

Combining the findings from Mitra et al. (1998) that showed reduction in motor output dimension and Bernstein's (1967) viewpoint of increments in the use of the redundant degrees of freedom there is preliminary evidence that challenges the previous assumption of uni-directional pathways of change over practice. Thus, it has been proposed that bi-directional changes in motor output dimension is dependent on the interaction of task constraints and the intrinsic dynamics of the system (K. Newell & Vaillancourt, 2001). Thus, it follows that with motor learning some task goals may drive (or require) an increase in dimension from that of the intrinsic dynamics. For example, in an isometric force production task the maintenance of a constant force level induces a highly irregular and variable trajectory that is reflected in an increased dimension of the output.

Recent evidence in sensorimotor tasks, such as manual tracking, have provided initial evidence of bi-directional changes in force output dimension as a function of practice (K. Newell, Broderick, Deutsch, & Slifkin, 2003; Sosnoff & Voudrie, 2009). For example, high performance levels with fixed point dynamics (e.g., constant force level) tasks are achieved with higher dimensional (i.e., increased dynamical degrees of freedom) force outputs; whereas, low performance errors in tasks with limit cycle dynamics (e.g., rhythmical force production) are organized through a lower dimensional force output. Previous findings have also shown that age influences the ability to adaptive modulate force output dynamics (Deutsch & Newell, 2003; Vaillancourt & Newell, 2003) and there are persistent changes in motor output dimension that occur over several days of practice (K. Newell et al., 2003; Sosnoff & Voudrie, 2009).

A dimensional analysis is based on the notion that a single time series of observed movement dynamics can be reconstructed in its state space that reflects the system's dimensionality (Grassberger & Procaccia, 1983; Takens, 1981). There are several analytical techniques that have been developed to quantify the dimension of an output. For example, the time domain analysis of approximate entropy (ApEn; Pincus, 1991) measures the degree of irregularity in a signal. High values of ApEn indicate less time-dependent structure and low degrees of regularity of a signal (i.e., white noise); whereas, low ApEn reflects predictable, regular patterns (i.e., sine wave). In human behavior, higher ApEn values have been inferred to reflect the use of additional control processes in the motor output (Pincus, 1991).

The issue of motor output dimension also relates to the growing evidence of 1/*f* processes in human behavior including timing perception (Gilden, Thornton, & Mallon, 1995), standing posture (Duarte & Zatsiorsky, 2000), reaction time (Van Orden, Holden, & Turvey, 2003) and isometric force control (Sosnoff et al., 2009). Conceptually, each sensorimotor process contributing to the behavior has a unique frequency (or time scale) and the relative contribution of the process is revealed in the power spectra. Generally, visuo-motor tracking performance is comprised of a broad frequency bandwidth that includes slow time scale (0-4 Hz), sensorimotor feedback processes (Miall, Weir, & Stein, 1985; Pew, 1974b; Slifkin, Vaillancourt, & Newell, 2000) and fast time scale (up to 10-12 Hz), internal feedforward mechanisms (Sosnoff and Newell 2005; Sosnoff et al. 2009; Pew 1974a).

Summary

The traditional approach of motor learning is the index of the change of performance outcome over time; however, this motor output is supported by the simultaneous activity of multiple feedforward and feedback mechanisms within the sensorimotor system (Schmidt 1975; Desmurget and Grafton 2000; Woodworth 1899). Thus, understanding how practice influences the collective organization of these multiple time scale processes relative to the criterion of the task can enrich our understanding of the nature of change in motor learning. Recent evidence has shown that the ability to adaptively modulate a broad bandwidth of frequency structures is dependent on the interaction of environmental, task and organismic constraints (see review, K. Newell Studenka, & Hu, in press); however, the dynamics of change of these time scale processes as a function of practice has received minimal attention. Therefore, the dissertation focuses on the change in the time- and frequency-dependent properties of force output dynamics that support performance outcome as a function of learning.

Part 2: Generalization of Motor Skills

In addition to learning a motor skill in a particular context, it is also important for an individual to exhibit the ability to perform the motor skills in a variety of circumstances that may (or may not) include variations of the task and changes in environmental information. For physical education teachers, sport coaches and physical therapist, the practical implications of the generalization of motor skill are important aspect in designing a practice environment that facilitates performance to novel situations. It is impractical (if not impossible) to have an individual learn every variation of a motor skill.

The construct of generalization of motor skills examines how past experiences influence future performance and has been an important issue in motor learning theory for over a century (Adams, 1987; Thorndike & Woodworth, 1901). Previous motor skills can exhibit different types (e.g., positive, negative or neutral) and direction (e.g., proactive and retroactive) of transfer on the ability to generalize a skill. For example, prior experiences of playing softball may facilitate the ability to field groundballs in a baseball game due to the similarity of the action. The skill of softball pitching, however, may have a negative (or neutral) influence on baseball throwing due to the different movement patterns that achieve the task goal. Overall, the empirical evidence suggests that motor skills are highly specific to the nature of the task and the following section highlights the theoretical emphasis that the acquisition of an invariant property facilitates the generalization of motor skills.

Traditional S-R interpretations

In general, the possibility of transfer of learning is based on the presence of identical elements during the training and test tasks. Historically, the relation between stimulus and response components of an action has predicted the degree of transfer between two situations. For example, repeated exposure to the same stimulus that requires one particular response will yield positive transfer. Conversely, a change in the response parameters for the same stimulus will alter the effect of transfer. It should be noted that the association between stimulus-response can be manipulated by altering only the stimulus, varying the required response, or modify both components. Therefore, a high degree of transfer is expected between two skills or actions that share similar elements and/or components. This is the basis for the identical elements theory, which was one of the first interpretations of transfer (Thorndike & Woodworth, 1901).

Within the stimulus-response perspective, various geometrical transfer surfaces have been developed in an attempt to predict the degree of transfer as a function of changes in either stimulus or response components. For example, Osgood's (1949) transfer surface proposed that the degree of transfer was a gradient surface that related positive and negative transfer to changes in the stimulus and response components of the motor output. The construction of Osgood's landscape was based on the contextual (or environmental) influence of initiating a response and implied that across the majority of changes there was neutral transfer. In contrast, Holding's transfer model (1976) emphasized that the characteristics of the individual, training conditions and task were the important components that determined the degree of similarity of the S-R components.

Schemas

The early approaches of the transfer of motor learning lacked formal definitions of what constituted a stimulus or response component and lead to a decline in the number of investigations in part due to the lack of a major theory that afforded testable predictions (Adams, 1987). The formulation of schema theory of motor skill learning (Schmidt, 1975), however, provided theoretical interpretations regarding the ability to transfer motor skills. In schema theory (Schmidt, 1975), an abstract rule (i.e., schema) governed the relation between the selection of movement patterns and movement outcome and the capacity to transfer motor skills was dependent on the development of a schema that is evidenced by an invariant movement property.

Earlier motor control theories (Adams, 1971; Keele, 1968) primarily addressed slow positioning movements that were controlled through feedback mechanisms. Schema theory (Schmidt, 1975) was an attempt to address the notion of open-loop control during rapid movements and accounted for the previous problems of memory storage and novelty of motor skills. In this framework, a generalized memory state was proposed to represent a particular class of movement patterns (i.e., throwing, kicking, etc). The development of the schema governing this generalized motor program allowed an individual the ability to select different movement parameters (i.e., force, distance, direction, etc) that meet the task goal. In the transfer of learning, schema theory (Schmidt, 1975) proposed that variable practice conditions afford an individual experience of different movement patterns that facilitated the development of the schema and that there was an invariant property of the motor program that would exhibit positive transfer effects in novel contexts.

The identification of an invariant feature (e.g., sequencing, relative timing, relative force) of motor behavior that generalized across task variations was examined in a variety of tasks. Handwriting is one example of an activity that has shown the property of invariance. For example, a particular spatio-temporal pattern is preserved when writing letters at different speed and sizes, or even different effectors (Lashley, 1942; Bernstein, 1947; Merton, 1972; Raibert, 1977). Another invariant feature identified in a generalized motor program has been the relative timing of sequential movement patterns. This invariant property has been identified through manipulations of the absolute movement duration that does not alter the relative timing between components that make up a sequence of events in patterning task such as typing (Terzuolo & Viviani, 1979) and piano playing (Shaffer, 1984).

The empirical evidence of invariant properties of motor output has been equivocal. Also, the invariance of the behavior does not hold when strict statistical criterion are applied to timing (Genter, 1987). In general, the property of invariance appears to be a strategic phenomenon (Heuer & Schmidt, 1988; Kwon et al., 2011) rather than a critical component of the movement organization.

Coordination Dynamics

The dynamical system approach to generalization is based on the mapping of the intrinsic dynamics of the system (Kelso, 1995) to the task-relevant information in the environment. The degree of motor skill transfer is based on the relative cooperation and competition between the task demands and pre-existing movement tendencies (Schöner & Kelso, 1988; Schöner, 1989). A key difference from previous approaches is the notion that learning does not necessarily rely on the buildup of motor representations; but, rather involves the modification of pre-existing coordination tendencies to achieve the demands of the task. One approach that has been used to quantify the initial state of learning is a scanning protocol (Kelso & Zanone, 2002; Yamanishi, Kawato, & Suzuki, 1980) that characterizes the stable movement patterns of the system prior to the influence of practice. Following a practice period, another scanning probe is conducted to assess learning as the relative change of the intrinsic dynamics toward the to-be-learned task.

In bimanual coordination tasks, the dynamics of behavioral change are captured in the dependent variable of relative phase (ϕ_{rel}) that measures the phase lag between the movements of joints. Prior to any influence of learning, the oscillation of two joints are strongly attracted toward two elementary coordination modes – in-phase (ϕ_{rel} close to 0°) and anti-phase patterns (ϕ_{rel} close to 180°). Thus, minimal learning can occur if the task requirements match the current state of the learner's intrinsic dynamics. Kelso and Zanone (2002) analyzed the initial intrinsic dynamics of the system prior to learning a novel coordination pattern and used pre-existing coordination tendencies to define the to-be-learned relative phase pattern independent across individuals. The results showed differences across individuals prior to learning, but that following learning performances followed similar trajectories that resulting in modifications of the intrinsic dynamics.

The scanning approach has primarily addressed the issues of learning and transfer through investigations of bimanual coordination; however, recent work has examined the acquisition of postural coordination patterns (Bardy et al, 1999; Bardy et al., 2002) and transfer across different types of postural tasks (Faugloire, Bardy, Stoffregen, 2011; James & Newell, 2011). In general, practice of a specified or required relative phase pattern results in a shift of the attractor landscape toward the to-be-learned coordination patterns. Additionally, the learning of a new coordination pattern affects the entire repertoire of coordination patterns (Zanone & Kelso, 1992, 1997). A recent finding, however, has shown that the transfer of a learned relative phase pattern may be dependent on whether the task affords redundant or non-redundant coordination patterns (James & Newell, 2011).

Overall, the dynamical systems approach to generalization is based on understanding the attractor dynamics of the perceptual-motor workspace that supports task performance. Unfortunately, there is limited knowledge about the definitive properties of dynamical organization of movement outcome over a wide range of motor tasks. The approach proposed by Newell (1996) suggests that principle predictions regarding motor skill transfer requires an understanding of not only the attractor dynamics, but also the transitions between different attractor states. This dynamical account is similar to what Bernstein (1967) called dexterity.

Summary

In summary, the generalization of motor learning has shown that motor skills are highly specific to the nature of the task and that negative transfer is typically observed with change in environmental and task constraints. Future theoretical and empirical work is necessary to understand how the properties of a movement pattern affect the performance of future motor actions.

Part 3: Practice Structure

The amount of practice on a motor task is the primary determinant of skill level and one of the main characteristics of expert performance level is the accumulation of practice time (Ericsson et al., 1993). Motor learning and generalization are also influence by other practice variables, such as the type of augmented feedback (Annett, 1972), distribution of practice (Adams & Reynolds, 1954) and variability of practice (Schmidt, 1975). Extensive research has been devoted to developing the optimal practice structure that facilitates the learning, retention and generalization of motor skills. However, despite the significant amounts of scientific inquiry, there currently lacks a coherent understanding of the role of practice. Here, the focus will be on the two primary theoretical frameworks proposed around practice variability – creating interference during practice and facilitating generalization.

Interference

The notion of creating interference during practice is related to memory formation of the motor skill and can be implemented through two different paradigms that offer distinct theoretical interpretations. The ABA design examines the type (i.e., positive, negative or neutral) and direction (i.e., retroactive and proactive) of transfer that occurs between two tasks and is typically related with ideas of memory consolidation (McGaugh, 2000). In contrast, creating contextual interference through random ordering of multiple tasks has been proposed to enhance the cognitive components of memory formation and task switching (Battig, 1972; Shea & Morgan, 1979).

The experimental design of an ABA interference protocol consists of an individual learning one task (A), then learning a different task (B) followed by subsequently testing of performance on the initially learned task (A). The influence of Task B can exhibit different directional effects in that it can retroactively (negative) or proactively (positive) interfere with the learning of Task A. Also, the established learning of task A can interfere with the learning of task B and is termed anterograde interference.

The time interval between learning two tasks (i.e., A and B) influences the stabilization process of memory formation. Competition between two memories is expected to occur if complete consolidation is not achieved prior to learning a new motor task. For example, the learning of a dynamic force-field perturbation is diminished when an opposite perturbation is practiced prior (< 4 hr) to the stabilization of the memory associated with the initial task (Brashers-Krug, Shadmehr, & Bizzi, 1996). In general, interference is usually studied on shorter time-scales with delays ranging from minutes to one day and whether consolidation is dependent on sleep processes (e.g., Brashers-Krug et al., 1996; Goedert & Willingham, 2002; Krakauer, 2009; Shadmehr & Holcomb, 1997; for a review, see Robertson, Pascual-leone, & Miall, 2004).

The effects of interference have also been examined with the notion of 'contextual variety' (i.e., contextual interference) during practice (Battig, 1972). The experimental design of contextual interference includes creating variation in the order (i.e., blocked vs. random) of the to-be-performed tasks over practice. In blocked conditions, an individual experienced low contextual interference by practicing one variation of the task before performing other variations (e.g., AAA, BBB, CCC, etc). Conversely, random conditions present the tasks in an unpredictable order (e.g., BACACBABC) resulting in higher degrees of contextual interference over practice trials. Inducing contextual interference has shown that random practice results in a transient decrement of performance during the acquisition phase compared to blocked practice; however, enhanced levels of performance are observed during retention and transfer tests (Battig, 1956; Shea & Morgan, 1979).

The effects of contextual interference have been shown in a variety of tasks including anticipation timing (Del Rey, Wughalter, & Whitehurst, 1982), force production (Shea, Kohl, & Indermill, 1990), and perturbed (i.e., dynamic force field or visuomotor rotation) reaching movements (Overduin, Richardson, Lane, Bizzi, & Press, 2006). Additionally, positive effects have been shown in a number of practical sporting environments including the badminton serve (Goode & Magill, 1986), rifle shooting (Boyce & Del Rey, 1990) and baseball batting (Hall, Domingues, & Cavazos, 1994). Maslovat et al. (2004), however, provided evidence that the effects of contextual interference may be dependent on skill level and amount of practice in bimanual coordination tasks. Also, the importance of random variation was challenged in a visuomotor adaptation investigation whereby similar levels of performance were observed for individuals that experience either random or gradual perturbations (Turnham, Braun, & Wolpert, 2012).

The proposed benefits of contextual interference are typically interpreted in two different cognitive frameworks – active reconstruction and elaboration. The active reconstruction hypothesis proposed by Lee and Magill (1983) holds that random practice requires an individual to re-construct the task solution on a trial-to-trial basis that would not be evident during blocked conditions. Alternatively, interference elaborates the memory representation of the task by comparing and contrasting different task solutions across trials (Shea, Zimny, & Magill, 1983). The reported effects of contextual interference, however, can also be accounted for by simple switching costs and exhibit low degrees of persistence when additional practice trials are included in retention and transfer tests (Russell & Newell, 2007). Finally, it is important to note that in previous investigations the amount of contextual interference used typically remains the same for most practice conditions over the time scale of a practice session

Generalization

Introducing variability during practice can also be viewed with the notion that motor learning should exhibit the ability to generalize beyond the specific practice conditions. Generalization can be defined as an individual's ability to adapt learned movement patterns in a particular context to perform the pattern in a wide variety of situations, including contexts that may or may not have been previously experienced. Schema theory of motor learning has been one approach that has had a strong influence on the construct of generalization (Schmidt, 1975). Schema theory, also, contains the variability of practice hypothesis that holds that task-induced variability facilitates the development of the rule governing the relation between movement parameters and movement outcome. In other words, an individual that experiences a wide range of parameter specifications within a particular class of actions during practice will learn a more task-appropriate rule that leads to improved retention and generalization.

Overall, the empirical evidence for the variability of practice hypothesis has been equivocal. It has been argued that the lack of fully developed schemas in children affords the greatest benefits of task-induced variability (Shapiro & Schmidt, 1982). Other supporting evidence includes enhanced generalization that extends to conditions that were beyond those previously practiced (Catalano & Kleiner, 1984; McCracken & Stelmach, 1977) and with changes in the availability of afferent visual information

(Tremblay, Welsh, & Elliott, 2001). Although, researchers have highlighted several confounding issues (discussed below) to the general interpretations of variability of practice.

Sensorimotor adaptation investigations have also examined the effect of task variability on the generalization pattern of perturbed reaching movements (Shadmehr, 2004). Similar to other discrete motor tasks, variability can be implemented over multiple dimensions (i.e., target number, direction and magnitude of perturbation, gain parameters) for reaching movements. However, the pattern of generalization in these experiments has been shown to be dependent on the type of perturbation (i.e., visuomotor and dynamic force field) and number of practice targets (i.e., single and multiple). For example, variable practice of visually perturbed reaching movements to multiple targets resulted in the same pattern of narrow generalization compared to training to a single target location (Mattar & Ostry, 2007).

The approach of the structural learning hypothesis has attempted to unify the conflicting evidence of generalization in the sensorimotor adaptation tasks (Braun, Aertsen, Wolpert, & Mehring, 2009; Braun, Mehring, & Wolpert, 2010; Turnham et al., 2012). Previous investigations have shown that learning a new sensorimotor mapping in a highly variable environment results in the learning of an ensemble average of the perturbation (Davidson & Wolpert, 2003; Scheidt, Dingwell, & Mussa-ivaldi, 2001; Wigmore, Tong, & Flanagan, 2002). Structural learning, however, proposes that individuals extract higher dimensional properties of the task (i.e., co-variation structures of the task) when exposed to variable practice environments (Braun et al., 2009, 2010).

The benefits of structural learning manifest in reduced interference with task switching and preferential exploration of a lower dimensional task subspace.

A number of factors challenge the notion that task-induced variability facilitates the generalization of motor skills. In a meta-analysis conducted by van Rossum (1990), minimal support for the hypothesis was found across a variety of tasks and populations. Van Rossum (1990) also emphasized issues pertaining to insufficient control groups and proximity effects that restrict the interpretation of previous findings. Proximity effects occur when the composite mean of the variable practice conditions is 'proximally' closer to the test criterion than the constant conditions. Several control groups are necessary to fully account for issues pertaining to the effects of proximity.

Variability at different task levels

Variability can be implemented across several dimensions of the task; however, standard investigations of the variability of practice hypothesis (Schmidt, 1975) have mainly focused on variations at the level of the task goal. This is due to schema theory's assumption that there is a direct mapping between the movement parameters and movement outcomes of an action. The highly constrained motor tasks (i.e., discrete positioning, rapid aiming, timing tasks) used in most variable practice investigations therefore minimizes (i) the influence of the redundancy that is present in the perceptual-motor system and (ii) the ability to examine a broad range of time scale processes (i.e., feedforward and feedback mechanisms) that generate motor output. The question remains whether the predictions of the variability of practice hypothesis apply to situations that afford redundant task solutions and the organization of the multiple time scales of force output dynamics.

The focus of task goal variability requires an individual to use different solutions for successful performance outcomes. For example, the distance of a basketball shot will determine the amount of force and angle of release that achieves the goal of shooting the ball through the rim; even though at any given distance the task goal can be accomplished with a variety of release velocities and angles. The presence of redundant solutions is important to consider in context of the actual performance of shooting the ball during a game. The dynamic environment restricts a basketball player's ability to successfully repeat the same movement pattern during shooting. In the basketball shooting example, introducing variability though the task constraints of different flight trajectories of the shoot with maintaining the same distance to the target would have more direct implications to the actual game environment. Thus, the questions becomes whether introducing variability at this level of the skill should be incorporated during practice in order to resemble the performance context (Ranganathan & Newell, 2013).

Introducing variability at the execution level of the task also supports the viewpoint that redundancy affords flexibility (Edelman & Gally, 2001). Flexibility is particularly important when situations arise that eliminate a single solution so that the overall performance of the task is not affected. Therefore, practice environments that require the use of redundant task solutions may promote flexibility.

Informational Constraints

An alternative view of practice is that an individual continuously explores the perceptual-motor workspace through a search process that seeks a task-appropriate movement solution (Fowler & Turvey, 1978; K. Newell et al., 1989; K. Newell, 1991). In this informational constraints approach to motor skill acquisition an individual uses environmental and task constraints to organize a movement pattern that achieves the task goal. For example, in some motor tasks like an infant learning to walk and riding a bicycle the information afforded in the organism-environment interaction is often sufficient for the learner to modify the coordination solution that meets the task demands.

The standard manipulations of practice structure (e.g., variable, block and random conditions) can also be interpreted in this framework as variations of task constraints, but there are a number of different forms of informational constraints. For example, during practice an individual has access to a variety of different sources of information that arise from environmental, task and organismic constraints. In addition to inherent properties of the individuals, information can also be viewed as augment feedback that is provided to the learner during (e.g., concurrent) or on completion (e.g., terminal) of the movement. The general notion is that feedback about the movement outcome (e.g., knowledge of results) has a strong influence on motor learning; however it may be an insufficient source for complex motor tasks that include coordination of multiple limb segments. In the latter case, transition information may be necessary to provide a qualitative change in the coordination of the movement pattern (K. Newell, Morris, & Scully, 1985). Overall, this framework suggests that changes in the practice environment are used to channel an individual's performance toward different sources of perceptual information that will lead to the emergence of a more task-appropriate movement solution.

Summary

The predictions of the variability of practice hypothesis (Schmidt, 1975) provided a theoretical framework that allowed the examination of different practice structures on motor learning. Overall there has been equivocal support for the notion that that task-induced variability during practice facilitates the learning of motor skills and there appears to be contexts in which constant repetitions aid performance. The roles of redundancy and informational constraints appear to provide a testable framework to further explore how the practice environment influences the organization of movement patterns for optimal learning and adaptability to novel situations.

CHAPTER 3. THE LEARNING OF ISOMETRIC FORCE TIME SCALES IS DIFFERENTIALLY INFLUENCE BY CONSTANT AND VARIABLE PRACTICE

Abstract

This experiment was set-up to investigate the influence of constant and variable practice on performance accuracy and the time- and frequency-dependent structure of the force output dynamics in the learning of an irregular isometric force pattern. During the practice phase, variability was induced along the force-time dimension of the target pattern for the variable practice condition (different wave forms), but all wave forms exhibited the same distributional properties of the frequency content (1/f noise: $\beta = -1.5$). The results showed that both practice conditions exhibited similar reductions in task error as a function of practice. However, constant practice produced greater changes in the force output structure than variable practice, including a higher relative change in the contribution from faster (4-12 Hz) time scale mechanisms. Collectively, the findings support the adaptive nature of force output structure and the perspective that practice conditions can produce differential effects at outcome and execution levels of motor behavior.

Introduction

Motor behavior is reflective of the simultaneous activity of multiple feedback and feedforward mechanisms within the sensorimotor system (Schmidt, 1975; Desmurget & Grafton, 2000; Woodworth, 1899). Developing an effective practice structure that facilitates the coordination of these different processes to task-relevant demands has traditionally been based on the contrasting principles of the generality and specificity of motor learning (Schmidt & Lee, 2005). Generalization reflects the ability to transfer performance to tasks in novel environments, whereas the notion of specificity of practice emphasizes the similarity between practice and testing conditions. The prevailing assumption is that task-induced variability of the movement outcome benefits generalization (Schmidt & Lee, 2005); however, given the multitude of feedback and feedforward mechanisms that comprise motor actions it may be that constant and variable practice conditions have different effects on outcome and execution variables (Ranganathan & Newell, 2010b).

A training session that includes variability in the task goal is consistent with the construct of generalization, whereby individuals adapt learned movement patterns in a particular context to perform the patterns in a wide variety of situations, including contexts that may or may not have been previously experienced. The variability of practice hypothesis, derived from schema theory for motor learning (Schmidt, 1975), holds that performing a range of parameter values within a given movement class facilitates the development of a governing rule (i.e., schema) for that particular class of behaviors. Numerous investigations support the predictions of variable practice that include enhanced performance during retention and transfer tests (Schmidt & Lee, 2005; Shapiro & Schmidt, 1982; Van Rossum, 1990).

Recent sensorimotor adaptation investigations have revived schema principles associated with the variability of practice hypothesis by applying Bayesian modeling techniques to contexts of task-induced variability (Braun et al., 2009; Turnham et al., 2012). The structural learning hypothesis proposes that individuals extract 'higher order' variables regarding the task structure (i.e., visuomotor rotation) when experiencing variations of the task that manifests in faster adaptation rates for feedforward and feedback processes. Several benefits have been ascribed to structural learning, including reduction in task space dimensions, reduced interference effects, and superior exploration along the learned structures (Braun et al., 2009).

Variable practice investigations have examined the benefits of generalization in a variety of tasks (e.g., timing, positioning and tracking tasks), but the notion of task outcome variability originates from the assumption of schema theory (Schmidt, 1975) that a movement outcome is directly related to the selected movement parameters. However, the redundant nature of motor behavior affords the ability to achieve the same desired outcome through multiple solutions (Bernstein, 1967) and allows task variations to be introduced at different levels of the action beyond the standard approach of manipulating the response outcome (Ranganathan & Newell, 2010b). For example, task-induced variability at the execution level (i.e., movement trajectories) of a striking task had a different impact on the effects of learning and generalization than that of manipulating the outcome (i.e., target locations) level (Ranganathan & Newell, 2010a).

In contrast to the proposed benefits of variable practice, there is also evidence to support the notion that constant repetition or a constant practice condition provides benefits to motor learning. For example, Keetch et al. (2005) showed that for skilled basketball players specific practice of the free throw shot manifested higher performance accuracy at this court location than what would have been predicted from performance at nearby distances. This localization of learning to specific contexts has been shown for the amount and rate of learning between two seemingly similar activities that required an important task-related balancing component (Bachman, 1961). These findings support the viewpoint of specificity of practice (Henry, 1968; Proteau, 1992; Tulving & Thomson, 1973), which holds that practice conditions should closely reflect those of the testing (e.g. transfer) conditions.

In this study, we used an isometric force production paradigm to investigate the influence of different practice conditions on the generalization or specificity of isometric force output. Subjects produced isometric force to an irregular target pattern that induces an interaction between the multiple time scale processes in the control of force output dynamics (Sosnoff et al., 2009; Sosnoff & Newell, 2005) either under a constant or variable practice condition. Generally, visuo-motor tracking performance is comprised of a broad frequency bandwidth that includes slow time scale (0-4 Hz), sensorimotor feedback processes (Miall et al., 1985; Pew, 1974b; Slifkin et al., 2000) and fast time scale (up to 10-12 Hz), internal feedforward mechanisms (Sosnoff & Newell, 2005; Sosnoff et al., 2009; Pew, 1974). However, the study of practice schedules on the control of these time scale mechanisms has been limited and is the focus of the present investigation.

The isometric force production protocol allows for the force target to be manipulated in a principled manner and affords a test of the predictions of the variability of practice hypothesis (Schmidt, 1975) on the execution level (i.e., time- and frequency-dependent properties) of force output dynamics. Variability in the current protocol was induced through the visual presentation of the target pattern such that the constant condition reflected force production to the same force-time wave form while the variable condition practiced to different force-time patterns. However, the key element to the design was that the target patterns in both practice conditions retained the *same* degree of irregularity that was defined by the distributional properties (i.e., 1/f spectral slope: $\beta = -1.5$) of the frequency content (Figure 3.1B). Therefore, the overall task goal remained invariant between the practice conditions at both the task outcome and execution level of force output. Also, the design manipulates the mapping between the response outcome and the time scales of force output to a greater degree than typical tasks that exhibit a strong relation between movement trajectory of the action and task goal.

The aim of the present investigation was to examine whether the control of multiple time scale processes in isometric force was differentially influenced by constant or variable practice conditions. The experimental design addressed the influence of practice structure on the task outcome (e.g., accuracy of tracking performance) and execution (e.g., time- and frequency-dependent properties) levels of force output during the learning of an irregular isometric force pattern. The presence of redundant task solutions at the execution level results in different predictions regarding the influence of constant and variable practice. If there is a direct (e.g., one-to-one) relation between the outcome and execution levels of the output, as assumed by schema theory (Schmidt, 1975), then practice conditions that include variability should facilitate the production of the multiple time scale processes in force output. On the other hand, if the task outcome and execution levels are distinct then the different practice conditions will produce differential effects of learning and generalization of the behavior (Ranganathan & Newell, 2010b).

Methods

Participants

Twenty-four healthy volunteers (10 females) ranging in age from 21 to 28 years old participated in the experiment. All participants had normal or corrected-to-normal vision and were right-hand dominant determined by writing preference. Each participant provided informed consent and the experimental protocol was approved by the Pennsylvania State University Institutional Review Board.

Apparatus

Participants sat in a chair with their right hand placed in a pronated position on the table with no external constraints (Figure 3.1A). Participants positioned the distal inter-phalangeal joint of the right index finger against a vertically-oriented load cell with all fingers comfortably extended and encouraged not to move the forearm or elbow position throughout the experiment. An Eltran ELFS-B3 load cell (1.27 cm in diameter) that was vertically fixed to a wooden block recorded the force data. Analog output from the load cell was amplified through a Coulbourn (V72-25) resistive bridge strain amplifier with an excitation voltage of 10 V and an amplifier gain of 100. A 16-bit A/D converter was used to sample the force output at 100 Hz. A laptop computer placed on an adjacent table collected the data. The target pattern was presented as a red line that was centered on the screen and extended across the width of a 43.18 cm LCD monitor.

Procedures

Estimation of Maximal Voluntary Contraction (MVC). Participants were instructed to produce maximal isometric abduction force with the distal phalange of the index finger in contact with the load cell. Visual feedback of the force trajectory was displayed on the monitor. Three 6 s maximal contraction trials were recorded with 30 s rest between each trial. The highest force level achieved over all trials defined the participant's MVC. The participant's MVC was determined on both practice days.

Experimental Task and Instructions. Participants adjusted the amount of force output to match the red target line displayed on the monitor. A white trajectory representing the individual's force output moved from left to right across the screen with time during the trials. The mean amplitude of the target line corresponded to 20 % of the participant's MVC obtained on that particular practice day. The target pattern amplitude spanned a range that consisted of ± 5 % of the participant's MVC.

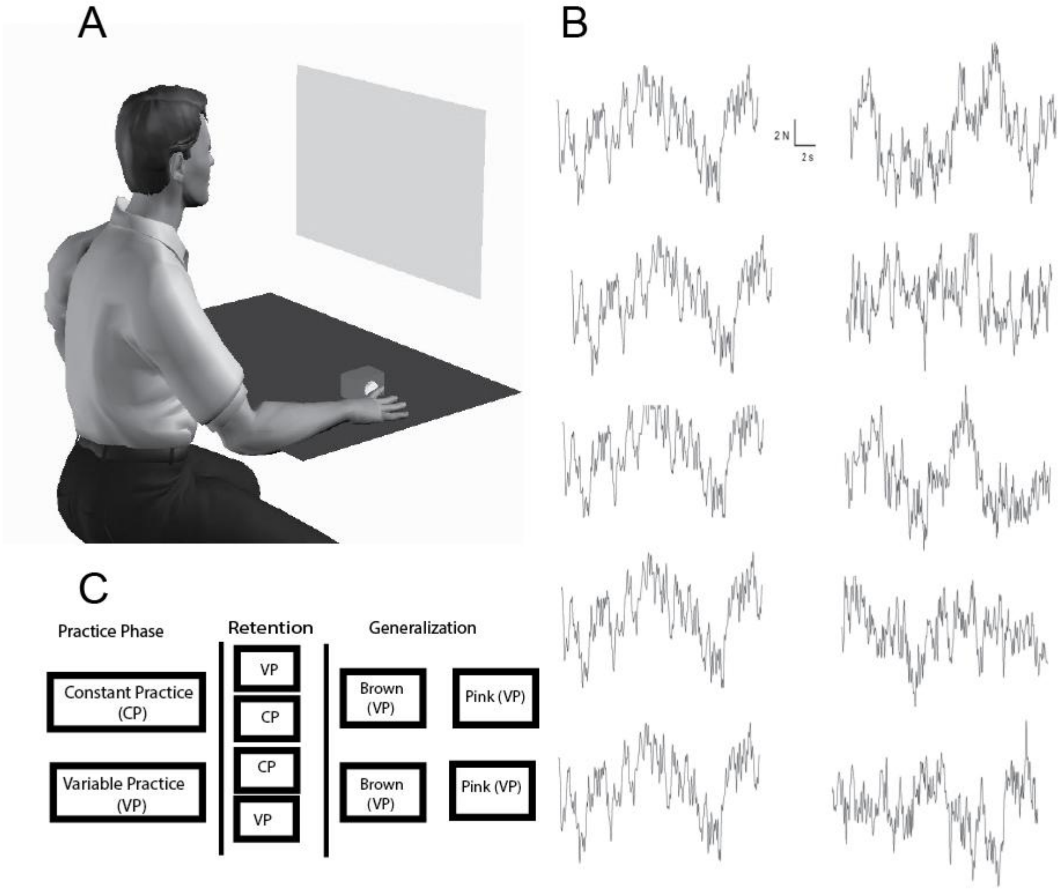

Figure 3.1. Experimental setup (A) and representative examples of target signals (B) presented under constant (left column) and variable (right column) practice conditions. The experiment phases (C) were performed in the same manner on both practice days.

Participants were instructed to minimize the deviation between their force output and the red target line throughout all trials. Following each trial a visually-displayed feedback error score was presented that reflected the root mean square error (RMSE) between the two signals and was calculated using the following equation:

$$RMSE = \left[\frac{\sum (s - f_i)^2}{n-1} \right]^{1/2} \tag{1}$$

where s is the value of the target, f_i is the i^{th} force sample and n is the number of data samples.

The experimental design consisted of a practice phase and three transfer tests that were administered in the same manner on two consecutive days.

For the practice phase of the experiments participants were counter-balanced between two experimental groups that differed in terms of the wave form presentation, though each wave form had the collective frequency characteristics of Brown/Pink noise (spectral slope $\beta = -1.5$) and a frequency range of 0 – 12 Hz. The constant practice (CON) group ($n = 12$) performed force production trials during the practice phase to the same force-time pattern (Figure 3.1B left). The variable practice (VP) group ($n = 12$) performed practice phase trials to different force-time patterns that were generated on a trial-to-trial basis (Figure 3.1B right) but that preserved the Brown/Pink noise ($\beta = -1.5$) properties. The practice phase consisted of 15 blocks of trials. A block consisted of 5 trials and each trial had a duration of 15s.

Following the practice phase, a retention test examined the influence of practice conditions on performance. A subset of control subjects was randomly selected from the initial groups (CON and VP) to remain in the same practice condition for the retention test. This control condition examined whether further practice in the same conditions resulted in additional changes. For example, a constant control (CON-CON) group ($n = 4$) continued force production to the same force-time pattern during practice and then remained in the constant practice condition during the retention. The same procedure was performed to create a variable control (VP-VP) group ($n = 4$). The control conditions allowed comparisons to determine whether continuation of the same practice condition resulted in additional effects of learning. The remaining participants performed the retention in the opposite practice condition. For example, the VP group (VP-CON) was shifted to force production to the same (i.e., constant practice condition) force-time pattern and the CON group (CON-VP) shifted to different (i.e., constant practice condition) force-time patterns. Again, the collective frequency characteristics of these targets resembled that of Brown/Pink noise.

The two generalization tests examined performance to novel irregular target patterns that exhibited different spectral properties than the wave form experienced during the practice phase. The Brown and Pink generalization tests contained target patterns with spectral slopes of $\beta = -2.0$ and $\beta = -1.0$, respectively and had a frequency bandwidth of 0 – 12 Hz. Participants returned following a 24 hr interval and proceeded through an identical protocol that included estimation of MVC, practice phase of 15 blocks, and three transfer tests.

The target wave forms were constructed in custom written software according to fractional Brownian methods so that different wave patterns retained a Brown/Pink spectral profile. Power estimates for all frequency components up to 70 Hz were taken from a Gaussian white noise signal that had a mean of 0 and a standard deviation of 1 and the phase of each frequency component within the signal was randomly selected between a range of $-\pi$ and π. The power estimates were then scaled according to a Brown/Pink $1/f$ spectral slope ($\beta = -1.5$). The signal was low-passed filtered with a 9th order Butterworth filter and a cut-off frequency of 12 Hz. The filtered power spectrum was subjected to an inverse Fourier transform resulting in the time domain representation of the wave form and scaled according to participant's MVC.

Data analysis

The initial 2 s and final 1 s of the data were removed to avoid effects of the stabilization period and any premature cessation of force production. Overall, the middle 12 s of the data time series were analyzed. All data processing was performed using custom-written software in MATLAB v7.11 (Mathworks, Natick, MA). Performance accuracy at the task outcome level was quantified by RMSE (Equation 1).

To examine whether participants in the constant or variable practice conditions were able to modulate the structure of their force output as a function of practice, the structure of force output was analyzed in the time and frequency domains. The time dependent structure of force output was assessed by approximate entropy (ApEn; Pincus, 1991). Power spectral analysis of the force data examined the frequency structure of the force output during each trial.

ApEn quantifies the regularity of a time series and a sine wave is characterized as a highly structured or regular signal that is reflected in ApEn values that approach zero. On the contrary, a less structured signal is reflected through an increase in ApEn. Larger ApEn illustrates higher irregularities in the time-dependent structure of the signal and is interpreted to be a consequence of an increase in the number of control processes (Pincus, 1991). The force time target patterns presented during the practice phase had ApEn values of ~0.54.

The power spectral analysis was computed through custom-written software that analyzed the force output in the frequency domain. For each trial, the amplitude of the Fourier components of the force data was computed through the 'fft' command in MATLAB. Each trial was normalized by the maximum power of the trial from 0 to 12

Hz resulting in the power ranging from 0 to 1. The sum of the normalized proportion of power (PoP) of three frequency bandwidths covering three 4 Hz ranges (0–4 Hz, 4–8 Hz, and 8–12 Hz) was examined.

Statistical Analysis

MVC values were evaluated between practice conditions and practices days through separate one-way ANOVAs. During the practice phase, each dependent variable was examined in a three-way mixed model (2 x 2 x 15) ANOVA with practice condition as the between-subject factor that was repeated over days and blocks. Two separate 2 x 2 x 2 (Day x Phase x Group) mixed model ANOVA on RMSE and ApEn were used to compare the effect of changing the practice condition on task performance during a retention test. The two phases corresponded to Block 15 of practice and Block 1 of transfer test. During the generalization tests, RMSE and ApEn were analyzed in separate three way (2 x 2 x 2) mixed model design (Day x Test x Group) ANOVAs. The within-subject factors were practice day and test (Brown and Pink target patterns) and the between-subject factor was practice group (VP and CP).

To assess the adaptability of force output structure to novel target patterns the relation between ApEn following practice to ApEn values during the transfer tests was examined. A correlation analysis was computed for ApEn values between the final block of the practice phase and initial block of the transfer test. The analyses were conducted separately for each transfer test and for each practice condition.

All statistical results were evaluated with alpha level criterion defined at 0.05. Violations of sphericity were corrected using the Greenhouse-Geisser correction. Bonferroni corrections were used for post hoc pairwise multiple comparisons when necessary. All statistical analyses were completed using SPSS v17 statistical package (IBM, Armonk, NY).

Results

MVC

Across both days of practice the participant's MVC ranged from 6.34 to 28.31 N with a mean of 17.26 N and a between-participant standard deviation of 7.15 N. There were no significant differences between the practice condition groups ($p > 0.05$) and individuals produced similar MVCs on both practice days ($p>0.05$).

Practice phase

Figure 3.2 shows the mean RMSE as a function of practice day and block for the constant and variable practice conditions. Statistical analysis revealed a main effect of block ($F_{14,280} = 29.10$, $p<0.001$) and practice day ($F_{1,20} = 55.04$, $p<0.001$). Also, a significant interaction between block and day ($F_{14, 280} = 15.69$, $p<0.001$) was observed. The main effect of group was not significant ($p>0.05$) and the interactions that included group also failed to reach significance.

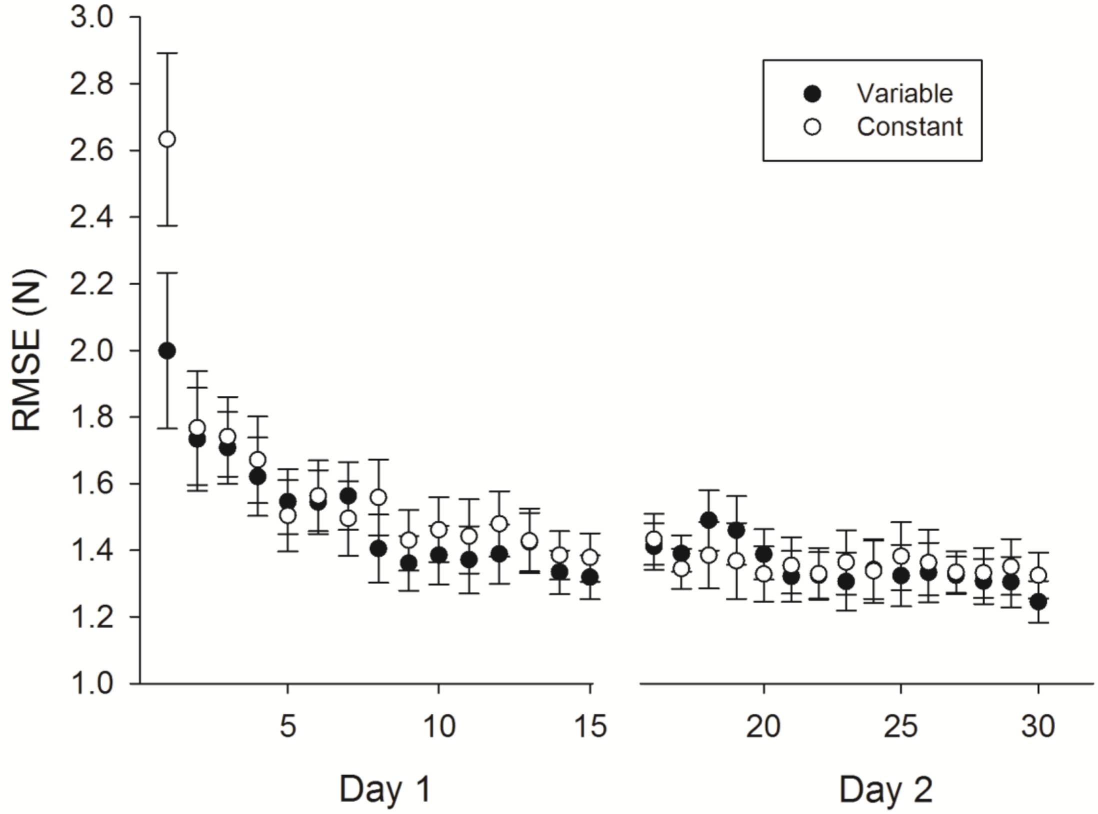

Figure 3.2 Root mean square error (RMSE) for variable (filled circles) and constant (open circles) practice conditions as a function of practice block and day. Each block represents the average of 5 practice trials. Error bars indicate standard errors.

Figure 3.3 illustrates the mean PoP within 0–4 (Figure 3.3A), 4–8 (Figure 3.3B), and 8–12 (Figure 3.3C) Hz bandwidths for both practice conditions as a function of block and practice day. There was a significant main effect of block ($F_{14, 280} = 6.08$, $p <0.001$) and group ($F_{1,20} = 13.187$, $p<0.01$) on the 0–4 Hz bandwidth. The interaction between block and group was also significant ($F_{14,280} = 3.25$, $p<0.05$). Post hoc comparisons showed that the constant practice condition had an overall lower 0-4 Hz PoP than the variable practice condition (Figure 3.3A) and this difference was evident from block 2 until block 15. The main effect of day was not significant ($p>0.05$).

There were main effects of block (($F_{14, 280} = 5.26$, $p<0.001$) and group ($F_{1,23} = 15.5$, $p<0.01$) on the 4-8 Hz PoP, that were mediated by a significant interaction between block and group ($F_{14, 280} = 3.74$, $p <0.01$). Post hoc comparisons showed that the constant practice condition had overall greater 4-8 Hz PoP than the variable practice condition and this difference was present for all blocks of practice except for the first block. There were no other significant effects in the 4-8 Hz bandwidth.

Statistical analysis on the 8-12 Hz bandwidth showed a significant main effect of block ($F_{14, 280} = 6.49$ $p<0.01$). The main effect of group failed to reach significance ($p>0.05$) which is evident by both groups showing similar increases in 8-12 Hz PoP as a function of block (Figure 3.3C). There were no other significant effects in this frequency bandwidth.

Figure 3.4 shows the mean ApEn value of force output as a function of practice block and day for both practice conditions. There was a significant main effect of block ($F_{14, 280} = 10.76$, $p<0.001$) and group ($F_{1, 23} = 10.24$, $p<0.01$) on ApEn values, that was mediated by a significant interaction between block and group ($F_{14, 280} = 5.32$, $p<0.01$). Additionally, a significant block by day interaction ($F_{14, 280} = 3.17$, $p<0.01$) was observed. Post hoc comparisons showed that the constant practice condition had overall higher ApEn values than variable practice and this difference was present from block 2 until the end of the practice phase excluding block 4.

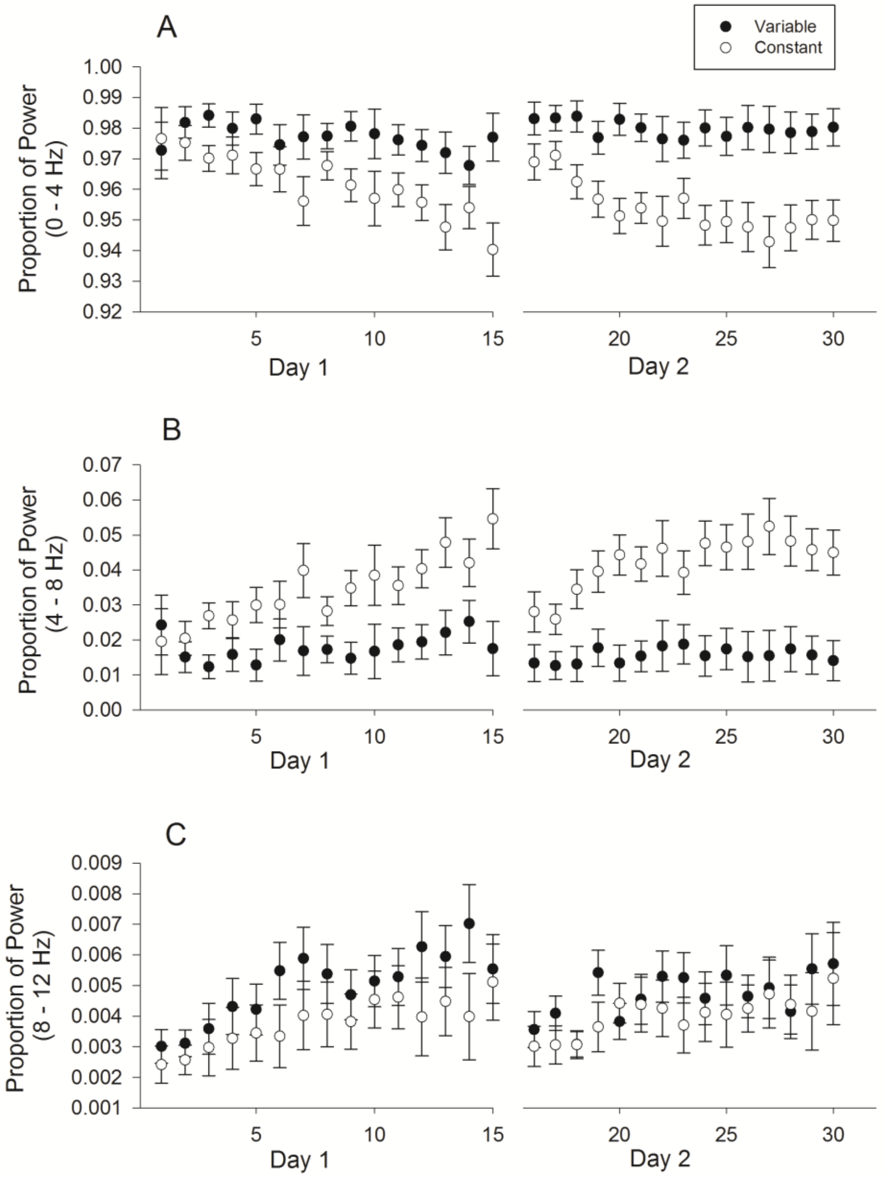

Figure 3.3. Mean (across participants) sum of proportion of power within 0–4 Hz (A), 4–8 Hz (B) and 8–12 Hz (C) bandwidths for variable (filled circles) and constant (open circles) practice conditions as a function of practice blocks and day. Each block represents the average of 5 practice trials. Error bars indicate standard error.

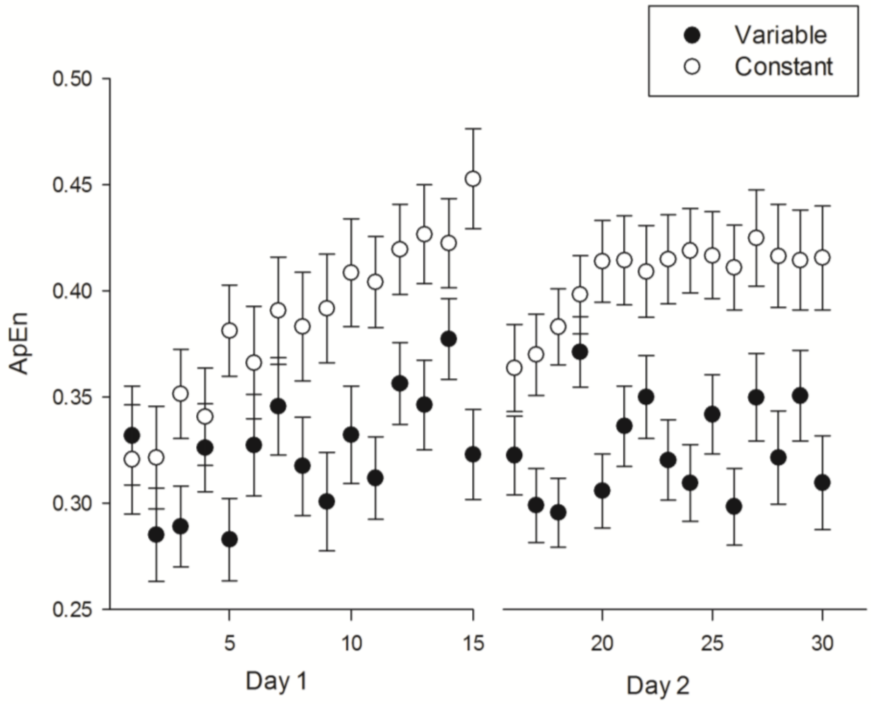

Figure 3.4. Mean (across participants) approximate entropy (ApEn) for variable (filled circles) and constant (open circles) practice conditions as a function of practice block and day. Each block represents the average of 5 practice trials. Error bars indicate standard error.

Retention Test

Following practice, participants either remained (VP-VP and CON-VP) or switched (VP-CON and CON-VP) practice conditions for the retention test. The statistical results revealed that the groups exhibited similar RMSE at the end of practice and during the initial block of the retention test (all $p>0.05$). Also, there were no significant interactions on RMSE (all $p>0.05$)

Figure 3.5 illustrates the mean ApEn value as a function of experimental phase for each group. The statistical results showed that there was a significant main effect of group ($F_{3,20} = 5.39$, $p<0.01$) and a significant interaction between group and phase ($F_{3,20} = 12.28$, $p<0.001$). Post hoc comparisons revealed that variable practice (VP-CON and VP-

VP) groups had significantly lower ApEn for block 15 of the practice phase than constant practice (CON-VP and CON-CON) groups (all p<0.05). Figure 3.5 also shows the effect of shifting practice condition during the retention tests. The change in practice condition resulted in a decrease in ApEn for the CON-VP group and an increase for the VP-CON group (all p<0.05). The VP-VP and CON-CON groups showed no change in performance across the two phases (p>0.05)

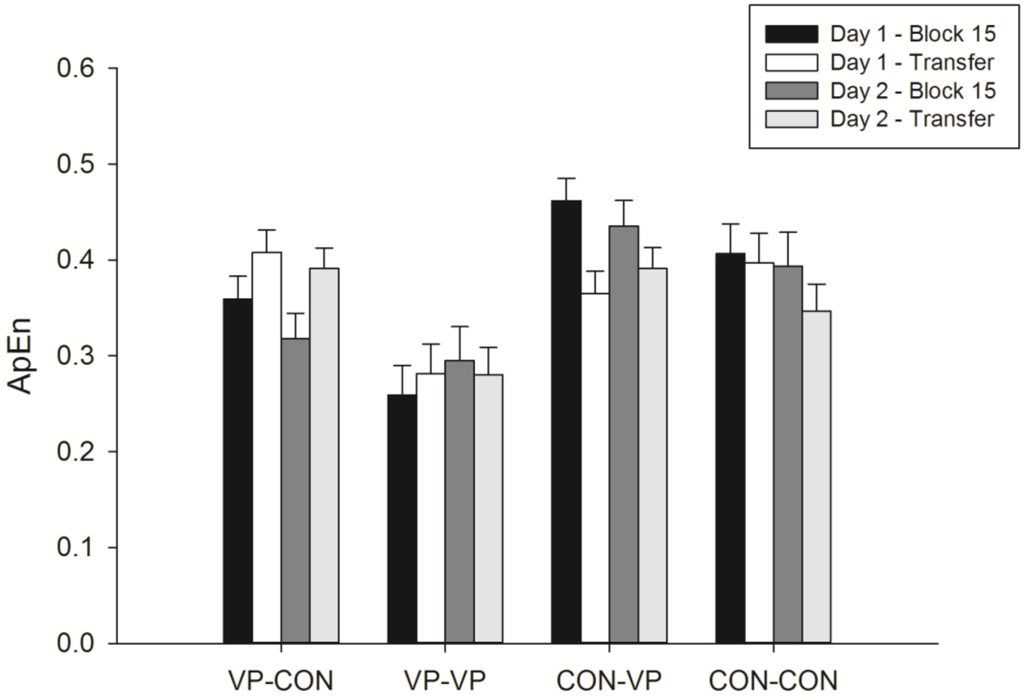

Figure 3.5. Approximate Entropy (ApEn) for the main- (VP-CON & CON-VP) and sub- (VP-VP & CON-CON) groups during four separate phases of the experiment: (1) Block 15 of practice phase on day 1, (2) Block 1 of Practice Condition Transfer on day 1, (3) Block 15 of practice phase on day 2, (4) Block 1 of Practice Condition Transfer on day 2. Each block reflects the within-group mean of 5 practice trials. Error bars indicate standard errors. VP – variable condition, CON – constant condition

Generalization Tests

The statistical results that assessed performance during the two generalization tests revealed a significant main effect of test ($F_{1,23}$ = 88.56, $p<0.001$) on RMSE that was mediated by the significant interaction between test and block ($F_{1,23}$ = 31.40, $p<0.001$). Post hoc comparisons revealed that RMSE was lower during the Brown generalization test compared to the Pink. Also, post hoc comparisons of the test and block interaction revealed that RMSE decreased during the Brown generalization test and increased during the Pink generalization test (all $p>0.05$). There was a significant main effect of test ($F_{1,23}$ = 81.68, $p<0.001$) on ApEn. Post hoc comparisons showed that ApEn was lower during the Brown generalization test compared to the Pink test ($p<0.05$).

Figure 3.6 shows the results from the correlation analysis of ApEn between block 15 of the practice phase and the Brown (B), Brown/Pink (C) and Pink (D) transfer tests as a function of practice condition. A significant positive correlation (ps < 0.05) was observed for the Brown (variable: $r^2 = 0.52$; constant: $r^2 = 0.52$), Brown/Pink (variable: $r^2 = 0.82$; constant: $r^2 = 0.62$) and Pink (variable: $r^2 = 0.51$; constant: $r^2 = 0.68$) transfer tests.

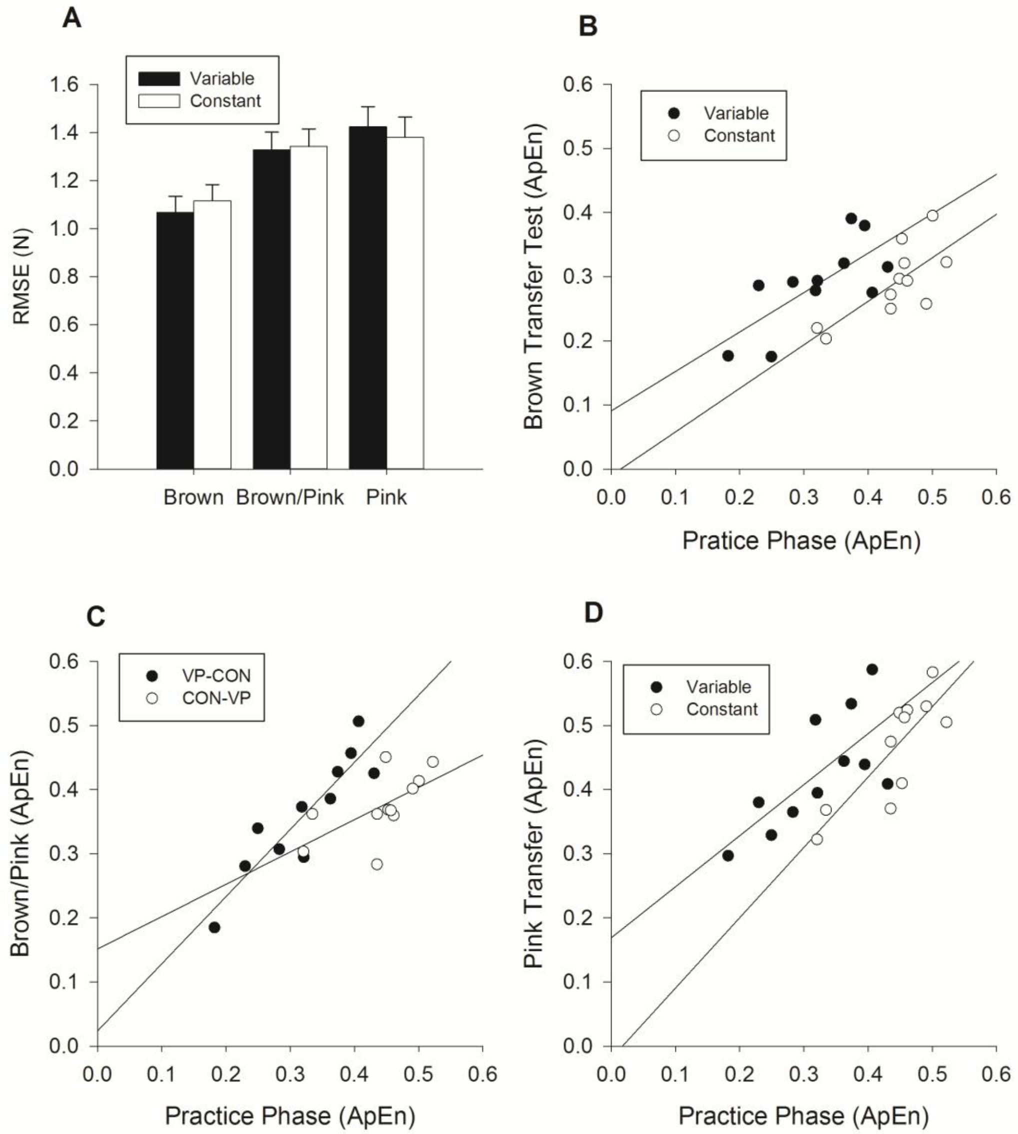

Figure 3.6. Transfer Tests. Performance accuracy (RMSE) as a function of transfer test for constant and variable practice conditions (A). Error bars indicate standard error. Correlation of ApEn between Practice Phase (block 15) on the abscissa axis and Brown (B), Brown/Pink (C) and Pink (D) Transfer tests on the ordinate axis for variable (filled circles) and constant (open circles) practice conditions. Correlation values reported in text. VP – variable; CON - constant

Discussion

This investigation examined whether constant and variable practice conditions differentially influenced the learning of performance accuracy and the multiple time scales of force output. Over two days of practice participants produced an isometric force output to either the same (e.g., constant practice) or different (e.g., variable practice) irregular target pattern that exhibited the same frequency distribution properties (e.g., $\beta = -1.5$). The results showed that task-induced variability at the execution level of the target patterns did not have a detrimental effect on performance accuracy, but did influence how individuals modulate the multiple time scales of force output as a function of practice. In contrast to the prediction of the variability of practice hypothesis (Schmidt, 1975; Braun et al., 2009), the constant practice conditions facilitated greater changes in the time- and frequency-dependent properties of the force output and led to greater changes in force output structure that exhibited a stronger matching of the target characteristics. Overall, the findings support the viewpoint that the effect of practice conditions can produce differential effects at the outcome and execution levels of behavior in motor tasks that afford redundant solutions (Ranganathan & Newell, 2010b).

Typically, task-induced variability at the outcome level results in lower performance accuracy compared with constant practice conditions. However, equivocal findings have restricted the generality of this effect with some studies reporting distinct performance differences during the acquisition phase (Shea & Morgan, 1979) and others showing minimal differences between constant and variable practice conditions (Kerr & Booth, 1978; Moxley, 1979). Also, manipulations of variability at the execution levels of a striking task did not result in performance decrements (Ranganathan & Newell, 2010a). An important distinction between the previous findings and the current experimental design is that the task goal at the outcome level remained invariant for both practice conditions and task variations were solely implemented at the execution level of the target patterns. Manipulations of various wave form properties, such as spectral slope or frequency bandwidth, would reflect variability at the outcome level in the isometric force production protocol.

Despite the similar patterns of improvement in performance accuracy for constant and variable practice conditions, the results revealed that changes in force output structure was dependent on force production to the same or different target patterns. This findings does not support the predictions of schema theory (Schmidt, 1975); but, rather, provides additional evidence for the notion of bi-directional changes in motor output dimension (K. Newell & Vaillancourt, 2001). Both practice increased the irregularity of force output structure as a function of practice; however the constant practice conditions manifested a greater ability to incorporate additional control processes (i.e., increased irregularity; Pincus, 1991; Sosnoff et al., 2009) into the task solution.

In general, all motor actions involve the contribution of feedforward and feedback mechanisms (Woodworth, 1899; Desmurget & Grafton, 2000). The practice-related changes in the temporal and frequency properties of the force output demonstrated a shift in the control strategy whereby the relative contribution from slower time scale, feedback mechanism diminished as a function of practice. This afforded greater relative contribution from feedforward mechanisms for the constant practice conditions compared to the variable practice conditions (Sosnoff et al., 2009; Sosnoff & Newell, 2005). Overall, force production to the same force-time pattern produced a stronger approximation of what has been termed global properties (i.e., approximate entropy, proportion of power) of the target force wave form (Pew, 1974; Stephen et al., 2008).

Previous investigations have shown that individuals modulate a broad frequency bandwidth (0 – 12 Hz) of time scale mechanisms that reflects feedback and feedforward processes (Desmurget & Grafton, 2000; Sosnoff & Newell, 2005). Also, it has been suggested that the accumulation of practice affords greater feedforward control through increases in target pattern predictability (Pew, 1974). Both practice conditions support these findings, but also illustrate that the constant practice condition allowed greater changes in force output structure that included faster time scale, higher frequency components of feedforward control (Desmurget & Grafton, 2000; Sosnoff & Newell, 2005). Conversely, the manipulation of the target pattern in the variable practice conditions induced a control strategy that exhibited a stronger role of slower time scale, sensorimotor feedback mechanisms (Miall et al., 1985; Slifkin et al., 2000; Sosnoff & Newell, 2005). This reactive nature of force output reflects a dual control problem whereby participants: (i) sought information regarding the changes in the force-time pattern; and (ii) modulated force output dynamics relative to these changes (Sosnoff et al., 2009). Thus, the task-related changes in the force output structure were dependent on the force-time pattern that either remained the same (i.e., constant practice) or changed (i.e., variable practice) as a function of practice.

In this visuo-motor task it is important to consider the potential mechanisms of change that accompanied the modulation of force output structure with learning. One factor to highlight is that the short duration of practice likely induced transient changes in the neural organization rather than persistent structural modifications (Duchateau, Semmler, & Enoka, 2006). Practice has shown to influence a variety of components of a motor action including slower (<1 Hz) time scale processes associated with cognitive strategies (Pressing & Jolley-Rogers, 1997). Also, rapid learning has been reported in other visual tasks (Karni & Sagi, 1993) and it has been argued that perceptual learning plays a large in the ability to successful perform an action (Mechsner, Kerzel, Knoblich, & Prinz, 2001). The current experimental design is limited in the interpretations regarding the specific changes in visual and motor processes as a function of practice; however, the protocol is robust to manipulations that allow future investigations to further address changes in visual and motor mechanisms.

An unexpected finding from the practice phase was the varying degrees of persistence observed in the time scales of force output at the beginning of the second day for performance accuracy. This pattern of results has two important implications. First, the relative permanent change in performance is a key element of most learning definitions (Schmidt & Lee, 2005). Thus, the task outcome level exhibited greater persistence compared to the practice-related changes in the multiple time scale processes. However, various levels of analysis of the perceptual-motor system exhibit different rates of changes as a function of practice (K. Newell et al., 2001). Also, this transient nature at the execution level extends previous isometric learning investigations that have only reported within day averages (K. Newell et al., 2003; Sosnoff & Voudrie, 2009). Second, the differences at the execution level for both practice conditions illustrated that redundant task solutions can produce the same task goal (Bernstein, 1967; Ranganathan & Newell, 2010a). Furthermore, the constant practice conditions failed to retain the practice-related modifications at the execution level, but exhibited minimal decrement at the outcome level.

An additional focus of the investigation was to examine whether the principles of generality or specificity were evoked for isometric force production following constant and variable practice conditions (Schmidt, 1975; Proteau, 1992). Following the practice phase on both days, transfer tests examined: (i) the influence of practice condition (i.e., constant to variable and vice versa) on performance; and (ii) the generalization of force output to target patterns with novel frequency distributions (i.e., Brown and Pink force wave forms). Overall, performance accuracy decreased with a broadening of the frequency distribution of the transfer wave form patterns independent of practice conditions (Figure 3.6A). Also, the ability to adaptively modify force output structure was related to ApEn values following practice and the degree of irregularity of the transfer target patterns (Figure 3.6 B-D).

A contrast between the constructs of generalization (i.e., variable practice; Schmidt, 1975; Braun et al., 2009) and specificity (i.e., constant practice; Henry, 1968; Tulving & Thomson, 1973; Proteau, 1992) relates to the formation of the memory representation of the motor action. Task-induced variability is held to facilitate the development of a rule (i.e., schema) that governs the direct relation between movement parameters and movement outcome. There are invariant properties (i.e., relative timing) within the rule that allows the action to be scaled across changes in the temporal or spatial dimensions of the task. However, the criticality of motor invariance appears to reflect a strategic behavior rather than a required component of the action (Heuer & Schmidt, 1988). Specificity emphasizes that constant repetition of a skill yields a stronger motor representation and predicts that novel contexts that deviate from the practice conditions will not yield the same level of generalization.

At the outcome level, performance accuracy was related to the degree of target regularity (i.e., scaling of β). Task error was lowest in the Brown transfer test even though participants had more experience with Brown/Pink pattern during the practice phase. A similar pattern of results was evident at the execution level whereby the ability to scale the structure of force output was dependent on two factors: (i) the frequency distribution (e.g., regularity) of the target pattern; and (ii) force output structure following practice. Standard approaches to the measurement of transfer performance typically emphasize task outcome variables (e.g., Schmidt & Young, 1987). However, as shown here, the mapping of the execution level in a control space relative to the task constraints emphasizes the underlying mechanisms that comprise the motor output rather than solely the response outcome (Newell et al., 2003).

According to Van Rossum (1990), the interpretations from the majority of variable practice investigations are confounded by the effects of proximity (e.g., similarity) and that there are often insufficient control groups to assess this effect. The proximity effect is reflected in testing conditions that are closely related to the experiences of the training period. In general, there has been limited investigations that address this important issue. Moreover, recent structural learning (Braun et al., 2009) investigations that have used a random visual rotation design do not circumvent the issue of proximity. For instance, a training session that contains a range of random rotation perturbations (± 60°) affords individuals experience to the transfer test condition (± 30° rotation angle) to a greater degree than control groups who trained with veridical feedback (cf. Figure 3, Turnham et al., 2012). The principles of similarity in transfer would predict faster adaptation rates for previously experienced conditions compared with novel conditions.

The present transfer findings cannot completely rule out the contributions of proximity based on the different frequency structures of the transfer task demands. For example, participants did not fully adapt their force output to the temporal or frequency characteristics of the target at the end of practice, thus creating a closer approximation (i.e., proximity) between the force output structure following practice and the Brown transfer test, which led to the lowest task error across the transfer conditions. This result supports the idea that mapping the changes at the behavioral level relative to the task constraints provides a direct way to index learning in the control space (Newell et al., 2003). However, further experimental and theoretical work is necessary to understand learning within this framework and to circumvent the effects of similarity during transfer tests.

In conclusion, the novel experimental manipulation that induced task variability in the force-time structure of the target pattern while maintaining the invariant distributional property of the frequency content revealed differential learning effects at the outcome and execution level of the behavior. The variability of practice hypothesis (Schmidt, 1975) proposes that variability strengthens the schema rule between response parameters and task outcome. However, the current findings support recent investigations in mental imagery (Coelho, Nusbaum, Rosenbaum, & Fenn, 2012), speech motor learning (Rochet-Capellan, Richer, & Ostry, 2011) and gait dynamics (Rhea, Wutzke, & Lewek, 2012) that are incongruent with this prediction. It appears that when the potential for redundant solutions is present that the proposed benefits of task outcome variability are reduced and may even be negated (Ranganathan & Newell, 2010b). Finally, analyses of behavioral changes at multiple level s (e.g., outcome and execution) captures a broader depiction of the processes of learning and transfer than standard approaches and may be a promising framework to address the differing viewpoints on the constructs of generality and specificity of motor behavior.

CHAPTER 4. THE INFLUENCE OF PRACTICE ON THE FREQUENCY STRUCTURE OF ISOMETRIC FORCE

Abstract

The present study examined the learning, retention and generalization of task outcome and the frequency-dependent properties of isometric force output dynamics. During practice participants produced isometric force to a moderately irregular target pattern. Retention tests examined the persistent influence of practice on the force output dynamics and generalization tests investigated transfer to novel irregular target patterns. The results showed that both constant and variable practice conditions exhibited similar reductions in task error but that the frequency-dependent properties were differentially modified across the entire bandwidth (0 – 12 Hz) of force output dynamics as a function of practice. The task outcome exhibited persistence on the delayed retention test whereas the increased contributions of faster time scales processes (i.e., 4- 12 Hz) achieved with practice were only transient in nature. Overall, the dynamical organization of force output structure during early practice and following the induced rest interval was characterized by the enhanced emphasis on the low frequency components related to sensory and motor feedback mechanisms.

Introduction

The perceptual-motor system is comprised of multiple degrees of freedom at numerous levels of analysis (i.e., biomechanical, muscular and neural) that can be used to achieve the desired task goal. The ability to coordinate and control these degrees of freedom relative to task constraints determines the overall successfulness of performance. The dominant viewpoint of motor learning and control theories (Bernstein, 1967; Kelso, 1995; Latash et al., 2007; Turvey, 2007) is that the perceptual-motor system addresses the degrees of freedom problem through formation of low dimensional control structures (i.e., synergies or coordinative structures). This perspective, however, is primarily based on reductions in the periphery (i.e., joint space) degrees of freedom with limited consideration for the multitude of feedforward and feedback processes that support task performance. Additionally, the dimension of motor output has been shown to increase or decrease depending on the task constraints (Newell, Broderick, Deutsch, & Slifkin, 2003; Newell & Vaillancourt, 2001; Sosnoff & Voudrie, 2009).

One benefit of a dimension analysis is that it provides information relative to the collective organization of the perceptual-motor system. For example, it has been used to quantify the dynamical degrees of freedom in a variety of motor tasks including posture (K. Newell et al., 1993), whole-body coordination (Haken, 1996), finger oscillations (Kay, 1988) and tremor (Morrison & Newell, 1996) to understand how the motor system organizes the multiple degrees of freedom of the body to achieve a task goal. Additionally, an assessment of motor output dimension can be applied to other levels of analysis. For example, in bimanual coordination the realization of different task constraints (i.e., in- and anti-phase patterns) induces changes in the dimension of the component and coupling levels differentially than the task output (James & Layne, 2013).

A limited number of investigation have examined the change in motor output dimension as a function of learning. Haken (1996) provided the initial evidence that individuals reduce the dimension of the desired movement pattern in that the coordination pattern of the limbs during a complex pedalo task was reduced to a single dynamical degree of freedom (quantified through principal component analysis) with learning. This finding supports Bernstein's hypothesis (1967) that movements are organized with fewer degrees of freedom than are available to meet the task constraints. This perspective has also been captured in the general notions that practice results in a decrease in the number of dynamical (or controlled) degrees of freedom and that movement variability is inversely related to skill level.

The general notion that learning results in a reduction in the dimensionality of the control strategy has been challenged through the theoretical perspective (K. Newell & Vaillancourt, 2001) that dimensional changes are dependent on task constraints and the intrinsic dynamics of the system (Kelso, 1995). The initial experimental support (Newell et al., 2003; Sosnoff & Voudrie, 2009) has shown that high performance levels with fixed point dynamics (e.g., constant force level) tasks are associated with higher dimensional (i.e., increased dynamical degrees of freedom) force output. Conversely, the task solution for tasks with limit cycle dynamics is characterized by a low dimensional motor output. The rationale for task-dependent changes in force output dynamics has also supported the loss of adaptability hypothesis in the elderly (Vaillancourt & Newell, 2002).

In adaptive control systems, such as isometric force production, the output is a product of multiple time scale processes that define the dimension of the force output and has been related to multiple feedback and feedforward mechanisms that support task performance (Desmurget & Grafton, 2000; Sosnoff & Newell, 2005). There are established techniques (e.g., approximate entropy and spectral analysis) that decompose the time- and frequency-dependent properties of the force output to examine properties of the dimension of the force output signal. For example, in a frequency-domain a spectral analysis reveals the relative power of sensorimotor and physiological processes (Sosnoff & Newell, 2005; Sosnoff, Valantine, & Newell, 2009). Overall, the nature of the task constraints has a strong influence on the relative contributions of these feedforward and feedback mechanisms and numerous investigations have supported the perspective that force output dynamics operate across a broad bandwidth of frequency-dependent properties (Sosnoff et al., 2009).

The ability to realize a task goal is dependent on an individual's capacity to modulate fast and slow time scale processes. Conceptually, the sensory and motor processes contributing to the behavior have unique frequency properties and the relative contribution of the process is indicated by the amount of power at its characteristic frequency. In a power spectral analysis, the changes in power as a function of frequency is denoted by the slope of the log-log plot and informs about the interaction of the underlying processes (Bassingthwaighte, Liebovitch, & West, 1994). In the isometric force production paradigm, the adaptability of feedforward and feedback processes is examined by instructing individuals to intentionally attempt to produce a $1/f$ noise-like structure. This is distinctly different from other reports of 1/*f* properties in cognitive reaction time task (Gilden, 1997; Van Orden et al., 2003).

Previous motor control investigations of isometric force production to 1/*f* target patterns typically provide individuals minimal amounts of practice in the attempt to match the task constraints. Thus, the control strategy invoked in this protocol is represented by modulation of long loop, slow time scale process (Miall et al., 1985; Slifkin et al., 2000) and is evident by the high power of low frequency components in the force output power spectrum. It seems likely that with additional practice individuals could modify the force control strategy used to track an irregular target pattern and that the properties of the force output dynamics may approach similarity to those of the 1/*f* target pattern.

While the overall properties of the target signal can be defined by the 1/*f* relation between power and frequency, the visual information present in the display of the target pattern can be manipulated such that the local fluctuations of the signal vary across trials. Here, two groups of participants practiced to the same overall 1/*f* target pattern (i.e., $\beta = -1.5$); but either generated a force output to the *same* (i.e., constant practice) or *different* (i.e., variable practice) target pattern. Therefore, in the variable practice condition the predictability of the target pattern on a local time scale (i.e., local fluctuations) varied across trials; however, over the entire trial the force control strategy necessary to achieve the task goal remains invariant. This experimental manipulation can also be related to the predictions of the variability of practice hypothesis associated with schema theory of motor learning (Schmidt, 1975).

The main aim of the present study was to examine the effect of practice on the transient and persistent properties of force output dimension. Based on the notion of task-dependent changes in motor output dimension (K. Newell & Vaillancourt, 2001), it was predicted that with practice to an irregular target pattern (i.e., 1/*f*-noise like pattern with $\beta = -1.5$) individuals would exhibit a broader power spectrum; although, it was not clear whether the force output structure would completely adapt force output structure to the task constraints. Additionally, the smaller frequency components that were defined over consecutive bandwidths (i.e., 0 – 4 Hz, 4 – 8 Hz and 8 – 12 Hz) were examined with a coarser frequency analysis that was related to the modulation of feedforward and feedback processes.

Methods

Twenty healthy young adult volunteers participated in this experiment. All participants had normal or corrected-to-normal vision and were right-hand dominant based on writing preference. Participants gave informed consent and the experimental protocol was approved by the University Institutional Review Board.

Apparatus

The experimental setup was the same as previous isometric force production studies (King & Newell, 2013; Sosnoff et al., 2009).

Procedures

Participants were instructed to produce a maximal amount of abduction force with their right index finger. Three maximal voluntary contraction (MVC) trials of 6 s were recorded with 30 s rest between each trial. The highest peak force achieved during the trials determined an individual's MVC.

The experimental protocol is depicted in Figure 4.1B and consisted of practice phase that included 10 blocks of trials, immediate retention and generalization phase that included 3 blocks of trials and delayed retention and generalization phase that included 3 blocks of trials. A block contained 5 trials and each trial had a duration of 20 s.

Participants were counter-balanced into two practice condition groups. The constant group (*n* =10) practiced to the *same* force-time wave form during the practice phase and the variable group (*n* =10) practiced to *different* wave form patterns. The wave form patterns presented during the practice phase were defined as moderately irregular target patterns (Figure 4.1A middle). Following practice, an immediate retention test was administered that involved participants performing force production tracking in the opposite practice conditions (i.e., constant to variable target presentation and vice versa). Additionally, two generalization tests were collected that involved force production to novel target patterns that were defined as low (Figure 4.1A left) and high (Figure 4.1A right) irregular wave forms. The condition of the generalization tests for each group matched that of the practice phase (Figure 4.1B). Participants returned following a 24-hr interval for delayed retention tests that also included the two generalization tests, to assess learning on a longer time scale.

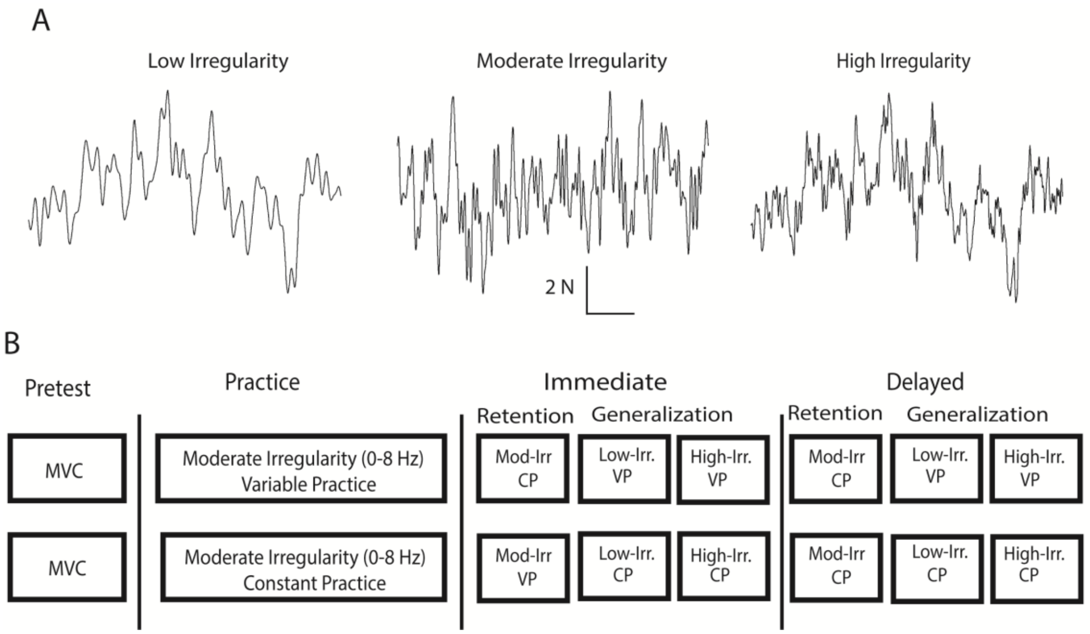

Figure 4.1. Experimental Protocol. (A) Representative wave form patterns used during practice (middle) and generalization phase (left and right). (B) Time course of the experimental phases. Delayed Retention tests were administered following a 24 hr time interval. CP – constant practice; VP – variable practice; Irr. – irregularity.

Data Analyses

Custom written computer software generated the target patterns based on the specified Brownian motion characteristics. The practice targets were characterized by the following frequency properties: (a) 0-8 Hz frequency bandwidth (Figure 4.1A - middle) and (b) distributional properties of the frequency content that reflected Brown/Pink noise (β = -1.5). The phase of the target pattern was randomly selected between $-\pi$ and π. The low and high irregular target patterns used in the generalization tests were defined constructed with a frequency bandwidth of 0 – 4 and 0 – 12 Hz, respectively. The distributional properties of the frequency content also reflected Brown/Pink noise (β = -1.5).

Participants were instructed to adjust their force output to minimize the deviation between the target pattern and their force output trajectory. Following each trial, participants were presented with a visually-displayed feedback score that reflected the root mean square error (RMSE).

Prior to analysis the first 3 s and last 2 s of data of each trial were removed to eliminate transient effects. Performance outcome was analyzed using root mean square error (RMSE). RMSE was computed as the deviation between the target pattern and force output trajectory. An additional measure of task performance was calculated by determining the correlation (CORR) between the target pattern and force output trajectory. A high correlation value indicates that participants were able to replicate the target pattern.

A frequency domain analysis assessed the multiple processes of force output. Custom-written software decomposed the force output trajectory time series into the frequency components through the 'fft' command in MATLAB. Each trial was normalized by the maximum power of the trial from 0 to 12 Hz and the sum of the normalized proportion of power (PoP) was computed for three (0 – 4 Hz, 4 – 8 Hz, and 8 – 12 Hz) frequency bandwidths. All data processing was performed using Matlab v7.11 (Mathworks).

Statistical Analyses

To examine the properties of learning and retention the dependent variables were analyzed using separate 4 x 2 (Block x Practice condition) ANOVAs. The four different blocks used for analysis were early practice (i.e., Block 1), late practice (i.e, Block 10), immediate retention and delayed retention. Two a priori contrasts were planned to compare performance between (i) Immediate and Delayed retention tests, and (ii) Block 10 and Delayed retention test to determine the persistent effect of practice over a short (i.e., immediate) and longer (i.e., 24 hr interval) time scale, respectively.

The generalization tests were analyzed using a 2 x 2 x 2 (Day x Irregularity x Practice condition) mixed-model design. The within-participant factors were irregularity (low and high) and day (Immediate, Delayed). The between-participant factor was practice condition. A significance level of $p<0.05$ was used for all analyses. Adjustments for multiple comparisons were conducted using the Least Significant Difference (LSD) method. All statistical analyses were completed using SPSS (v19, IBM).

Results

Task outcome performance.

Figure 4.2A shows the mean root mean square error (RMSE) values for constant and variable practice conditions as a function of learning. The statistical analysis revealed a significant main effect of block, F (3,54) = 28.52, p<0.001, on RMSE. The pair-wise comparison of block revealed that RMSE in late practice was significantly lower compared with early practice (p<0.001). The RMSE on late practice did not differ significantly from the immediate and delayed retention tests (p>0.05).

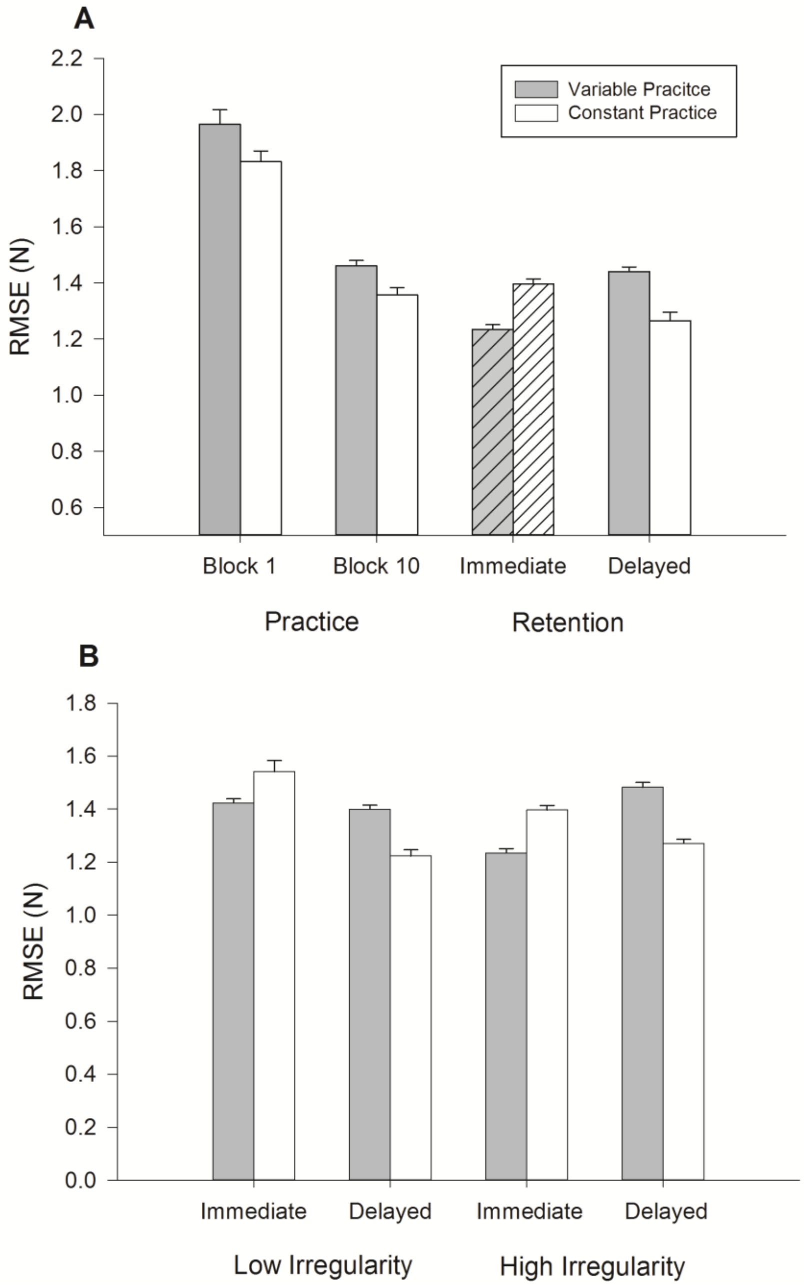

Figure 4.2. Root mean square error (RMSE) as a function of learning (A) and generalization (B) for constant and variable practice conditions. The immediate retention test was conducted in the opposite practice condition (see Figure 4.1) and is indicated by the coarse filled pattern in the respective bars. The generalization tests are as a function of day (immediate and delayed) and irregularity (Low and High). Error bars represent standard error.

The generalization tests (Figure 4.2B) showed a main effect of day, F (1,18) = 14.03, $p<0.0,1$ on RMSE that was mediated by a significant day x practice condition interaction, F (1,18) = 17.19, $p<0.01$. Post hoc comparisons revealed that RMSE was similar for both practice conditions during the immediate generalization tests, but on the delayed tests the constant group exhibited lower RMSE than the variable practice condition.

Force-target correlation.

Figure 4.3A shows task performance as measured by the correlation between the target and output trajectories as a function of learning. There was a significant main effect of block on CORR, F (3,54) = 16.91, $p<0.001$, that was mediated by the interaction between block and practice condition, F (3,54) = 4.73, $P<0.05$. Post hoc comparisons revealed similar initial CORR values for both practice conditions; but that in late practice (i.e., Block 10) the constant practice conditions exhibited significantly higher CORR compared to variable practice ($p<0.05$). There was not an effect of practice condition during the immediate retention test; but the constant practice condition showed higher CORR on the delayed retention test ($p<0.001$).

Figure 4.3B shows the mean CORR values during the generalization tests as a function of day and irregularity. There was a significant main effect of day, F (1,18) = 163.44, $p<0.001$, that was mediated by the significant day x practice condition interaction, F (1,18) = 216.51, $p<0.001$. Post hoc comparisons showed that variable practice had higher CORR than constant practice on the immediate generalization tests, but that constant practice conditions exhibited significantly higher CORR on the delayed generalization tests. There was also a significant main effect of irregularity, F (1,18) =

12.54, p<0.01, in that low target irregularity had higher CORR values than the high target irregularity.

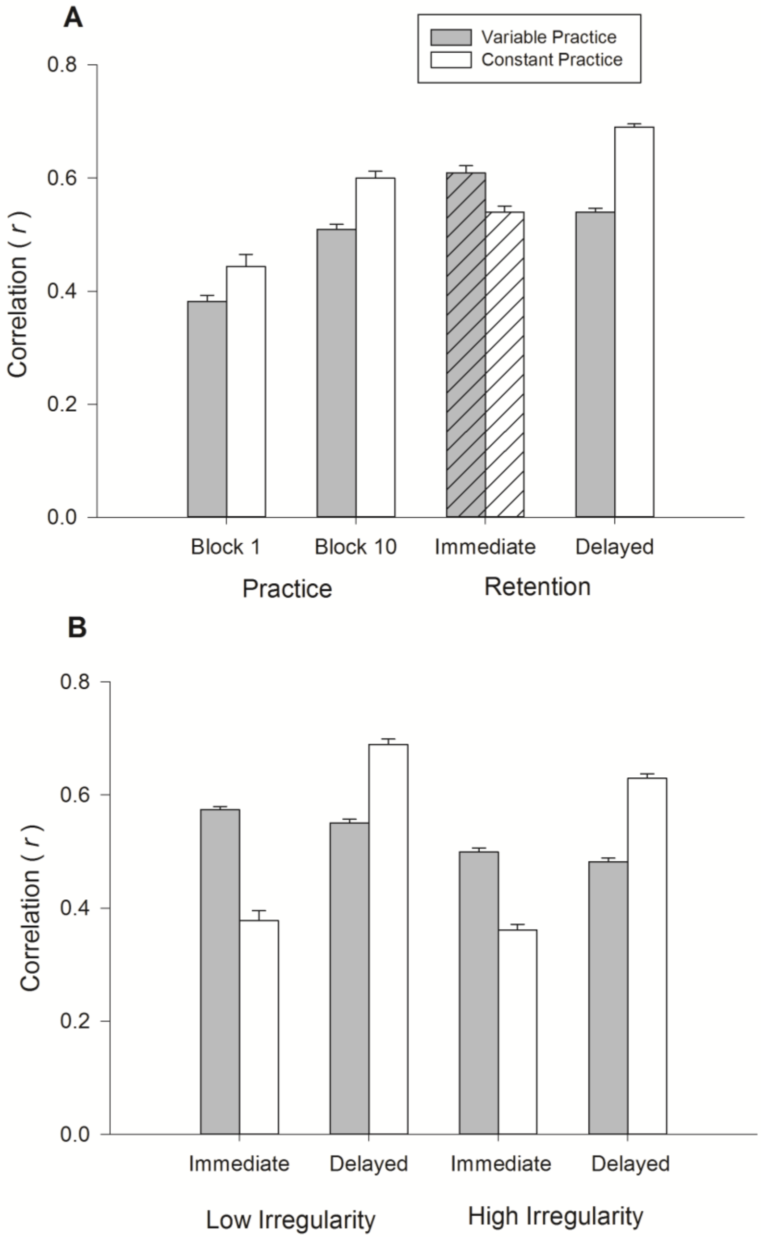

Figure 4.3. Correlation between force output and target signal as a function of learning (A) and generalization (B) for constant and variable practice conditions. The immediate retention test was conducted in the opposite practice condition (see Figure 4.1) and is indicated by the coarse filled pattern in the respective bars. The generalization tests are as a function of day (immediate and delayed) and irregularity (Low and High). Error bars represent standard error.

Spectral slope

Figure 4.4A shows the spectral slope of force output dynamics as a function of learning. There were significant main effects of block, F (3,54) = 11.30, $p<0.001$, and practice condition, F (1,18) = 8.86, $p<0.01$, that was mediated by the interaction, F (3,54) = 4.27, $p<0.05$. Pair-wise comparisons of the block effect revealed that at the end of practice individuals exhibited a broader spectral profile ($p<0.001$) compared initial slopes, but this effect did not persist on the delayed retention test ($p>0.05$). An inspection of the significant interaction showed that constant practice exhibited broader spectral slopes compared to variable practice on Block 10 and delayed retention test ($p<0.05$); but not significant difference on the immediate retention test.

Figure 4.4B shows the mean spectral slope as a function of generalization for constant and variable practice conditions. There was a significant main effect of irregularity, F (1,18) = 10.79, $p<0.01$. Post hoc comparisons revealed that the high irregularity generalization test showed broader spectral slopes compared to the low irregularity test. The main effect of practice condition trended toward significance ($p = 0.06$). There were significant day x group, F (1,18) = 10.37, $p<0.01$, and day x irregularity, F (1,18) = 8.08, $p<0.05$, interactions (see Figure 4.4B).

Frequency-dependent properties.

The mean proportion of power (PoP) for each of the three frequency bandwidths as a function of learning and practice condition is shown in Figure 4.5. There was a significant main effect of block for PoP 0 – 4 Hz, F (3,54) = 5.01, $p<0.01$, PoP 4 – 8 Hz, F (3,54) = 4.90, $p<0.05$ and PoP 8 – 12 Hz, F (3,54) = 8.37, $p<0.001$. Post hoc comparisons revealed that 0 – 4 Hz PoP in late practice was significantly lower than early practice and that 4 – 8 Hz and 8 – 12 Hz PoP increased from Block 1 to Block 10 for both frequency bandwidths. The same general pattern was revealed during the immediate and delayed retention tests in that the PoP was retained following practice, but was only transient as evident by the PoP on the delayed retention test (Figure 4.5).

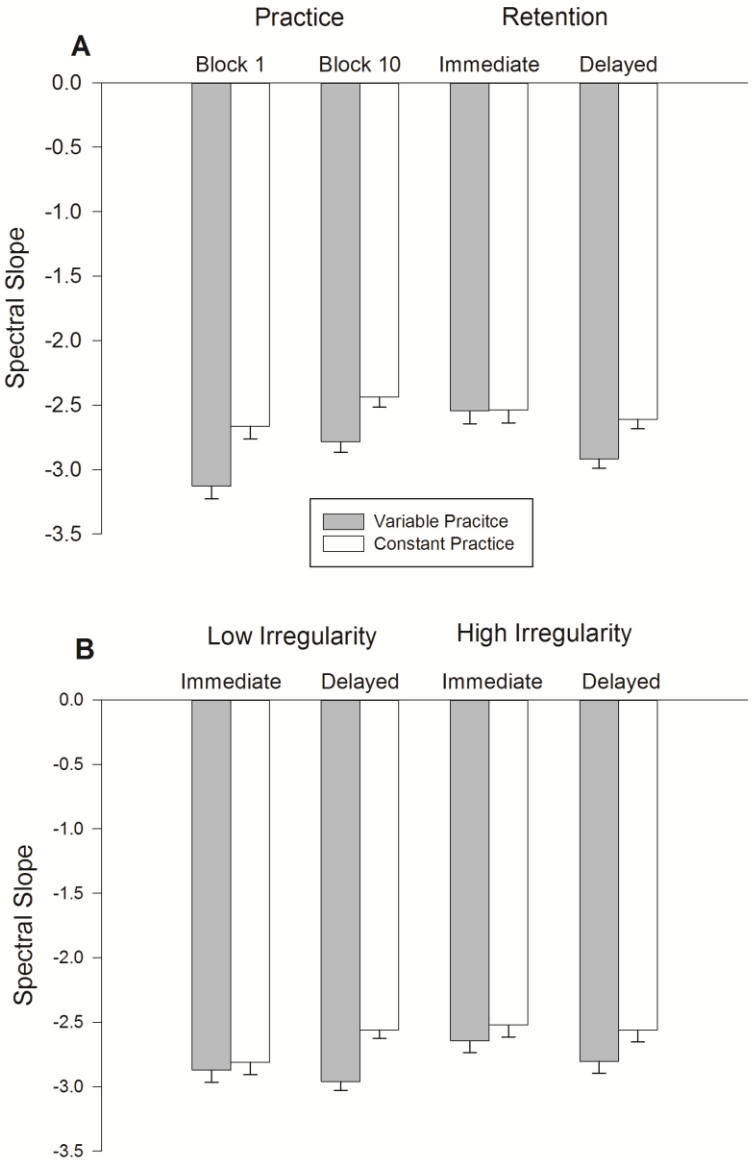

Figure 4.4. Spectral as a function of learning (A) and generalization (B) for constant and variable practice conditions. The immediate retention test was conducted in the opposite practice condition (see Figure 4.1) and is indicated by the coarse filled pattern in the respective bars. The generalization tests are as a function of day (immediate and delayed) and irregularity (Low and High). Error bars represent standard error.

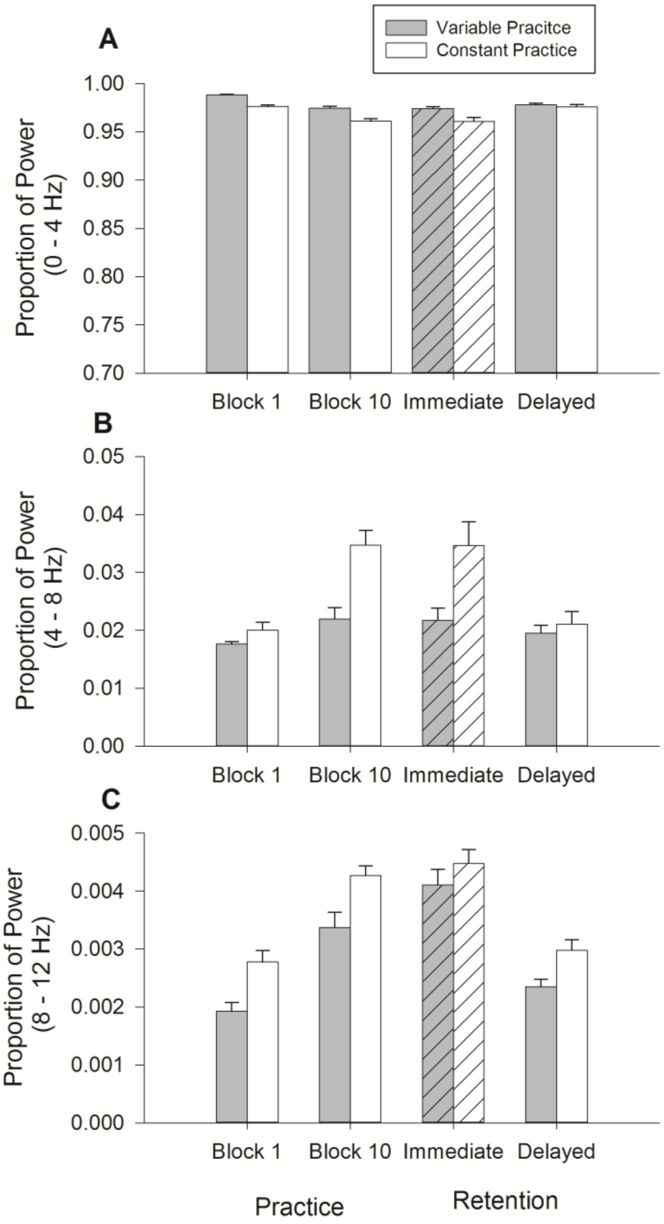

Figure 4.5. Proportion of Power (PoP) for 0 – 4 Hz (A); 4 – 8 Hz (B); 8 – 12 Hz (C) as a function of practice and retention for both practice conditions. The immediate retention test was conducted in the opposite practice condition (see Figure 4.1) and is indicated by the coarse filled pattern in the respective bars. Error bars represent standard error.

The generalization of the frequency properties of force output structure to novel target patterns that exhibited higher and lower degrees of irregularity was assessed for each frequency bandwidth as a function of practice condition. There was a significant triple (target x time x practice condition) interaction for the 0 – 4 Hz PoP, $F(1,18) = 6.58$, $p<0.05$. The overall pattern showed that the low irregular target patterns had greater 0 – 4 Hz PoP than the high irregular target patterns and that the delayed tests exhibited greater 0 – 4 Hz PoP compared to the immediate generalization tests.

There was also a significant triple interaction for the 4 – 8 Hz PoP, $F(1,18) = 6.94$, $p<0.05$. The main effect of day showed that lower PoP during the delayed generalization tests compared to the immediate test and the high irregularity target patterns showed greater 4 – 8 Hz PoP than the low irregular target patterns. The findings for the 8 – 12 Hz PoP showed significant main effects of day, $F(1,18) = 15.39$, $p<0.01$ and irregularity, $F(1,18) = 14.25$, $p<0.01$. Post hoc comparisons revealed that 8 – 12 Hz PoP was lower during the delayed tests compared to the immediate transfer tests and that high irregularity target patterns exhibited greater PoP than the low target patterns.

Discussion

The present study examined how practice influenced the learning, retention and generalization of the frequency-dependent properties of isometric force output dynamics. In addition to an overall measurement of force output dimension (i.e., $1/f$ structure), the segmentation of three different frequency bandwidths provided a more focused analysis of the influence of practice on the multiple feedback and feedforward mechanisms that generate force output dynamics. The results showed that practice induced the predicted increase in force output dimension through the adaptive modification of force structure across a broad bandwidth of time scale processes (i.e., 0 – 12 Hz). The findings also showed that the dynamics of task outcome and force output structure operate on different time scales of change in that the effects of learning were mediated by the frequency-dependent properties of force output structure.

The findings support the notion that the task constraints can drive either an increase or decrease in motor output dimension with practice (K. Newell & Vaillancourt, 2001). Previous investigations have used constant force level or rhythmical target patterns to illustrate the bi-directional change in dimension (Newell et al., 2003; Sosnoff & Voudrie, 2009) and the current results extend this notion to irregular 1/*f* target patterns. The initial low levels of performance were likely a consequence of the high power in the low frequency components that limited the ability to adaptive adjust force production to the task constraints. The pathway of change during practice, however, included a shift in the control strategy to generate higher relative contributions of faster time scale processes (i.e., 4 – 12 Hz) that facilitated reduction in task error. These changes suggest that the contributions from sensorimotor feedback mechanisms have a strong influence on the initial intrinsic dynamics of the system (Kelso, 1995) and that with practice individuals transiently altered the state of the system with modifications of higher frequency components (up to 12 Hz) of force output dynamics.

In addition to the effects of practice, the interaction of the multiple feedforward and feedback mechanisms that generate force output dynamics has been shown to be dependent on a variety of factors. For example, the visual information present in the target pattern (Sosnoff, Valantine, & Newell, 2009) or the force trajectory feedback (Hu & Newell, 2010) modifies the use of faster time scale processes. The current results illustrate that with practice individuals broaden the frequency spectrum of the force trajectory to include increased contributions of faster time scales processes even though the visual information of the target pattern did not contain the higher frequency components (i.e., 8 – 12 Hz). These findings illustrate an adaptive shift in control strategy that involves the modulation of multiple feedback and feedforward mechanisms to achieve the task goal of minimizing error (Desmurget & Grafton, 2000; Sosnoff & Newell, 2005).

Previous investigations that have examined force production to irregular target patterns (i.e, 1/*f* noise-like signal) have provided limited practice. The control strategy invoked in such conditions has been proposed to reflect a reactive, feedback-dominant tracking behavior (Sosnoff et al., 2009). As predicted, practice induced a broadening of the spectral slope of force output that reflected a shift toward a more open-loop, feedforward control strategy than was initially present. Individuals, however, did not fully adapt to the frequency properties of the target pattern (Pew, 1974b). The influence of the target's irregularity and slow time scale components (i.e., low frequency, sine wave patterns) likely limited the relative change in higher frequency components of force output dynamics. Further work is necessary to understand the dynamic properties of force output with additional practice.

Human tracking behavior is dominated by low frequency components (i.e., high 0 – 4 Hz power) that are related to sensory and motor feedback processes. Two prominent feedback processes that operate within this bandwidth are vision and proprioception that operate at approximately 2 and 0.5 Hz, respectively (Slifkin et al., 2000). The current findings show that with practice the majority of change in power occurred in the low frequency bandwidth that may be related to these two feedback processes. However, it was also been shown that error detection and correction mechanisms related to specific neural activity operate on a faster time scale (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Higgins & Angel, 1970). One main finding of the present study was the difference in persistence between the slow and fast time scale processes during the delayed retention tests. It is also important to note that the aim of this approach is not to identify particular mechanisms, but rather to characterize the collective, dynamic organization of the behavior that is revealed through complex interactions of multiple time scale processes (Desmurget & Grafton, 2000; Gilden, 1997; Sosnoff et al., 2009; Van Orden, Holden, & Turvey, 2003).

Continuous force production during constant and variable practice conditions resulted in similar reductions in task error as a function of practice and in contrast to the predictions of the variability of practice hypothesis (Schmidt, 1975) exhibited non-significant differences in task outcome performance during the transfer tests. However, inspection of the other properties (i.e., power spectrum and CORR) of the force output trajectory revealed a potential trade-off between the practice conditions. During practice, constant practice conditions facilitated greater relative contributions of higher frequency components of force output in that the control strategy used in this condition included faster time scale processes related to feedforward control. In contrast, variable practice conditions resulted in higher target-force output correlations (Figure 4.3). This result was evident during practice and immediate transfer tests and suggests that individuals in the variable practice condition focused on different properties of the target pattern; however, this effect was mediated across days. Overall, these findings underscore the notion that the practice conditions exhibit a transient influence on performance variables of the behavior rather persistent effects of learning (Russell & Newell, 2007).

There are potentially several strategies that will lead to reductions in task error during continuous isometric force production. One approach that has been proposed is for individuals to decrease movement amplitude (Poulton, 1974). Also, target irregularity and amount of visual information (relative to the target and force output feedback) influence whether individuals modulate local or global mechanisms of force control to reduce task error (Studenka & Newell, in press). Inducing trial-to-trial variations of the target pattern altered the local spatial-temporal fluctuations, but retained the overall frequency characteristics of the target signal. Consequently, the role of target visual information that was manipulated on a local time scale may have contributed to the different strategic behaviors exhibited in constant and variable practice conditions. Additionally, the progression-regression hypothesis (Fuchs, 1962; Jagacinski & Hah, 1988) of tracking behavior proposes that individual shift to higher order derivatives of information (i.e., velocity and acceleration) as a function of skill level. Further modeling work is necessary to link the relation between such changes and the multiple time scale of force output structure. Overall, this finding extends the notion that visual information serves multiple roles in the control of force output dynamics that operate within *and* between practice trials (Sosnoff & Newell, 2005).

The persistent and transient effects of practice were mediated across the entire frequency spectrum of force output in that the faster time scale processes (i.e., 4 – 12 Hz) showed minimal levels of delayed retention. This finding has several important implications. The difference in the persistent changes of task outcome and force output structure illustrates that redundant task solutions can be used to achieve similar levels of performance. Force production over a longer time scale (e.g., 20 s) increases the potential of redundancy that is typically minimized in discrete (single degree of freedom) movements that dominate the motor learning literature, but also is an experimental protocol that allows for the examination of broader time scale processes. Also, the novelty of force production to an irregular target pattern is likely to require practice over a longer time scale of learning than was used in the current investigation.

In conclusion, individuals adaptively modified a broad range of the frequency-dependent properties of isometric force output as a function of practice that is consistent with the framework of task-dependent changes in motor output dimensionality (K. Newell & Vaillancourt, 2001). The generalization findings revealed a transient influence of practice on performance that was dissipated with the time interval between practice days. Also, the persistent and transient influence of practice is mediated across a broad bandwidth of frequency-dependent properties of force output. Finally, the findings provide support for the notion that learning is not a single adaptive mechanism that evolves on a distinct time scale of change, but rather should be characterized by the adaptive nature of multiple processes in relation to the confluence of task, environmental and organismic constraints (Kelso, 1995; K. Newell & Vaillancourt, 2001; Van Orden et al., 2003).

CHAPTER 5 SELECTIVE VISUAL SCALING OF SHORT TIME SCALE PROCESSES FACIILTATES ISOMETRIC FORCE PRODUCTION

Abstract

The present study investigated the effects of practice and visual scaling of relatively short time scale processes on the learning of a continuous isometric force tracking task. During practice three groups of participants tracked an irregular target pattern under a fixed gain, intermediate (i.e., 4 – 8 Hz) or high (i.e., 8 – 12 Hz) visual scaling of feedback information. The persistent effect of learning was examined over two consecutive days of practice that also included two transfer conditions (i.e., fixed gain and 8 – 12 Hz visual scaling). All groups reduced tracking error over practice, with the error lowest in the intermediate scaling condition followed by the high scaling and fixed gain conditions, respectively. In the transfer tests, the intermediate scaling group exhibited enhanced adaptability in that individuals achieved the lowest task errors in all transfer conditions. The visual scaling effect on task performance and force output dynamics was generally greater for the intermediate scaling condition; but there was also evidence that the high visual scaling group used the shorter time scales of visual information, albeit with a slower rate of change than the intermediate condition. In general, the findings support the notion of an adaptable range of force output dynamics that can also be differentially influenced by the interaction of selective visual scaling of feedback information and practice.

Introduction

An issue that has dominated the motor learning literature has been the influence of the structure of practice on the ability to acquire motor skills. Traditional approaches, including the theoretical interpretations of variable practice (Schmidt, 1975), contextual interference (Shea & Morgan, 1979) and specificity of practice (Proteau, 1992), have examined the effect of different practice environments on the capacity to learn, retain and transfer motor skills. The general findings from these frameworks, however, have been challenged (Ranganathan & Newell, 2013; Van Rossum, 1990; Williams, Davids, & Williams, 1999) as they tend to emphasize a single or dominant process of change as a function of practice. An alternative framework views practice as a continuous search process of the perceptual-motor workspace that seeks task-appropriate movement solutions whereby changes in the practice environment induce different search strategies of the workspace (Fowler & Turvey, 1978; K. Newell et al., 1989; K. Newell, 1991).

During practice individuals have access to information about the environmental and task constraints that they can use in the organization of movement patterns. The standard manipulations of practice structure (e.g., variable, block and random conditions) can also be viewed in this informational constraints approach to motor skill acquisition (K. Newell et al., 1985; K. Newell, 1991, 1996). However, informational constraints can take on several forms and have often been interpreted in reference to augmented performance information. For example, post-performance feedback scores (e.g., knowledge of results) have been shown to be robust in facilitating the improvement of performance toward a pre-defined task criterion. In contrast, augmented information in the form of demonstrations or instructions can be presented prior to the learner executing the motor skill (Hodges & Franks, 2004; Kernodle & Carlton, 1992).

Environmental constraints (e.g., visual feedback information and lighting conditions) are another form of informational constraints that can channel an individual's performance toward more task-appropriate perceptual information. For example, the learning of a one-handed catching skill has been shown to be influenced by whether the practice environment included normal light conditions, only visual information of the ball trajectory or intermixed conditions (Bennett et al., 1999; Whiting, Savelsbergh, & Pijpers, 1995). Additionally, the different practice environments lead to non-proportional performance during retention and transfer tests. These results have challenged the generality of the specificity of practice hypothesis in that individuals do not necessarily develop a sensory-specific representation of the motor skill (Proteau, 1992).

During continuous motor tasks, such as manual tracking, augmented visual information in the form of concurrent feedback aids an individual's performance in acquisition and maintenance of the task goal. Similar to discrete movement paradigms, there are a number of different manipulations (e.g., delay, gain, intermittency, etc) that can be applied to the visual display of performance feedback and such changes in visual information strongly influence motor performance (Jagacinski & Flach, 2003). For example, visual gain – the ratio of pixel representation to motor output – has been used to alter the feedback display of motor output. The typical finding is that enhanced levels of performance are observed with small increments of gain, but that beyond a critical gain value performance decrement occurs (K. Newell & McDonald, 1994; Sosnoff & Newell, 2006). The role of visual information is important in adaptive manual control because slower time scale mechanisms of sensorimotor feedback are insufficient in maintaining task performance (Jagacinski & Flach, 2003).

The manipulation of visual gain can also be used to influence the relative contribution of slow and fast time scale processes of isometric force output. For example, in continuous force tracking tasks sensorimotor feedback mechanisms tend to dominate the frequency structure of output trajectories (e.g., evident in high 0 – 4 Hz power) resulting in reduced visual information of faster time scale processes related to feedforward control. The standard approach of gain for visual feedback has been to enhance the display of all the frequency components of force output by the same gain factor (Beuter, 1995; Jagacinski & Flach, 2003; Newell & McDonald, 1994; Sosnoff & Newell, 2006), a strategy that preserves the same relative contributions of frequency structures. One implication of this approach is that visual information of shorter time scale processes may be reduced due to the characteristic properties of rapid, small amplitude oscillations. In contrast, Hu and Newell (2010) introduced a novel manipulation that enhanced the visual information of shorter time scale processes through a selective scaling of higher frequency bandwidths of isometric force output. Effectively, the application of visual gain to particular force frequency structures (i.e., 4 – 8 Hz and 8 -12 Hz) changed the information in the feedback display to enhance the relative influence of shorter time scale processes.

In typical discrete motor tasks changes in the practice environment tend to emphasize one informational source over another and lack the ability to examine a broader range of time scale processes that are evident in continuous tasks, such as tracking. Investigations of manual tracking have used a variety of target patterns (i.e., step, impulse, sine wave, etc) to examine the changes in feedforward and feedback control (Jagacinski & Flach, 2003; Pew, 1974a; Poulton, 1974). The output of continuous tracking can be decomposed into a set of frequency structures (Bassingthwaighte et al., 1994) that reveals the task-dependent interaction of slow and fast time scale mechanisms.

In the learning of continuous manual tracking tasks, the progression-regression hypothesis (Fitts, 1964; Fuchs, 1962; Jagacinski & Hah, 1988) proposes that the ability to use higher order derivatives of the error signal (e.g., velocity and acceleration) to accurately track a target signal is directly related to skill level and that induced factors such as stress or interference result in the regression of performance to lower derivatives of the signal. The ability to use higher order error information may be related to faster time scale processes of motor output; however, there have not been any direct tests, although a task-dependent shift in the frequency structure of motor output with practice has been reported (Miall, Weir, & Stein, 1996; Stanley & Franks, 1990). More generally it has been proposed that motor output is organized based on the frequency structure of the target signal (Bernstein, 1967; Gallistel, 1980; Stanley & Franks, 1990); though, there has been little empirical investigation of this hypothesis.

In isometric force production, changes in the frequency structure of force output have been reported over a broad bandwidth (out to ~ 12 Hz) of time scale processes (Sosnoff, Valantine, & Newell, 2009) and the confluence of constraints to action influence that ability to adaptively modulate the multiple time scale processes that generate force output dynamics (see review, Newell, Studenka, & Hu, in press). There have, however, been a limited number of investigations that examine the effect of practice on the changes of the force frequency structures (although see, King & Newell, 2013; Newell, Broderick, Deutsch, & Slifkin, 2003; Sosnoff & Voudrie, 2009). The influence of learning on the slow and fast time scale processes of motor output provides a window into the persistent and transient changes of the perceptual-motor system as a function of the frequency structures that generate the output (K. Newell et al., 2001).

The current investigation examined isometric tracking performance as a function of selective visual scaling and practice. The visual feedback display of force output trajectory was manipulated to provide different relative information of the multiple time scale processes of isometric force production. From the informational constraint approach (K. Newell et al., 1985; K. Newell, 1991), it was hypothesized that augmented visual information of particular isometric force frequency components would channel performance toward more task-appropriate movement solutions that would facilitate the ability to accurately track the target pattern. To examine this hypothesis, two experimental groups practiced the force production task with the selective visual scaling of force frequency components and a control group practiced with a standard fixed gain.

One experimental group received selective visual scaling of intermediate (4 – 8 Hz) force frequency components during practice. The manipulation of the intermediate range of frequency structures has been proposed to enhance information of visual-motor processes that operate within the bandwidth (Carlton, 1992). The second experimental group practiced isometric force production with augmented information of higher force frequency components typically related to feedforward control (Sosnoff et al., 2009). The bandwidth of the multiple time scale processes of force output has been shown to be adaptable up to ~12 Hz and the characteristic property of faster time scale processes is reflected in rapid, smaller amplitude oscillations. Thus, visual information of these mechanisms is usually limited in computer-aided displays. It was hypothesized that the interaction of practice and selective visual scale of higher force frequency components would facilitate the use of shorter time scale processes. If realized, such a finding would provide further evidence that individuals have the ability to adaptively modulate faster time scale processes that is dependent on the environmental (e.g., feedback information) and task (e.g., target dimension) constraints (Sosnoff et al., 2009).

Finally, a control group was included to investigate the hypothesis that the practice and selective visual scaling interaction facilitates task performance and alters the frequency structure of force output dynamics. Participants in the control group practiced force production under a fixed gain condition that has been shown to enhance performance compared to other gain levels with limited amounts of practice (Hong & Newell, 2008; Sosnoff & Newell, 2006). Following the practice phase, individuals from all groups were tested in two transfer conditions that were the same as the fixed gain and high frequency scaling groups to examine the persistence and generality of the practice-induced changes of force output structure with and without enhanced visual scaling of feedback information.

Methods

Participants

Twenty-two young adults (10 females, mean age = 24 years) volunteered to participate in this study. All participants were right-hand dominant as determined by their preferred writing hand and were free of any neuromuscular disorders or injuries to the limbs. Informed consent, that was approved by the Pennsylvania State University Institutional Review Board, was provided prior to participation.

Apparatus

An Eltran ELFS-B3 load cell was used to measure isometric force output produced by the participants. Force data were collected at a sample rate of 160 Hz. Participants sat comfortably in front of a 43.2 cm LCD monitor with arms placed in a prone position on the table. The participant's hand was placed with the distal interphalangeal joint of right index finger against the vertically fixed load cell. During trials, participants were instructed to maintain a fixed position of the fingers, hand and forearm against the table. The experimental setup was similar to (King & Newell, 2013).

Task

At the beginning of the experiment, participant's maximal voluntary contraction (MVC) was determined by producing isometric abduction force. Force was generated with the right index finger toward the midline of the body by pushing against a load. Each participant completed three MVC trials of 6 s with 20 s rest between trials. The participant's MVC was defined by the highest force level achieved over the trials.

During all trials, participants adjusted their force output to match a red target line displayed on the monitor and viewed online visual feedback of their performance displayed as a series of yellow dots. The force trace moved left to right across the screen with time. The same force target was used throughout the practice and transfer phases (Figure 5.1). The target pattern was characterized by a fractal dimension that consisted of frequency content from 0 – 12 Hz and exhibited a spectral slope between Pink and Brown noise (i.e., $\beta = -1.5$). The wave form was constructed according to fractional Brownian motion (see King & Newell, 2013; Sosnoff et al., 2009). The target line mean was matched to 10 % of the participant's MVC and the amplitude of the wave form was scaled to ±5 % of the participant's MVC.

A visually displayed feedback score was presented after each trial and participants were instructed to reduce the score as a function of practice. The score was the root mean square error (RMSE) and was calculated with the following equation: RMSE = $[\Sigma(s-f_i)^2/ (n-1]^{1/2}$ where s is the value of the target, f_i is the i^{th} force sample and n is the number of data samples.

Procedures

Participants were assigned to one of three experimental groups that were defined by the visual scaling condition of the feedback information of force output trajectory.

Two experimental groups, intermediate (n = 8) and high (n = 8) frequency scaling, practiced the isometric task with a selective visual scaling of 4 – 8 Hz and 8 – 12 Hz frequency components, respectively. For example, the visual feedback display of the force trajectory for the intermediate frequency scaling was manipulated by applying a gain factor to the middle frequency components (i.e., 4 – 8 Hz) of the force output. The procedure of selectively scaling particular frequency components included the use of a band pass filter with a pass-band of 4 – 8 Hz that was applied to the force output trajectory. The filtered output was then multiplied by a fixed scaling factor (i.e., gain = 4) and added to the original force trajectory. The concatenated signal that included the original and filtered force was displayed to the participants. The same procedure was applied in the high frequency scaling condition except that the band pass filter was applied to 8 – 12 Hz components. The scaling manipulation of the force signal generated a 70 ms and 50 ms feedback delay for the 4 -8 Hz and 8 – 12 Hz scaling conditions, respectively. The temporal resolution of such delays, however, has been shown to have no significant effect on task performance and force output dynamics (Sosnoff & Newell, 2008).

A third group of participants (*n* = 6) served as controls in that these individuals practiced the task with a fixed gain factor of the visual feedback display of force output trajectory. The fixed gain factor was defined a priori and related to the ratio of pixel representation of force output that had previously been shown to approximate the production of best performance (Hong & Newell, 2008; Sosnoff & Newell, 2006). The visual gain was 100 pixels per Newton (p/N) of force.

After 10 blocks of 5 trials in the practice phase, performance was examined in two transfer conditions: (a) a fixed gain test in which the test condition was the same as that practiced by the control group (i.e., experimentally defined fixed gain) and (b) a visually scaled test in which the test condition was the same as that practiced by the high frequency scaling group (i.e., scaling of 8 – 12 Hz). The order of the tests was counter balanced with the constraint that two similar tests were not conducted consecutively. The transfer tests consisted of 2 blocks of 5 trials. The experimental procedures were repeated in the same manner over two consecutive days of practice.

Data Analysis

For each trial, the initial 2 s and final 1 s of force trajectory data were removed to avoid the initial force stabilization and/or any premature cessation of force production. Data processing was performed with software written in MATLAB Version 7.0.

The force output trajectory was analyzed with two dependent variables that related to task performance. The root mean square error (RMSE) was used to assess task error as a function of practice and transfer. Also, a correlation analysis was conducted between the force output trajectory and target pattern for each trial to examine the ability to map the force output to the desired 1/*f* target signal in the time-domain.

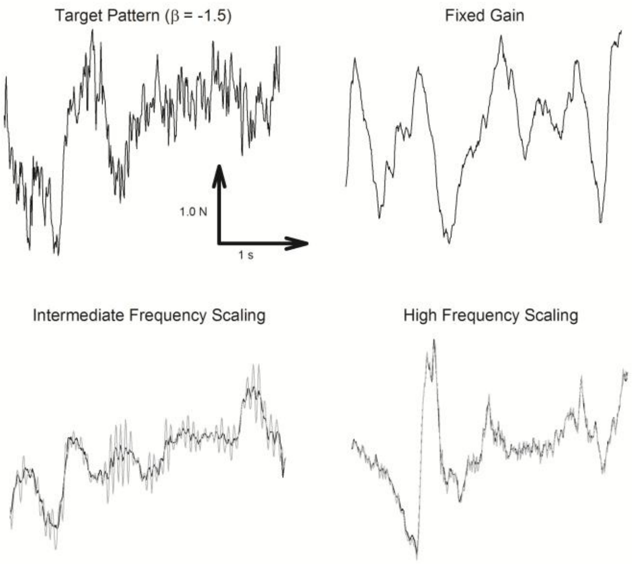

Figure 5.1. Experimental condition examples. (A) Target pattern displayed to the participants. (B) Actual force output for a representative participant in the fixed gain condition. (C) and (D) Actual and visually scaled feedback force trajectories for the intermediate (i.e., 4 -8 Hz) and high (i.e., 8-12 Hz) selective scaling of feedback information. Black thick lines represent the actual force output and gray lines represent the visually scaled feedback force.

The structure of force trajectory was analyzed in the frequency domain through a power spectral analysis. Custom-written software in MATLAB Version 7.0 was used to compute the power spectrum of the force trajectory for each trial. Then, a linear regression was performed on the log-log spectrum over a bandwidth that included 0 – 12 Hz with the DC component removed from the signal. The linear slope of the spectral analysis (β) provides an index of the change in power as a function of frequency.

Statistical Analysis

To examine the interactive effects of visual scaling and practice the dependent variables were independently examined in separate three-way (2 x 10 x 3) repeated measures analysis of variance (ANOVA) with day (2), block (10) and practice condition as the main factors. The initial two factors were within-participant factors and practice condition was a between-participant factor. Post hoc analysis of the block effect was restricted to early (Block 1), middle (Block 5) and late (Block 10) phases of practice. Performance during the transfer test was examined by a 2 (day) x 2 (visual scaling) x 3 (Practice condition) mixed-model ANOVA. The within-participant factors were day and visual scaling (i.e., no scaling, 8-12 Hz scaling) and the between-participant factor was practice condition.

Greenhouse-Geisser corrections were used in cases of violation of sphericity. Post hoc comparisons for the between-participant factor were conducted using the LSD (Least Significant Difference) method. All statistics were evaluated using SPSS (IBM) and significance was defined when there was less than a 5% chance ($p<0.05$) of making a Type I error.

Results

MVC

The mean MVC over both practice days was 19.61 N (*SD* = 5.88). There was not a significant difference between day 1 (*M*= 19.74, *SD* = 6.31) and day 2 (*M*= 19.48, *SD* =

5.56). There was also a non-significant difference between the three practice conditions ($p>0.05$).

Practice

RMSE. Figure 5.2 shows the mean RMSE as a function of practice and visual scaling condition. There was a significant day x scaling condition interaction [$F(2,19) = 5.64$, $p<0.05$] as well as significant main effects of day [$F(1,19) = 25.76$, $p<0.001$] and block [$F(9,171) = 30.42$, $p<0.001$] on the RMSE. Post-hoc analysis found no significant ($p>0.05$) difference across days for the fixed gain condition, but a significant decrease over days for the intermediate and high visual scaling ($p<0.001$) conditions. The pair-wise comparison of early (Block 1), middle (Block 5) and late (Block 10) revealed that RMSE was significantly reduced over practice time ($p<0.05$).

Despite the lack of significance ($p>0.05$) for the block x scaling condition interaction we were interested in whether the effect of visual scaling influenced the amount of change of RMSE from early (Block 1) to late (Block 10) practice. Table 5.1 shows the result of an effect size analysis (Cohen's *d*) that supports the statistical results of the practice block effect, but also illustrates that the intermediate frequency scaling condition exhibited the greatest reductions in task error.

The change in performance outcome was different for each practice condition on both practice days (Figure 5.2). The influence of practice restricts the ability to make direct comparisons of the effect of visual scaling on task error. To further examine the interaction between practice block and visual scaling condition we analyzed the residual practice effects on performance. Residual practice effects would be manifested if there were performance differences between equivalent visual scaling conditions. For example, comparison of performance during the initial exposure to high frequency visual scaling condition across groups would address the residual effects of practice. Therefore, we compared the initial practice trials (Blocks 1 and 2) of the high frequency visual scaling group to the performance of the other groups during the transfer trials that included the same visual scaling condition. Similarly, the procedure can be applied to the initial exposure of the fixed gain conditions.

The RMSE data for corresponding initial exposure to the high frequency visual scaling condition was analyzed in a 3 (visual scaling condition) x 2 (block) ANOVA. The within-subject factor of block included equivalent high frequency visual scaling conditions (i.e., Blocks 1 and 2 of practice for the high scaling group and Transfer Blocks 1 and 2 of high frequency scaling for the intermediate scaling and control groups). There was a significant main effect of visual scaling condition [$F(2,19) = 5.77$, $p<0.01$] on RMSE. Post hoc comparisons revealed that the high frequency visual scaling showed higher RMSE compared to fixed gain ($p<0.05$) and intermediate frequency ($p<0.01$) scaling conditions. The visual scaling condition x block interaction trended toward traditional levels of significance ($p = 0.09$) and suggests that different trajectories of RMSE occurred over blocks for each visual scaling condition.

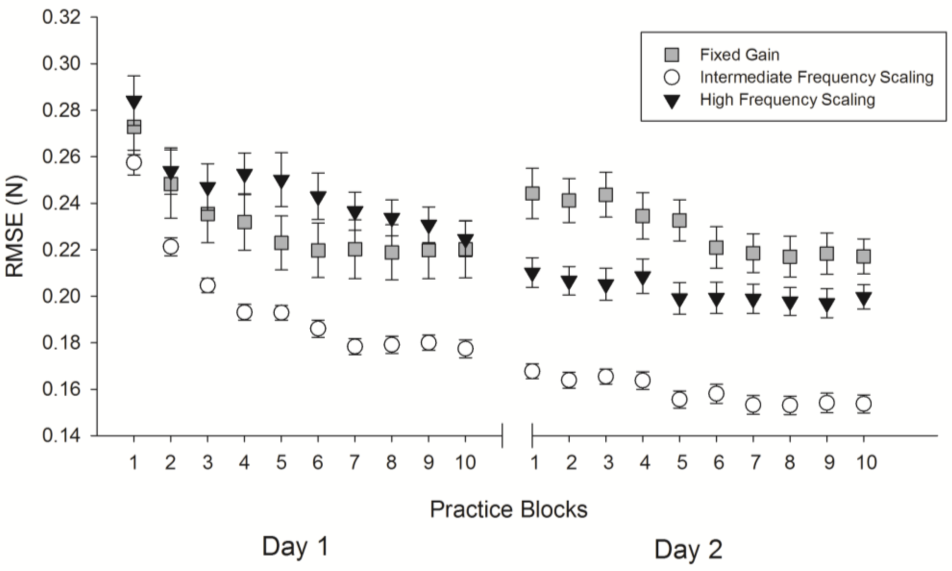

Figure 5.2. RMSE as a function practice and visual scaling condition. Error bars represent standard error across participants.

Another analysis was conducted in the same way to address performance during equivalent fixed gain conditions. The corresponding fixed gain trials (i.e., Blocks 1 and 2 of practice for control group and Transfer Blocks 1 and 2 of fixed gain for the intermediate and high scaling groups) were examined in a 3 (visual scaling condition) x 2 (block) ANOVA. Significant main effects of group [$F(2,19) = 4.53$, $p<0.05$] and block [$F(1,19) = 5.39$, $p<0.05$] were found for RMSE. Post hoc analysis again revealed that the fixed gain condition exhibited significantly higher RMSE compared to the intermediate ($p<0.01$) and high ($p<0.05$) visual scaling conditions when comparing initial exposures to the fixed gain condition. Also, RMSE was significantly lower during Block 2 compared to Block 1 ($p<0.05$). The results illustrate that practicing force production has a positive residual effect on task error independent of the visual scaling condition.

Table 5.1. Early (Block 1) and late (Block 10) practice means (SDs[a]), and effect size data (Cohen's *d*) of RMSE as a function of practice condition.

	Block 1	Block 10	*d*
No Scaling	0.273 (.0714)	0.220 (0.054)	0.72
Intermediate Frequency Scaling	0.225 (0.053)	0.176 (0.025)	1.61
High Frequency Scaling	0.279 (0.070)	0.222 (0.050)	0.94

[a] SD - standard deviation

Correlation. Figure 5.3 presents the mean correlation (CORR) between force output trajectory and target pattern as a function of practice and visual scaling condition. Significant day [F(1,19) = 88.01, $p<0.001$], block [F(9,171) = 38.30, $p<0.001$] and group [F(2,19) = 4.59, $p<0.05$] main effects were found for CORR. The day x block interaction [F(9,171) = 11.65, $p<0.001$] was also significant. The day x block x group interaction was also significant [F(18,171) = 2.03, $p<0.05$]. Post-hoc analysis of the day and block effects revealed that CORR was significantly higher on day 2 compared to day 1 ($p<0.001$) and that within each practice day CORR significantly increased (i.e., Block 10 > Block 5 > Block 1) as a function of practice ($p<0.01$).

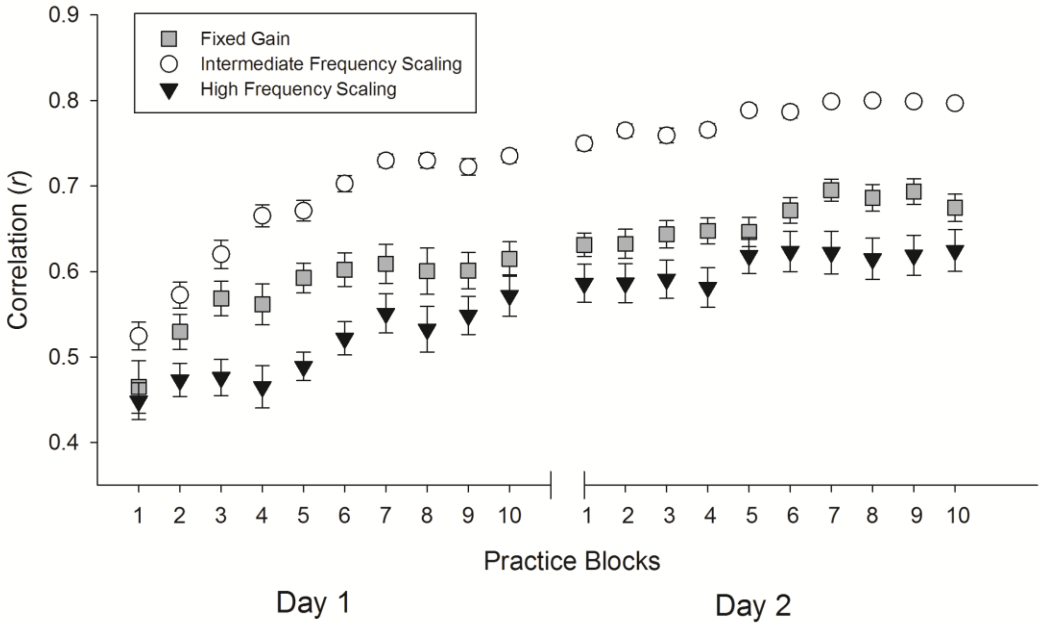

Figure 5.3. Correlation between force output and target trajectories as a function of practice and visual scaling condition. Error bars represent standard error across participants.

Spectral Slope. Figure 5.4 illustrates the mean spectral slope (β) for each practice condition as a function of practice. There were significant main effects of day [F(1,19) = 15.10, p<0.01] and block [F(9,171) = 11.58, p<0.001] on spectral slope. The day x group interaction [F(2,19) = 3.63, p<0.05] was also significant. Post hoc comparison of the day effect revealed that spectral slopes were significantly broader (β = -2.31) on day 2 compared to day 1 (β = -2.54). Post hoc analysis of the block effect revealed that spectral slope in early practice block was significantly (p<0.01) steeper (β = -2.65) compared to mid (β = -2.37) and late (β = -2.33) practice. Over the two practice days, the fixed gain group did not have a significant change in spectral slope (p>0.05); however, the intermediate and high frequency scaling groups showed a significant change in spectral slope over practice days toward broader frequency profiles ($p<0.001$ and $p<0.05$, respectively).

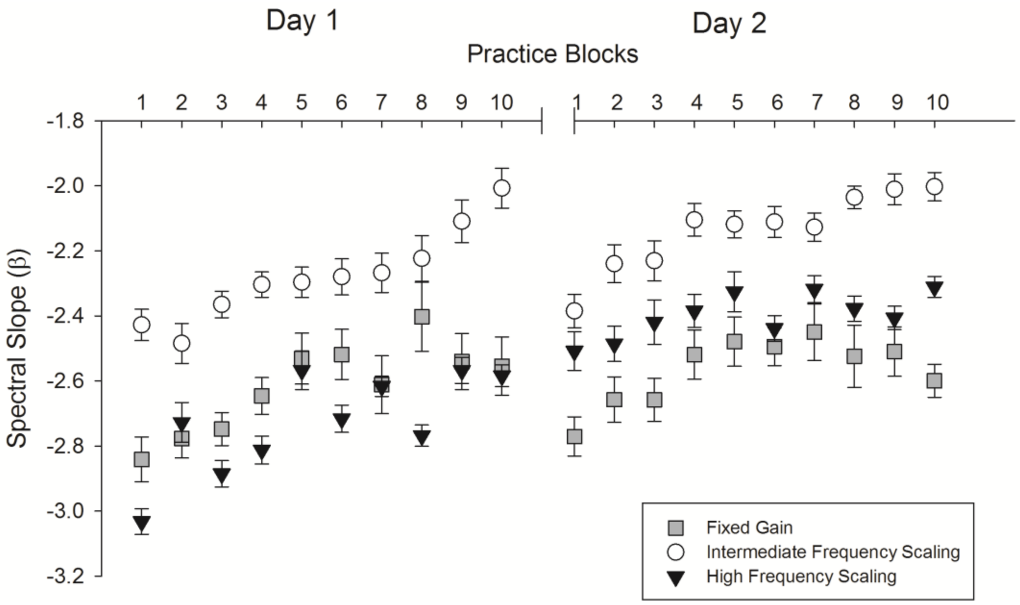

Figure 5.4. Spectral Slope (β) as a function of practice and visual scaling condition. Error bars represent standard error across participants.

Transfer

RMSE. Figure 5.5A shows the mean RMSE during the transfer tests as a function of day, transfer condition (i.e., fixed gain vs. high frequency transfer) and scaling group. There was a significant triple interaction of day, transfer condition, and visual scaling group [$F(2,19) = 3.71$, $p<0.05$]. Post hoc analysis of the day factor revealed that both intermediate and high visual scaling groups significantly reduced RMSE over both days and both transfer tests ($p<0.05$), but that the no visual scaling group showed non-significant changes in RMSE ($p>0.05$).

Correlation. During the transfer tests, task performance quantified through the correlation analysis showed a significant effect of group [F(2,19) = 3.85, p<0.05]. There was also a significant main effects day [F(1,19) = 46.44, p<0.001] that was mediated by the significant day x transfer condition interaction [F(1,19) = 7.66, p<0.01]. Post-hoc analysis of the group effect revealed that the intermediate frequency scaling group exhibited significantly higher correlations compared to both fixed gain (p<0.05) and high frequency scaling (p<0.01) groups.

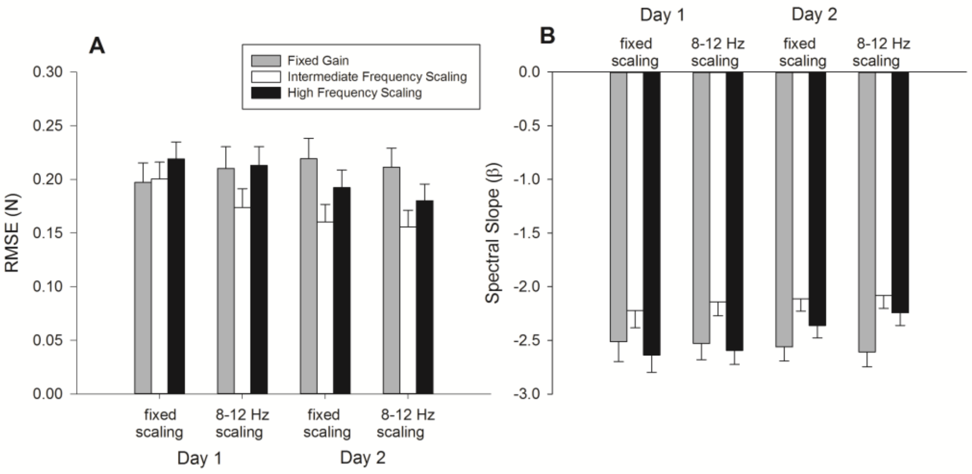

Figure 5.5. RMSE (A) and Spectral Slope (B) as a function of day and transfer condition (i.e., no- and 8-12 Hz scaling for the three visual scaling practice conditions. Error bars represent standard error across participants.

Spectral Slope. Figure 5.5B shows the mean spectral slope (β) as a function of day, transfer condition and group. The statistical results revealed a significant main effect of group [F(2,19) = 3.50, p<0.05] on spectral slope. Post hoc comparisons showed that the intermediate frequency scaling group exhibited significantly broader spectral slopes during the transfer tests compared to the other two groups (p<0.05).

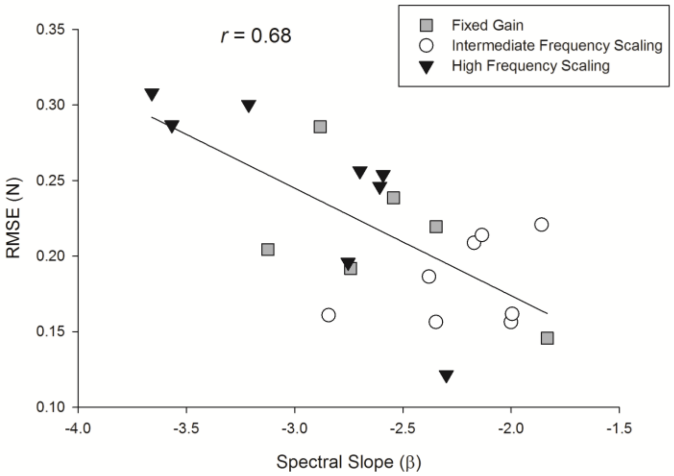

Figure 5.6. Correlation between Spectral Slope (β) and RMSE during the 8 – 12 Hz visual scaling transfer condition.

The effectiveness of the visual scaling manipulation is dependent on the presence of higher frequency components (i.e., broader spectral slope) in the force output trajectory. Individuals also exhibit a different organization of the frequency structures of the force output that is reflected in linear regression (i.e., β) of the power spectrum. To further examine the influence of selective visual scaling on feedback information, a correlation analysis was computed across all participants between spectral slope (β) and task error (RMSE) during the high frequency transfer test. Figure 5.6 shows a significant ($p<0.001$) inverse relation (*r* = 0.68) in that individuals with broader spectral slopes exhibited lower RMSE compared to individuals with steeper spectral slopes. The significant correlation provides further evidence that individuals used the faster time scale visual information to achieve the task goal.

Discussion

This investigation examined how practicing under different informational constraints influenced tracking performance and the learning, retention and transfer of multiple time scale processes that support force outcome. Three groups of participants practiced an isometric track task either in a fixed gain, intermediate-, or high-frequency scaling condition to examine whether the selective visual scaling of particular force frequency components facilitated reduction in task error. A secondary issue was how the visual scaling manipulation influenced the interaction of the multiple time scale processes of force output dynamics as a function of practice. All groups reduced tracking error and exhibited the predicted shift in force output structure over practice with error lowest and spectral slope flatter in the intermediate scaling condition followed by the high scaling and fixed gain conditions, respectively.

The performance outcome showed a reduction of task error within each day of practice for all visual scaling conditions; however, the amount and persistence of this change was dependent on visual scaling. In particular, the intermediate and high scaling conditions exhibited the greatest reductions in task error (Table 5.1) and showed consistent improvement in performance across both days of practice (Figure 5.2). Conversely, while the fixed gain condition showed reduction in error within each practice day there was no effect of practice day on RMSE. These findings supported the hypothesis that selective visual scaling of short time scales of feedback information would facilitate performance outcome to a greater degree that the fixed gain condition. Overall, the effect of visual scaling on RMSE was greatest in the intermediate (4-8 Hz) bandwidth, but the high visual scaling condition (8-12 Hz) also exhibited a progressive reduction in task error over trials and days albeit at a slower rate of change than the intermediate scaling condition.

The different pathways of change in task performance between the intermediate and high visual scaling conditions may be related to several factors. First, the separate bandwidths have different characteristic properties of force output dynamics and the implementation of the same visual gain factor over these time scale processes may have been insufficient for the higher frequency bandwidth. Hu and Newell (2010) showed different patterns of results over a range of scaling factors and, therefore, the effect of practice most likely interacts with the scaling of long and short time scale processes. There may also be influence of processing limitations to faster time scale of visual information (Carlton, 1992). Lastly, enhanced visual information of shorter time scale processes may incorporate the presence of postural tremor (i.e., ~8 Hz) in the frequency bandwidth the feedback of which may hinder task performance.

Similar to RMSE, there was also an interaction of practice and visual scaling condition on the ability to map force output to the target pattern as a function of practice. Again, the effect of practice was observed in all visual scaling conditions in that the force output-target pattern correlation increase over practice (Figure 5.3). However, the intermediate visual scaling condition exhibited enhanced mapping of the force output trajectory to the target pattern compared to the other conditions. In contrast to RMSE, fixed gain showed higher correlations than the high scaling condition over practice. The different pathways of change observed in the two performance outcome measures (RMSE and CORR) suggest that providing augmented feedback information for force frequency structures channels performance toward different properties of the target pattern (Pew, 1974a).

In addition to task outcome performance, we were interested in whether the selective scaling of force frequency components differentially influenced how individuals changed the organization of force output structure as a function of practice. Similar to task performance variables, all visual scaling groups exhibited flatter spectral slopes over practice (Figure 5.4) that supports previous isometric learning investigation showing task-dependent changes in force output structure (King & Newell, 2013; K. Newell et al., 2003; Sosnoff & Voudrie, 2009). Also, the selective visual scaling manipulation induced broader spectral slopes than the fixed gain condition. Previous investigations have shown a change in shorter time scale processes, such as minimum visual processing time (Carlton, 1992), as a function of practice. The focus here however is not on the change of a single sensory or motor mechanism, but rather on how an individual changes the complex interaction of slow and fast time scales of motor output over learning. There has been limited examination on how 1/*f* dynamics shift as a function of practice (King & Newell, 2013; Wijnants, Bosman, Cox, & Van Orden, 2009) and is an important aspect of motor behavior for future research.

In the informational constraints approach to skill acquisition (K. Newell et al., 1985; K. Newell, 1991, 1996) the manipulation of environmental and task constraints is proposed to channel performance toward different movement solutions and the pick-up of different perceptual information. Previous evidence from learning the skill of one-handed catching has shown that practicing under different informational constraints induces different performance strategies (Bennett et al., 1999; Whiting et al., 1995).

Here, it was proposed that the selective scaling of shorter time scales of visual information would drive performance toward more task-relevant properties of the target pattern. Overall, the findings supported this prediction in that the scaling manipulation afforded individuals to progressively increase the contribution of faster time scale processes to the full isometric force output signal.

The characteristic properties of slow and fast time scale processes are typically equally enhanced during the standard manipulations of visual gain. Here, we used an experimental design introduced by Hu and Newell (2010) to alter the relative contributions of slow and fast force frequency structures. The visual scaling of the selected bandwidths (i.e., 4 – 8 Hz and 8 – 12 Hz) was proposed to augment feedback information of different time scale processes. The results showed that independently scaling each bandwidth induced changes over the *collective* organization of the interaction of multiple time scale processes. This pathway of change holds some similarities to the progression-regression hypothesis of skilled tracking behavior (Fitts, 1951; Fuchs, 1962; Jagacinski & Hah, 1988) in that faster time scale processes may contribute to the ability to progressively use higher-order derivatives (e.g., velocity and acceleration) of error signals during manual tracking tasks.

An additional focus of the investigation was to examine the persistence of practice-induced changes of force output structure with transfer tests that included the fixed gain and high scaling conditions. The results showed that the enhanced levels of performance manifested during practice by the intermediate scaling condition persisted in the transfer conditions. In particular, the intermediate scaling condition exhibited lower task error compared to the other conditions (Figure 5.5), despite the fact that neither of the transfer conditions matched the visual feedback condition of the practice phase.

Overall, the transfer results did not support the prediction of the specificity of practice hypothesis (Proteau, 1992) that performance decrement occurs during transfer conditions that are different from practice with respect to the dominant afferent information. Accordingly, in this view task performance would be greatest for the fixed gain and high scaling groups in the respective transfer tests; however, this was not the case and further challenges the generality of the specificity of practice approach across different motor tasks (Bennett et al., 1999; Whiting et al., 1995).

A final note on the transfer results is with respect to the significant relation between spectral slope and task error found in the 8 – 12 Hz scaling condition (Figure 5.6). Operationally, the effectiveness of selective visual scaling of faster time scale processes was dependent on the presence of short rapid oscillations in an individual's force output trajectory. The potential situation arises that an individual with lower power in the higher (i.e., 8 – 12 Hz) frequency bandwidth would have limited visual information of shorter time scale processes in comparison to an individual with higher power. Thus, the inverse relation of spectral slope and task error (Figure 5.6) suggests that the ability to modulate force output dynamics is related to the shorter time scales of visual feedback information. Similarly, Sosnoff et al. (2009) reported that individuals use the visual information of lighter-colored (i.e., white and Pink) noise patterns to modulate faster time scales processes. Overall, the results support the notion that both environment and task constraints influence the ability to adaptively modulate faster time scales of force output dynamics.

In summary, the current findings supported the hypothesis that the ability to adaptively use faster time scale processes was dependent on the interaction of practice and information available in the environment. The selective visual scaling of intermediate (i.e.,. 4 – 8 Hz) and to a lesser extent higher (8 – 12 Hz) force frequency components induced a broadening of the spectral slope and facilitated a respective improvement in task performance over practice. The results also showed that the use of shorter time scale processes was dependent on the amount of practice, an issue that should be explored in future investigations. Previous investigations have shown the adaptive nature of force output dynamics with limited amounts of practice (Hu & Newell, 2010; Sosnoff et al., 2009) and further investigations are necessary to better understand the dynamics of change of force frequency structures as a function of learning.

CHAPTER 6. GENERAL DISCUSSION

The dissertation examined the learning, retention and generalization of the production of isometric force frequency structures that varied in their regularity. The focus of the experimental studies was on how practice-induced changes in force output dynamics supported the learning of isometric tracking tasks. The main aims of the dissertation were: (1) to examine how the structure and environment of practice influenced the learning of shorter time scale mechanisms of force output, and (2) to analyze the transient and persistent properties of the practice induced changes of force output structure.

A continuous tracking task affords the examination of a wide range of sensori-motor processes to study motor learning and control (Jagacinski & Flach, 2003). Motor output over extended time periods (e.g., 20 s) leads to a broad distribution of trajectory properties that reveal the relative contribution of feedforward and feedback control processes (Bassingthwaighte et al., 1994; Desmurget & Grafton, 2000). In isometric force tracking, there is a task-dependent interaction of these multiple time scale processes that can be changed systematically by manipulating the constraints to action (K. Newell, Studenka, & Hu, in press). There have however been limited investigations of the relative persistent change of force output dynamics in motor learning.

First, we examined whether task-induced variation of the target pattern to be tracked: (i) differentially influenced the use of the multiple time scales of force output; and (ii) facilitated the ability to generalize force output dynamics to novel target patterns. Second, we examined the transient and persistent properties of force output structures through a fine-grained analysis of three consecutive, smaller frequency bandwidths (0 –

4, 4 – 8, and 8 -12 Hz) of force output. Lastly, we tested the hypothesis that the interaction of practice and augmented visual feedback information would facilitate the learning of shorter time scale processes. The findings from the experiments are discussed with respect to the inter-related constructs of motor learning, retention and generalization.

Motor Learning

Standard definitions of motor learning emphasize the relative persistent change of behavior over time (Schmidt & Lee, 2005). Traditionally, the index of motor learning has been inferred primarily from changes in performance outcome measures which can mask the effect of practice on the coordination and control of the movement pattern that supports the goal of the task. Also, many motor learning investigations have used experimental tasks that constrain the potential usage of redundant movement solutions (Bernstein, 1967). Furthermore, there are transient and persistent properties of change that influence the inference of motor learning that is drawn from performance dynamics. Therefore, a main focus of the dissertation was to address these limitations through investigation of the learning of the organization of force output that supports isometric tracking performance.

At the task outcome level, the findings showed that the pattern of change in performance (i.e., RMSE) followed a negatively accelerating change over practice that reflected the persistent properties of change that index motor learning (A. Newell & Rosenbloom, 1981; K. Newell, Mayer-Kress, & Liu, 2006). In Experiments 1 and 2, the reductions in task error was independent of whether isometric force tracking was performed to the same (i.e., constant practice) or different (i.e., variable practice) target pattern. This finding does not support previous investigations that typically show a decrement of performance during practice conditions that included task-induced variability at the outcome level (Schmidt, 1975; Shea & Morgan, 1979). The influence of the practice environment on performance outcome was evident in Experiment 3 in that augmented visual feedback information facilitated the learning of isometric tracking as a function of practice. The enhanced performance levels achieved through the interaction of practice and selective visual scaling of shorter time scale force processes supported the informational constraints approach to motor skill acquisition (K. Newell, Morris, & Scully, 1985; K. Newell, 1996).

At the force output structure level of analysis, the results showed that the ability to modulate the time- and frequency-dependent properties of force output was strongly influenced by the structure and environment of the practice session. The constant practice conditions in Experiments 1 and 2 showed greater increases in the relative contribution of shorter time scale processes compared to variable practice. Thus, the predictions of the variability of practice hypothesis (Schmidt, 1975) failed to extend to the properties of the movement pattern (Ranganathan & Newell, 2010a). In Experiment 3, the selective scaling of shorter time scales of visual information facilitated the task-dependent learning of these mechanisms.

In general, the change in performance at the task outcome level (i.e., reduced RMSE) was facilitated by the ability to adaptively modulate force output structure over practice. In each experiment, individuals showed the predicted task-dependent modification of force output structure that included changes over a broad frequency bandwidth (i.e., up to ~12 Hz) of time scale processes (Desmurget & Grafton, 2000; Pew, 1974; Sosnoff, Valantine, & Newell, 2009). However, in contrast to task error, there was a rapid decay in the contribution of shorter time scale processes to force output dynamics over the rest interval between practice sessions. This lack of persistence in the faster time scales does not support the standard interpretation of motor learning (Schmidt & Lee, 2005).

The decrement in performance of force output dynamics occurring after rest intervals does not preclude the interpretation that there was no effect of learning. Indeed, the basis for most learning functions has been that of the persistent trend in performance outcome, but there are also transient properties of change that are typically neglected in these approaches. For example, the experimental results showed that the performance trajectory of force output structure on subsequent practice days resembled that of a warm-up decrement (Adams, 1952, 1961). This rapid, transient change over the initial periods of practice suggests that additional trials are necessary to attune the contributions of faster time scale processes to force output structure. Thus, even though the organization of the motor system shifted toward an emphasis on slower time scale force components during the rest interval individuals showed a persistent trend within each day to increase the relative use of faster time scale processes over trials. Future studies may quantify this trend with additional days of practice through the time scale of change (e.g., adaptation) that returns performance to previously achieved levels (Liu, Mayer-Kress, & Newell, 2006; K. Newell et al., 2009).

The increased contribution of faster time scale processes of force output dynamics as a function of practice holds similarities to the progression-regression hypothesis of manual tracking. Fitts' and colleagues (Fitts, 1954; Noble, Fitts, & Warren, 1955), along with other (Fuchs, 1962; Jagacinski & Hah, 1988) have shown that there is a progression of position-velocity-acceleration control as a function of practice whereby individuals use the higher order derivatives of the movement trajectory to enhance tracking performance. Also, there is a regression to lower derivatives under conditions of stress. In the current investigations a change in the practice environment (i.e., transfer tests) or the rest intervals (i.e., retention) could be considered a "stress" condition that induced a regression of performance to lower levels of error signals. There may be additional links between the ability to use higher order error information and the adaptive use of faster time scale processes but further modeling work is necessary.

Another viewpoint of motor learning proposes that individuals learn to organize a movement pattern with respect to component frequencies (Marteniuk & Romanow, 1983; Stanley & Franks, 1990). This notion is consistent with the proposals of Gallistel (1980) and Bernstein (1967) that a Fourier transform originates in cortical areas of the brain, but that lower levels of the motor system handle the details of the movement pattern. With respect to this interpretation, the findings show that an individual learned different Fourier components of the target pattern as evident by the broadening of the frequency distribution of force output over practice; however, these changes dissipated over the rest interval to reflect the transient nature of the changes induced by practice.

Overall, the findings revealed that there are differential effects of practice environment on the learning of performance outcome and force output dynamics. This was revealed through different pathways of change at these two levels of analysis and challenges previous notions of variability of practice (Braun et al., 2009; Schmidt, 1975; Shea & Morgan, 1979). Thus, it appears that when the potential for redundant tasks solutions is expanded the proposed benefits of task outcome variability are reduced and may even be negated (Ranganathan & Newell, 2010a). Therefore, motor learning theory needs to account for the transient and persistent properties of motor behavior at both the task outcome and movement organization levels of analysis.

Generalization

The construct of generalization can be defined as how learned movement patterns transfer to a wide variety of situations, including those that may or may not have been previously experienced. Transfer of motor skills is another index of motor learning and has been a focal point in the literature for well over a century (Adams, 1987; Thorndike & Woodworth, 1901). In each of the experiments task performance was examined in transfer tests to investigate how the practice environment influenced the transfer of performance outcome and force output to novel contexts.

In Experiments 1 and 2 the target isometric tracking pattern was manipulated to test whether the predictions of the variability of practice hypothesis (Schmidt, 1975) could be extended to the multiple time scales of force output. The variable practice condition consisted of trial-to-trial variation of the spatial-temporal properties of the target signal; although, the $1/f$ frequency structure was the same as the constant practice condition. In Experiment 3 the visual feedback information of force output trajectory was manipulated through a selective scaling of shorter time scale processes to examine the relative persistent effect of practice-induced changes of force output structure in novel circumstances.

In the three experiments, the type of transfer (e.g., positive or negative) was dependent on the relation between the frequency distributions of the target pattern and the force output. Experiment 1 showed positive and negative transfer to target patterns that were more (i.e., Brown noise) and less (i.e., Pink noise) regular than that of the wave form experienced during practice, respectively. In Experiment 2 the delayed retention tests revealed that the shift toward a more regular force output structure (i.e., steeper spectral slopes) over the rest interval (i.e., 24 hrs) resulted in lower task error with low than high dimensional tracking target patterns. Finally, in Experiment 3 the level of performance during the transfer test was related to the individual's spectral slope of force output signals. In particular, the finding that broader spectral profiles resulted in lower task error supports the notion that individuals used faster time scale processes to reduce tracking error.

The generalization (Schmidt, 1975; Braun et al., 2009) and specificity (Henry, 1968; Tulving & Thomson, 1973; Proteau, 1992) theories of motor learning provide two contrasting viewpoints on how the practice conditions influence the formation of the memory representation of the motor action. In the framework of the variability of practice hypothesis (Schmidt, 1975) the results showed that isometric tracking to variable target patterns did not result in enhanced generalization compared to practicing to the same target pattern. In Experiment 2 there was, however, a transient effect of variable practice conditions on the ability to map force output trajectories to the target pattern, but the benefit was negated on delayed retention tests. One interpretation of the trial-to-trial variability of the target pattern is that it may have induced a dual control problem in that individuals sought information regarding the changes in the force-time pattern and were required to modulate force output dynamics relative to these changes (Sosnoff et al., 2009).

The specificity of practice approach proposes that individuals develop a specific sensorimotor representation that takes into account the available afferent information (Proteau, 1992). Using this framework, the target pattern and visual feedback information can be considered the dominant sources of afferent information during isometric force tracking. Accordingly, individuals would acquire specific motor skills that emphasize these properties of visual information. In Experiment 1 and 2 the transfer tests manipulated the visual information of the target pattern relative to practice and the findings showed both positive and negative effects of transfer that did not support the prediction of the specificity approach (Proteau, 1992). This may be in part due to the nature of the tasks that are typically examined. The effects of specificity of practice have shown performance decrements in rapid aiming movements during transfer tests that include the removal of visual feedback information. Previous isometric investigations have also demonstrated the role of visual information in the maintenance of tracking performance (K. Newell et al., 2003; Slifkin et al., 2000; Sosnoff & Newell, 2005). However, performance decrement is not taken to infer that there was no learning, but rather that force output is constructed based on the available information and this interpretation is further supported by the selective visual scaling manipulation found in Experiment 3.

In summary, performance outcome variables have been the standard measure of motor learning and transfer (Schmidt & Young, 1987); however, the findings of the experimental studies suggest that these measures are insufficient to index the degree of motor learning and generalization. Also, traditional motor learning investigations have focused on task outcome or discrete measures (e.g., relative timing and relative force) with a limited examination of how practice conditions influence the learning of the movement pattern. An alternative framework is to map the dynamics of the movement organization in a control space (e.g., approximate entropy and spectral profile) relative to environmental and task constraints. Thus, shifting the emphasis to the learning and transfer of the underlying mechanisms rather than solely the response outcome (Mitra et al., 1998; K. Newell et al., 2001). This approach allows for the examination of redundant task solutions and challenges the notion that there is direct relation between movement parameters and movement responses (Schmidt, 1975). There is however a need to gain a better understanding of the attractor dynamics that support task outcome over a wide range of motor skills. In this framework, future studies should investigate what Bernstein (1967) defined as dexterity – the capacity with which an individual realizes the task demands across changing conditions and constraints on action (cf. K. Newell, 1996).

Limitations

There are limitations to the current investigations that should be addressed in future experiments. First, the visual feedback of the force trajectory that was presented on the screen moved from left to right on the monitor whereas the abduction force applied to the load cell with the right index finger was toward the left direction. This in effect meant that participants had to map the right-to-left movement on the load cell to a left-to-right trajectory of the feedback display in the screen space. Thus, there may be a compatibility issue between the direction of motion presented in the visual display of force feedback information and that of the motion of the index finger.

The predictions of the variability of practice hypothesis derived from schema theory (Schmidt, 1975) focus on induced variations at the task goal level. However, the issues of redundancy (Bernstein, 1967) and movement variability (K. M. Newell & Slifkin, 1998) open the window to implementing task-induced variation at multiple levels of movement patterns. In particular, force output structure has been shown to be influenced by a variety of manipulations (e.g., force level, visual intermittency, visual gain, time gain) and future investigations could manipulate these variables as a function of practice to examine the transient and persistent changes of how the perceptual-motor system adaptively modulates motor output to different environmental and task constraints.

Finally, manual tracking tasks afford the examination of a broad range of frequency structures of motor output and the ability to accurately track a target pathway requires the interaction of a multitude of sensori-motor mechanisms at different levels of analysis. It is also likely that the use of these mechanisms in motor output changes as a function of practice. For example, visual mechanisms in searching and discrimination tasks have been shown to be influenced by practice (Karni & Sagi, 1993) and changes in cortical drive have been reported following extended resistance training protocols (Carson, 2006). Thus, there may have been changes at these other levels of analysis that are supporting and channeling the realization of the task goal.

Conclusions

In summary, the dissertation allowed the following key conclusions:

(1) Different pathways of change in the degrees of freedom of the perceptual-motor system exist in motor learning. Individuals exhibited the ability to adaptively modulate the multiple time scale processes of force output to a task constraint that was of a higher dimension than that of the intrinsic dynamics present at the beginning of practice. The dynamics of change at the task outcome level and within the control space (i.e., force output structure) showed different trajectories that were related to the practice environment which suggests that these two levels of analysis evolve on distinct time scales of change.

(2) Force frequency structures exhibit transient and persistent properties of change over practice. Though practice-induced changes were observed in the time- and frequency-dependent properties of force output dynamics the degree of persistence decreased as a function of frequency structure over the time interval between practice sessions.

(3) Variability of practice conditions can be used to channel different movement solutions. In isometric force production protocols, task-induced variability at the level of the target pattern had a greater influence on the organization of force output than performance outcome. This suggests that manipulations of the practice environment can influence how an individual uses different time scale processes during motor skill acquisition and may be useful to induce search strategies that seek more task-appropriate movement solutions.

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Education

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Peer-Reviewed Publications

King, A. C., & Newell, K. M. Effect of practice and visual scaling on the learning of shorter time scale isometric force processes *Attention, Perception & Psychophysics* (in preparation)

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