The Role of Attention in Motor Learning and Control

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Abstract

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The Role of Attention in Motor Learning and Performance.

Directed by Professor Alice F. Healy and Associate Professor David E. Sherwood

Abstract: Research on the focus of attention (FOA) has been ongoing since initial experiments over 15 years ago (see Wulf, 2007a; 2007b). Since that time, research on the FOA has evolved considerably and experimental data has revealed physiological changes underlying behavioral effects of attention. These experimental developments integrate the FOA with other robust findings in motor learning and control (e.g., choking under pressure and implicit learning). This dissertation investigates how an external FOA (e.g., on the goal of a movement) leads to better performance than an internal FOA (e.g., on the body's own movement). Previous research has measured movement outcomes (e.g., accuracy) but not the quality of movement itself (e.g., neuromuscular efficiency, movement variability, movement kinematics). Thus, the current experiments use biomechanical analysis and surface electromyography to explore the role of attention in coordinating movement at the neuromuscular level up to the level of the movement outcome. Data from five experimental studies in this dissertation suggest that attention changes the control structure of the motor system: an external focus of attention reduces variation in the nominal, goal-dimension of the task, whereas an internal focus of attention reduces variation in the pattern of the movement itself (at the expense of task performance; Chapter 4). Underlying the effects of an internal focus of attention are increases in cocontraction of the muscles around a given joint (Chapters 2 and 3). Increasing mechanical impedance in the limb by increasing cocontraction is useful for reducing variability in the movement pattern, but has ancillary consequences of reducing movement efficiency and, often, effectiveness. Furthermore, the FOA appears to affect the performance of learned motor skills rather than the rate of learning itself (Chapter 5). These findings suggest significant expansion of current theories on the focus of attention in order to predict these physiological changes that mediate the attention-performance relationship. A neurophysiological framework for the role of attention in motor control is present in Chapter 6, based on these findings. This framework posits that an internal focus of attention invokes motor control structures that were active early in the learning process (e.g., dorsolateral prefrontal cortex) impairing coordination, efficiency, and effectiveness.

Dedication

I’d like to thank my mother and my father and my sister and my brother and all those people who’ve been there from the start.

We don’t see each other often enough, but rest assured you’re all close to my heart.

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Table of Contents

List of Tables

List of Figures

Chapter 1: A Review of Attentional Focus Effects in Motor Learning and Control

> *"I feel like I'm throwing three different kinds of tosses, thinking about what to do with my arm, what to do with my legs, am I leading with my shoulder, those kinds of things. I just need to stop thinking about that so much and do what I need to do."*
>
> – Tim Lincecum, San Francisco Giants Baseball Club (Haft, 2011)

The quote above suggests a common experience for many people who have tried to perform complex skills in demanding or stressful environments. The performer's mind is awash with ideas, and how individuals direct their attention can have profound effects on their success. Research in human performance has shown for a long time that 'paying too much attention' can be detrimental to the execution of a skill, especially when that skill is well learned (e.g., Baumeister & Showers, 1986). Anyone with experience performing in athletics, music, or dance can anecdotally report "choking" under pressure, especially when trying very hard to perform at his or her best (choking in this case being a sudden and severe drop in a person's level of performance.) But the deterioration of skilled performance is not only an issue in these aesthetic pursuits, highly practical skills (e.g., for soldiers, pilots, surgeons, crane operators) can suffer attention-induced changes in performance. Similarly, perfunctory skills can also suffer from increased attention; for instance, do you make more errors typing alone, by yourself, or when a supervisor is reading over your shoulder and you are trying very hard not to make errors? This seemingly paradoxical effect of increased attention in skilled performance is well documented (Beilock & Carr, 2001; Gray; 2004) and well accepted by the scientific community, at least when it comes to studies of experts.

When it comes to novices, on the other hand, the effects of attention on skilled performance are more contentious. Most theories of motor skill acquisition suggest that novices must progress through a stage of learning where they focus on the mechanics of their own movement before developing the robust sequence-representations that will allow them to perform with the fluidity, automaticity, and effectiveness of experts (Adams, 1971; Anderson, 1983). Fitt & Posner (1967; see also Fitts 1964) suggested that novices had to progress from a *cognitive* stage of learning, in which the learner is actively trying to figure out how the movement needs to be controlled, before they can enter an *associative* phase. In the associative phase, the learner has acquired the basic movement pattern and can now make more subtle adjustments that allow for greater success and more reliable performance.

Finally, after many hours of practice (perhaps thousands; Ericsson, Krampe, & Tesche-Römer, 1993) the learner reaches the *autonomous* phase, in which movements are not only reliable and accurate, but they are also highly efficient, showing reduced co-contraction between agonist/antagonist muscle groups (Gribble, Mullin, Cothros, & Mattar, 2003; Osu et al., 2002), showing the exploitation of external forces to reduce the need for internally generated forces (such as gravitational or Coriolis forces; Gentile, 1998), and showing flexibility or transfer to new environments (e.g., reliable outcomes in a hammer swing from different starting positions, Bernstein, 1967).

Evidence for this progression from explicit and inefficient modes of control seen in novices to the more implicit and efficient control seen in experts comes from cross-sectional studies of attention that compare expert and novice performance under dual-task conditions. In these studies, a primary task is conducted (such as ball handling in soccer) while the expert/novice simultaneously performs a distracting secondary task (such as counting auditory tones or doing mental arithmetic). Across a range of athletic tasks, experts show less of a decrement under secondary-task conditions than novices (Abernathy, 1988; Jackson, Ashford, & Norsworthy, 2006; Leavitt, 1979; Smith & Chamberlain, 1992), suggesting that experts have developed much more efficient control (what some might call automaticity) and performing the primary task thus demands fewer attentional resources.

These findings have led many theorists to suggest that novices need to focus on the step-by-step execution of motor skills (Beilock & Carr, 2004; Gray, 2004), whereas experts possess a higher level of control and can execute a more complex skill as a continuous “unit” or motor program. For instance, an expert tennis player might have a well-tuned motor program for hitting an ace, and this program might be different on grass versus clay, but for novices “hitting an ace” is computationally meaningless because they cannot represent the motor skill at that high a level (Schack, 2004; Schack & Meschner, 2004).

Intuitively, it seems appropriate that novices must focus more attention on the step-by-step execution of their movements than experts and use a more explicit mode of control early in the learning process (i.e., directing attention to the movement itself, rather than the outcome of the movement). To a certain extent, this assertion must be true because for any learned, voluntary movement, a novice will need some idea of what the movement should look like/feel like in order in order for error-driven learning to occur. However, the exact nature of how attention should be directed is much more nuanced. For instance, Wulf and Weigelt (1997) studied skill acquisition in novice subjects learning how to use a ski-simulator. One group of subjects was given explicit instructions about when to exert pressure during the movement in order to maximize the amplitude of side-to-side displacement of the simulator platform. (The goal in riding a ski-simulator is to make oscillatory movements as quickly as possible with the largest possible amplitude, simulating slalom skiing.) A second group of subjects was not given this explicit movement information about the movement technique and were thus free to discover (or not discover) the proper movement form on their own. Although both groups started out with similar levels of performance (about 20 cm/s; using amplitude X frequency of platform deviations as an index of performance), after three days of training the group that had been given explicit movement instructions was doing significantly worse (27 cm/s) than the self-discovery group (38 cm/s) who had learned the appropriate movement dynamics to a greater extent, despite not having explicit instructions. Furthermore, a psychologically stressful transfer test on the third day of training (subjects were told their performance was now being evaluated by a ski expert) exacerbated this difference and the self-discovery group actually improved (40 cm/s) whereas the explicit instruction group did slightly worse (25 cm/s).

Hodges and Ford (2000) had a similar finding in a study of bimanual coordination in which detailed instructions on how to perform the movement were withheld from one group of subjects. In this task, the goal was to move the hands forward and backward in the horizontal plane with one hand lagging behind the other by a quarter of a cycle; for novices this is a difficult phase relationship to maintain. Subjects were given feedback on a computer screen in the form of a Lissajous curve (a system of parametric equations that describe complex harmonic motion). When the correct phase relationship (a quarter-cycle lag) is maintained, the display shows a circle, deviations from this relationship create ellipsoids that flatten into straight lines when the movements are either fully in-phase or fully anti-phase. The explicit instruction group was given detailed information on how to produce the stable pattern to generate the circle on the screen. In contrast, the self-discovery group was only told the image on the screen depended on their movements and that their goal was to generate and maintain a circle. Like the study by

Wulf and Weigelt (1997), Hodges and Ford found that the self-discovery group did better than the explicit-instruction group on a transfer test (this time the test was to produce the circle while counting backwards by threes).

So what is happening here? Why is it that paying *more* attention to a skill can actually be detrimental to performance? Clearly, there seems to be a non-linear relationship between attention and performance where paying very little attention or being distracted is bad (e.g., Wine, 1971), but paying too much attention can also be detrimental. This end of the attention-performance spectrum is exemplified by research on "choking under pressure," defined as the significant decrease in performance that occurs when the need/desire to perform is increased (Baumeister, 1984; Lewis & Linder, 1997). There is considerable empirical evidence that increased pressure to perform increases a performer's self-awareness, inappropriately focusing attention on the performers' own movements, rather than on the goals he or she is trying to achieve.

For example, Pijpers, Oudejans, and Bakker (2005) studied the quality of movement in identical climbing traverses in an indoor climbing facility. The traverses were identical in terms of the placement of hand and foot holds, but one traverse (low-anxiety) was set 0.4 m off the ground and the other (high-anxiety) was set 5.0 m off the ground. Anxiety on each route was validated through self-report measures. In the high-anxiety condition, subjects made more "exploratory movements" (i.e., touching hand or foot holds without actually using them for support), stayed on a given hold longer, and took more time when moving between holds. All of these factors contributed to increases in overall climbing time for the high-anxiety traverse. In this instance, the increased anxiety from the fear of falling led to more explicit, step-by-step control.

Similarly, Gray (2004, Experiment 2) used a baseball simulation to study the relationship between batting performance and the performer's explicit awareness of the quality of the movement. Batting performance was defined as successful "hits" in the simulator and explicit awareness was measured by having subjects make judgments regarding the direction of the bat motion (up or down) when a tone was presented during the swing. Consistent with the hypothesis that complex movements benefit from less explicit control, Gray found that a significant positive correlation between number of hits and number of judgment errors. This correlation suggests that when subjects' explicit awareness of what the bat was doing was low subjects' implicit control of the bat was quite high, because they were doing much better on the task. In contrast, when performance was poor, subjects were more explicitly aware of the position of the bat. Because this finding is correlational, it is possible that skill-focused attention led to a decrement in performance, or that subjects were deliberately using skill focused attention to correct their poorly coordinated swing. Although the causality is unclear, poor performance was clearly associated with self-focused attention.

Furthermore, Gray (2004, Experiment 3) created a high-pressure situation by telling subjects that they would receive $20 if they were able to increase their batting performance by 15%. Increasing the pressure to perform led to fewer hits, but also fewer judgment errors about the motion of the swing, further suggesting that when the pressure to perform increases, attention becomes more self-focused, and this self-focused attention has the paradoxical effect of hurting performance.

Beilock, Carr, MacMahon, and Starkes (2002) conducted a similar study with experienced soccer players, requiring the players to dribble through a slalom-course of cones using either their dominant or nondominant foot in either a skill-focused condition or a distracting, secondary-task condition. In the skill focused condition, when a probe tone was presented, subjects were required to answer aloud whether the inside or outside of their foot was touching the ball at that time. In the dual-task condition, subjects had to monitor a stream of words and repeat aloud a target word when it was present in the stream. Although dribbling performance with the dominant foot was greater in the secondary-task condition, as would be predicted if explicit monitoring impairs performance, when subjects were using their nondominant foot, performance was better in the skill focused condition. This finding suggests that the relationship between attention and performance might indeed depend on skill-level.

The Focus of Attention

The relationship between anxiety, attention, and performance has led some researchers to suggest learning should be done as implicitly as possible (Masters, 1992, 2000), giving learners only information about the goal of the task and then allowing self-discovery of the appropriate movement. Although this may be a functional approach for some skills, such an extreme position quickly falls apart when more complex skills are considered. Imagine trying to throw the discus after being handed the 2.2 kg disc and simply being told to make it “go” as far as possible, or standing at the top of a black-diamond ski run and being told that you should just get to the bottom as fast as possible. Thus, the implicit learning data leaves us with an applied problem. Focusing attention on high-level effects is certainly more appropriate for experts than novices (e.g., Beilock et al., 2002), but focusing too much on the movement itself can be detrimental for novices as well as experts (Hodges & Lee, 1997; Wulf & Weigelt, 1997). This line of thinking led to an experiment by Wulf, Höβ, and Prinz (1998) that would become critically important in research on motor learning and control.

In that experiment, Wulf, Höβ, and Prinz (1998) manipulated attention not through distracting secondary tasks or high/low anxiety conditions, but through the verbal instructions given to subjects. Groups of novice subjects were given instructions about *how* a movement should be performed on a ski simulator (creating the largest amplitude and fastest oscillations they could), but one group of subjects was instructed to exert force on the platform with their outermost *foot* and focus on that foot (the *internal focus* group) whereas the other group of subjects was instructed to focus on the force they exerted on the outermost *wheels* of the platform (the *external focus* group). A third group of subjects served as a control group, who were only told to generate the largest and fastest oscillations possible. Over two days of training, the external focus group showed progressively better performance compared to the internal focus and control groups, and this advantage that was maintained even during retention testing on Day 3, when no explicit attentional instructions were given. The internal focus and control groups displayed the same rate of learning and level of performance during training and retention testing.

In their second experiment, Wulf, Höβ, and Prinz (1998) replicated the advantage of an external focus of attention in a dynamic balance task by having subjects stand on a stabilometer and try to keep the platform parallel to the floor. For the internal focus group, instructions were to focus on their feet and to try to keep them at the same height. For the external focus group, instructions were to focus on red markers on the stabilometer platform and to try to keep the markers at the same height. These markers were placed directly in front of a subject’s feet so the spatial difference between the internal and external foci was minimal, making the conceptual difference between the two conditions the salient difference. Furthermore, visual attention was controlled by requiring subjects to look straight ahead during the task, removing the confounding of visual attention. In the stabilometer experiment, there was again an advantage for the external focus of attention that emerged over practice and led to superior performance on a delayed retention test.

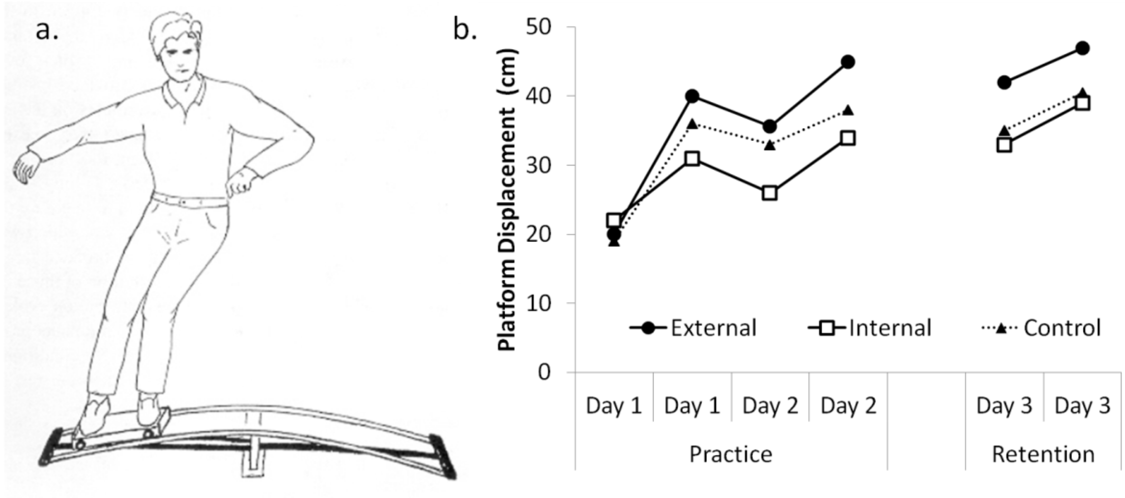

Figure 1. *(a) A schematic representation of the ski-simulator apparatus used by Wulf et al. (1998) in Experiment 1. (b) The results of training using the ski-simulator under different attentional focus conditions. Performance was measured as the amplitude of platform displacement (in cm) and is plotted as a function of session, day, and early versus late trials for that day. Adapted from Wulf et al. (1998).*

These early studies on attention (Hodges & Ford, 2000; Wulf & Weigelt, 1997; Wulf et al., 1998) led to an explosion of research on the effects of attention in motor learning and control. The range and theoretical implications of these studies will be reviewed next (for more detailed reviews see Wulf, 2007a, 2007b). This review should demonstrate that the advantages of an external focus of attention over and internal focus of attention have been shown in a wide range of tasks and with a wide variety of subject populations, but the review should also make clear that a number of serious questions remain. For instance, how does an external focus of attention confer an advantage to performance (i.e., what physiological changes mediate the attention—performance relationship)? Is the advantage of an external focus of attention visible immediately, or does this advantage emerge over time? Does the optimal focus of attention change over time and, if so, how? (This question could relate to a larger time scale, such as comparing attention in novices to experts, or on a smaller time scale, such as comparing attention during a training session to a subsequent test.)

In following sections, studies will first be reviewed by the type of task and type of subject population in order to show both the breadth of research on the focus of attention and the robustness of the effect. Second, current explanations of the effects of attentional focus in motor performance will be explained. These are the *constrained action hypothesis* (Wulf, 2007a; Wulf, McNevin, & Shea, 2001) and *explicit monitoring theory* (Beilock & Carr, 2001; which will be considered together with *re-investment theory*, Masters, 1992; Masters & Maxwell, 2008). Following these hypotheses, more recent research will be presented that moves beyond behavioral measures of performance (such as accuracy) to show that the focus of attention affects the quality of movement itself (e.g., neuromuscular coordination, metabolic cost, and kinematic variability). As will be discussed, these more recent data cannot be explained by either the constrained action hypothesis or explicit monitoring theory. This lack of explanatory power in current theories about the focus of attention is the motivation for the experiments in this dissertation, which will be detailed at the end of the chapter.

Previous Research on the Effects of Focus of Attention

Balance. Many of the previous experiments on the focus of attention have studied forms of balance. In all of these studies, an external focus of attention (broadly defined as attention directed to the effect of a movement on the environment) led to superior balance performance over an internal focus of attention (broadly defined as attention directed to the motion of the body itself). For instance, in studies on stabilometer platforms, an external focus of attention (to markers on the platform in front of the feet) leads to smaller amplitude and higher frequency platform deviations than an internal focus (on the feet themselves; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001). Increasing the spatial distance of the external focus can increase this effect (e.g., by placing markers farther away from the feet on the platform; McNevin, Shea, & Wulf, 2003). When exposed to both an internal and external focus of attention, subjects (on average) recognize their improved performance and will spontaneously adopt an external focus when given the choice in subsequent tests (Wulf, Shea, & Park, 2001). Furthermore, simply distracting learners from focusing internally is not equivalent to focusing externally. Subjects who train with an external focus of attention perform better on subsequent retention tests (when no focus instructions are given) relative to subjects who trained with a distracting secondary task, or subjects who trained with an internal focus (Wulf & McNevin, 2003).

Other studies have used compliant surfaces (rather than the rigid stabilometer platform) to study the maintenance of balance under different attentional focus conditions. Wulf, Töllner, and Shea (2007) showed that not only did an external focus lead to better performance than an internal focus, but the size of this effect also increased as a function of task difficulty (i.e., the external focus advantage was greater on a foam surface than a solid surface and was greater with a 1-legged stance than a 2-legged stance).

Wulf, Mercer, McNevin, and Guadagnoli (2004) had subjects stand on an inflatable rubber disk while holding a pole horizontally between their hands; creating a postural task (maintaining balance on the disk) and a suprapostural task (keeping the pole horizontal). The disk was placed on a force-plate to record center of pressure (COP) measurements for the magnitude of postural sway and the frequency of postural adjustments. Subjects completed four different attentional focus conditions: an external-postural focus (minimizing movement of the disk), an internal-postural focus (minimizing movement of the feet), an external-suprapostural focus (minimizing movement of the pole), and an internal-suprapostural focus (minimizing movement of the hands). Both external foci led to reduced postural sway compared either of the internal foci and the frequency of postural adjustments increased when subjects were focused on the postural task compared to focusing on the suprapostural task.

Finally, Vuillerme and Nafati (2007) studied the effects of attentional focus by having subjects stand on a solid force-platform. Subjects were asked to stand as immobile as possible on the force-platform under what the authors refer to as *control* and *attention* conditions. In the control condition, subjects were not given explicit instructions on how to direct their attention and were simply instructed to be as still as possible. In the attention condition, subjects were told "to deliberately focus their attention on their body's sway and to increase their active intervention into postural control (p. 193)". Using COP data from the force-platform, the authors calculated two important variables: the vertical projection of the center of gravity (COG; which is assumed to be the controlled variable in most postural tasks) and the difference between COP and COG (COP-COG; which approximates the stiffness of the legs, especially the ankle joint, in postural control). Although motion of COG was not significantly influenced by attention, consciously attending to posture led to increased amplitudes and frequencies of COP-COG. The authors interpreted this finding as attentional focus promoting the use of less automatic control processes, which severely degraded the efficiency of controlling posture during quiet standing, but not necessarily the effectiveness (as COG motion was no different between the two conditions).

A common finding in these studies of balance is that the effects of attention do not appear immediately, but develop as a function of practice, emerging late in training or during retention testing (McNevin et al., 2003; Wulf et al., 1998; Wulf & McNevin, 2003; Wulf, McNevin, &

Shea, 2001). This finding would suggest that focusing externally does not confer an immediate benefit to control of the movement, but instead confers a benefit to motor learning, ultimately optimizing control of the motion.

Golf. Wulf, Lauterbach, and Toole (1999) conducted the first experimental investigation of attentional focus effects on golf performance by having novice golfers practice a “pitch” (a short-distance, lofted shot in golf). Both groups were given instructions about the appropriate technique for the pitch shot, but the internal focus group subjects were instructed to focus on the motion of their arms, whereas the external focus group subjects were instructed to focus on the motion of the club. During the training session, subjects completed 80 trials under either internal or external focus conditions. During training, an external focus resulted in a greater overall level of accuracy than an internal focus. The following day, subjects returned for a retention test of 30 trials without explicit instructions on how to focus their attention. As with training, an external focus of attention led to significantly greater accuracy during retention.

Elaborating on this initial result, more recent studies have shown that the optimal focus of attention changes as function of experience; novices benefit from a more proximal (but not necessarily internal) focus of attention whereas experts benefit from a more distal focus of attention. Perkins-Ceccato, Passmore, and Lee (2003) compared internal and external foci in novice golfers and found that novices were more *precise*, but not necessarily more *accurate* with an internal focus of attention. The instructions used in this study were relatively vague however; subjects were told to focus on the form of the swing and adjust the force of the swing in the internal focus condition. Because there is considerable latitude in how this instruction could be interpreted (“from” could lead a subject to focus on either the posture or arms, which would be internal, or the motion of the club, which would be external), I think it is best to interpret the results of Perkins-Ceccato et al. as evidence that a proximal focus is beneficial for novices, not necessarily that an internal focus is beneficial. Other studies (Bell & Hardy, 2009; Wulf & Su, 2007) with more concrete instructions have shown that accuracy is improved by an external focus of attention for both experts and novices. However, experienced players benefit more from a distal-external focus (on the landing point of the ball) than on a proximal-external focus (on the motion of the club) whereas novices benefit from the proximal-external focus (Bell & Hardy, 2009). Thus, it seems appropriate to conclude that experts benefit from more distal foci, whereas novices benefit from more proximal foci, but not necessarily internal foci.

Basketball. Two experimental studies of basketball free-throw shooting have found an advantage for an external compared to an internal focus of attention (Al-Abood, Bennett, Hernandez, Ashford, & Davids, 2002; Zachry, Wulf, Mercer, & Bezodis, 2005). In the study by Al-Abood and colleagues, subjects saw a demonstration by an expert model accompanied by attentional focus instructions directed to either the model’s movements (internal) or the effect (external). The internally focused group who attended to the model’s movements showed no improvement from pre-test to post-test, whereas the externally focused group who attended to the effect of the movement improved significantly from pre-test to post-test. Zachry et al. came to a similar conclusion about the effects of attention on behavioral measures of performance (i.e., an external focus of attention led to improved accuracy), but also measured muscle activity through surface electromyography (sEMG) in the shooting arm. sEMG analysis revealed that not only did an external focus of attention lead to improved accuracy, but also subjects were doing so with reduced muscle activity. Thus, it would appear that an external focus of attention leads not only to more effective performance, but also to more efficient performance (because less energy was being expended to produce a superior outcome).

Darts. For dart throwing, Marchant, Clough, and Crawshaw (2007) found that verbal instructions inducing an external focus led to improved performance relative to an internal focus, but not to a control condition in which no explicit focus instructions were given. The general instruction given to all three groups of subjects was to aim for the bulls-eye of the dart-board and to be as accurate as possible, but subjects in the internal focus group were explicitly instructed to (a) feel the weight of the dart in their hand; (b) think about drawing the dart back to the ear; (c) feel the bend in the elbow; and (d) feel the dart as it left the finger tips. Subjects in the external focus groups were encouraged to: (a) focus on the center of the dart board; (b) slowly begin to expand upon perspectives of the dart board; (c) then refocus to the center of the dart board, expanding the center and making it as large as possible; and (d) toss the dart when so focused.

In contrast to these highly detailed instruction sets, Lohse, Healy, and Sherwood (2010) simply instructed subjects to focus on either the motion of their arm (internal) or the flight of the dart (external) and when they were off-target, they should correct this mistake by adjusting the motion of their arm/the flight of the dart. In all conditions subjects were instructed to visually focus on the bulls-eye and to try and be as accurate as possible. Similar to the findings of Marchant et al. (2007), an external focus of attention led to increased accuracy. Additionally, it was revealed that an external focus of attention led to reduced muscle recruitment through detailed sEMG analysis of the biceps brachii and the triceps muscle during the throwing motion (shown in Figure 2; similar to Zachry et al., 2005). Thus, this study provided further evidence that an external focus of attention improved movement efficiency as well as effectiveness. Importantly, Lohse et al. also used video analysis to study kinematic changes in the throwing motion as a result of attention. Compared to an internal focus of attention, an external focus of attention led to increased variability in the angle of the shoulder at the moment of release, suggesting changes in the coordination of the throw allowed improved accuracy with reduced muscle recruitment. This was the first study to do a detailed kinematic analysis of the quality of movement and, as will be discussed below, these kinematic effects have important theoretical implications for the focus of attention.

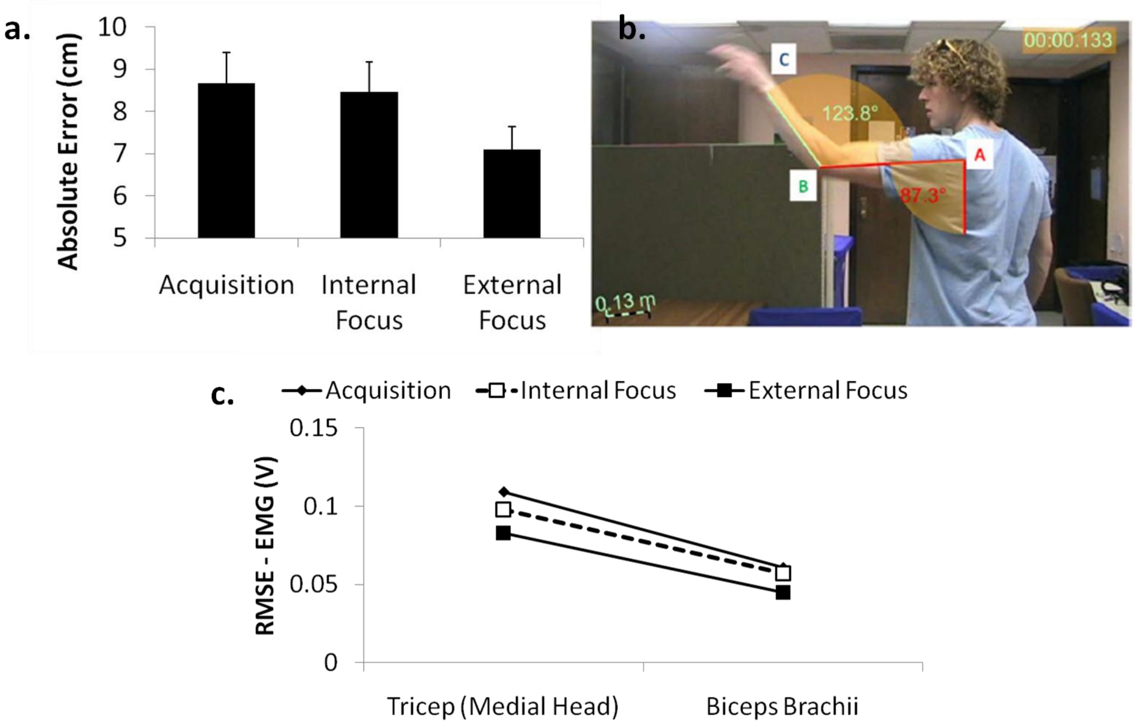

Figure 2. *A summary of the results from Lohse et al. (2010). (a) Absolute radial error in the dart throwing task as a function of phase. The external phase was significantly different from the acquisition and internal focus phases. (b) Example kinematic data for the moment of release on a single trial. (c) Surface EMG activity, shown as root-mean-square error (RMSE) of the raw wave-from, as a function of phase and muscle. Adapted from Lohse et al. (2010).*

Jumping ability. Wulf, Zachry, Granados, & Dufek (2007) showed that subjects jumped significantly higher in an external focus condition than in either an internal focus or control condition, with the latter two resulting in similar jump heights. Furthermore, the vertical displacement of the center of mass (COM) was greatest when participants were instructed to adopt an external focus. The vertical jump is an interesting test of attentional focus effects because the vertical jump requires the complex coordination of multiple limb segments in order to ensure maximum force production and thus maximum jump height. Wulf and Dufek (2009) found that not only was COM displacement increased with an external focus of attention, but also impulses and joint moments about the ankle, knee, and hip joints were significantly greater in the external focus condition, suggesting that coordination under external focus conditions was optimizing force production. Furthermore, an external focus of attention has been shown to create reduced sEMG activity in the leg musculature during a vertical jump (Wulf, Dufek, Lozano, & Pettigrew, 2010). Individual muscle onset times were identical between external and internal focus conditions, but magnitude of activation was greater with an internal focus. This increased sEMG activity (Wulf et al., 2010) with reduced joint torques (Wulf & Dufek, 2009) clearly demonstrates inefficient patterns of motion as a result of adopting an internal focus of attention (e.g., a higher level of cocontraction between agonist/antagonist muscles).

Similarly, broad-jump performance has also been found to be enhanced by an external focus relative to an internal focus (Porter, Ostrowski, Nolan, & Wu, 2010). A between-subject design was used in that study, and subjects in the internal focus group were instructed to focus on extending their knees as rapidly as possible, whereas externally focused subjects were asked to focus on jumping as far past the start line as possible. Focusing externally resulted in a broad jump significantly longer (10 cm on average) than jumping with an internal focus. These findings in both vertical jumping and broad jumping illustrate the generalizability of the external focus advantages for tasks requiring the production of maximum forces.

Force production. Other studies of force production have shown that focusing externally (on the object to be moved) improves the efficiency and accuracy of the force being produced. For instance, maximum force production in elbow flexion is improved by focusing externally on the bar being lifted compared to focusing internally on the muscles doing the actual work. In these cases, an external focus of attention increases peak joint torque at the elbow (Marchant, Grieg, & Scott, 2009), reduces activation of biceps and triceps muscles relative to an internal focus (Vance, Wulf, Töllner, McNevin, & Mercer, 2004), and also reduces muscle activation relative to an uninstructed control condition (Marchant, Greig, & Scott, 2008).

Studies of sub-maximal force production have come to similar conclusions; an external focus of attention leads to more accurate force production whether force is being produced with the feet (Lohse, 2012) or the tongue (Freedman, Maas, Caliguiri, Wulf, & Robin, 2007). Furthermore, the advantage of an external focus of attention was not found immediately, but emerged overtime during the training session (similar to the studies on balance mentioned earlier). Similarly, Lohse (2012) trained participants to produce either 25% or 50% of their *maximum voluntary contraction* (MVC) in a plantar flexion task. Participants trained under either external (focusing on the force platform) or internal focus (focusing on the agonist muscle) conditions. Although both groups had equal accuracy in early trials, by the end of training (60 trials), the external focus group was significantly more accurate than the internal focus group. One week later, both groups returned to the laboratory for retention and transfer testing without any instructions on how to focus their attention. Not only did the external focus subjects remain significantly more accurate on the retention test, these subjects were significantly more accurate than the internal focus group on the transfer test, suggesting that an external focus of attention improved participants' ability to re-parameterize the movement to remain accurate at new percentages of their MVC.

Movement speed. Totsika and Wulf (2003) conducted an experiment in which they trained subjects to ride a Pedalo, an apparatus that consists of two small platforms (one for each foot) between sets of wheels that moves by alternately pushing the upper platform forward and downwards (similar to a bicycle), down a straight 7-m track. External training resulted in increased movement speed relative to instructing them to focus on pushing their feet forward (internal focus), but in contrast to previous studies, this effect was consistent both early and late in the training session. The advantage of an external focus was observed during the practice phase and also on transfer tests, which included requirements to perform the task under time pressure, to ride backward with time pressure, and to simultaneously count backward by 3s (transfer tests were conducted 1 day after the training session).

Porter, Nolan, Ostrowski, and Wulf, (2010) found a similar advantage for running performance in an “L-run”, an agility test with two 5-m segments joined at a 90° angle. Subjects were required to start at a cone at one end of the L, sprint to the middle, turn, weave around the cone at the other end, and then sprint back to the start. As such, this task requires considerable coordination to accelerate/decelerate in the turns and force to be produced in the straight-aways. In all conditions, subjects were instructed to “run through the course as quickly as you can with maximum effort.” External focus instructions, which directed their attention towards accelerating between the cones and pushing off the ground in the turns, significantly decreased running time relative to both internal focus and control conditions. In the internal focus condition, a subject’s attention was directed towards moving his or her legs as quickly as possible and planting his or her foot firmly in the turns.

Movement speed has also been studied in swimming in two different studies, one focused on novice/intermediate swimmers (Freudenheim, Wulf, Madureira, Corrêa, Araras, & Corrêa, 2010) and one focusing on elite swimmers (Stoate & Wulf, 2011). In both of these studies, an external focus of attention led to increase movement speed in the front-crawl (or ‘freestyle’ swimming stroke). Giving swimmers external focus instructions related to the arm stroke in crawl swimming (e.g., “pushing the water back”) was more effective than internal focus instructions that directed attention towards the swimmer’s arms (e.g., “pulling your hands back”). Interestingly however, the relationship between the control condition and the external focus condition changed between these two studies. Intermediate swimmers performed similarly in the internal focus and control conditions (Freudenheim et al., 2010), whereas in experts the external focus and control conditions resulted in similar swim times (Stoate & Wulf, 2011). These results suggest that experts had already discovered the value of an external focus and adopted one on demand or habitually (e.g., Gray, 2004). Self-report data from the Stoate and Wulf study indicated that experts’ focus in the control condition differed between subjects; some swimmers reported more of an internal focus in the control condition (e.g., hip rotation, spinning my arms, high elbow), others reported focusing on the overall outcome (e.g., speed, tempo, going fast, swimming hard) or “nothing”. Interestingly, those who adopted an internal focus in the control condition had slower swim times (13.55 s) than those who did not (13.02 s). These group differences in the control condition reinforce the idea that an internal focus disrupts automaticity and results in poorer performance.

Endurance. Marchant, Greig, Bullough, and Hitchen (2011) recently completed the first study to explicitly test the effect of attention on endurance and specifically on muscular resistance to fatigue. In their study, Marchant et al. measured the number of repetitions subjects took to failure in three different weight lifting exercises: the Smith Machine bench press (in which an external apparatus constrains motion, allowing vertical movement only), a free weight bench press (in which movement is unconstrained), and a free weight back-squat (a more complex movement in which movement is also unconstrained). The load in all of these exercises was fixed to be approximately 75% of the subject’s maximum load. An external focus of attention (on the bar and weight being lifted) led to a significantly greater number of repetitions before failure than an internal focus (on the muscles doing the work) in all three exercises. Intriguingly, the effect size of the attentional focus manipulation increased as the movements became more complex; the effect size was smallest for the Smith machine bench press and largest for the back squat.

Attentional focus effects in clinical subject populations. Clearly the effects of attentional focus are robust across a wide range of tasks, but these effects are also seen in studies of subjects with clinical motor impairments. For instance, the advantage of focusing externally also holds in studies of motor performance following stroke, specifically in the speed of reaching movements (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002). An external focus also improves postural stability in Parkinson’s disease patients (Landers et al., 2005; Wulf, Landers, Lewthwaite, & Töllner, 2009) and in patients with musculoskeletal injuries (in this case, ankle sprains; Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007).

Current Theories of the Focus of Attention

One explanation of attentional focus effects is *explicit monitoring theory* which comes from research on implicit learning and choking under pressure (also referred to as the conscious processing hypothesis). Explicit monitoring theory (Beilock & Carr, 2001; Beilock et al., 2002; Masters, 1992) posits that explicitly attending to movement disrupts motion by unnecessarily engaging cognitive control. This hypothesis suggests that well-learned, or proceduralized, skills do not require cognitive control and largely operate outside of working memory (Allport, Antonis, & Reynolds, 1972; Fitts & Posner, 1967; Keele & Summer, 1976; Kimble & Perlmuter, 1970). Thus, when explicit monitoring is increased by attending to movement (as in an internal focus of attention), skilled performance is disintegrated into a sequence of smaller, independent units, similar to how the skill was represented early in learning (Koedijker, Oudejans, & Beek, 2007; Masters & Maxwell, 2008), thus slowing down processing and increasing the likelihood of movement errors (the transition between component movements introduces more opportunities for errors that are not present in an integrated control structure). In this way, explicit monitoring theories predict that internally-directed attention and conscious control may be beneficial for novice performers in the initial stages of skill learning, but this internal focus of attention becomes counterproductive as learning continues and execution becomes more "automatic".

An alternative, perhaps dominant, explanation in research on an internal focus of attention leading to impaired performance is the *constrained action hypothesis* (Wulf, 2007b; Wulf et al., 2001), which posits that an internal focus induces a top-down constraint on otherwise implicit motor behaviors. This intervention of explicit control disrupts automatic mechanisms in guiding motor behavior, ultimately slowing processing and hurting performance. In support of the constrained action hypothesis, Wulf (2007b) cites three major findings: (a) an internal focus of attention reduces a subject's attentional capacity relative to an external focus (Wulf, McNevin, & Shea, 2001), (b) an external focus of attention leads to increased frequency of movement adjustments (suggesting faster and more efficient control mechanisms; McNevin et al., 2003; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001), and (c) actions performed with an external focus of attention generally show reduced muscular activity (Lohse et al., 2010, Marchant et al., 2008, Vance et al., 2004; Wulf et al., 2010; Zachry et al., 2005). However, as Wulf (2007b) points out, explicit monitoring theory is not necessarily in opposition to the constrained action hypothesis because explicit monitoring does not necessarily imply an internal focus of attention. Explicit monitoring simply means devoting more attention to the action, but this additional attention could theoretically be paid to the outcome or to the movement itself (Wulf, 2007b).

The constrained action hypothesis has been criticized, however, for not being integrated with larger theories of motor control (Oudejans, Koedijker, & Beek, 2007) and because the precise mechanisms that constrain action need to be better specified in order to make the hypothesis testable (Raab, 2007). For instance, in its current form, the constrained action hypothesis does not make specific predictions about the details of movement (e.g., the kinematics or dynamics of movement) under internal versus external focus conditions, nor does the constrained action hypothesis directly predict the electrophysiological findings that an external focus of attention leads to more efficient muscle recruitment. Although Wulf (2007b) cites efficient muscle recruitment as evidence for the constrained action hypothesis, these findings are only *in line* with the hypothesis that an internal focus disrupts the automatic control of movement and *not* a direct prediction of the hypothesis. Thus, because the constrained action hypothesis is not theoretically equipped to predict physiological changes as a result of shifting attention, it is agnostic about how attention operates at the neuromechanical level.

One reason the constrained action hypothesis does not address biomechanical or energetic details is that the majority of studies on focus of attention have been limited to the effects of attention on motor outcomes (e.g., accuracy, balance, speed), and less work has been done to explore the effects of attention on the kinematic and dynamic properties of movement itself. More recent research has begun to move beyond behavioral measures of performance to study the effects of attention on the quality of movement. This recent work (reviewed in the next section) suggests that a new theory on the role of attention in motor control is needed.

Beyond Behavioral Measures of Performance

sEMG data. Using sEMG to study muscle recruitment patterns under different attentional foci has been incredibly informative for research on the focus of attention, because it provides the first data that physiological changes mediate the attention—performance relationship. In general, these studies have been very consistent in their findings that an external focus of attention leads to reduced muscular activity compared to an internal focus of attention, often while simultaneously improving the outcome (Lohse et al., 2010; Marchant et al., 2008, Vance et al., 2004; Wulf et al., 2010; Zachry et al., 2005).

This effect of reduced muscular activity coincident to improve performance parallels what is typically seen in highly skilled performers. There is evidence from studies using a variety of methods that, with continued practice, movement outcome (e.g., weight lifted) is enhanced, and at the same time movements are produced more efficiently (e.g., with less neuromuscular activity). Using magnetic resonance imaging, for example, researchers have demonstrated increased efficiency in muscle recruitment as a function of practice (e.g., Conley et al., 1997; Green & Wilson, 2000; Ploutz et al., 1994). Furthermore, electromyographic recordings during studies of aimed reaching movements suggest that cocontraction of muscle pairs (the simultaneous activation of antagonist muscles around a joint) decreases as a function of practice (Gribble, Mullin, Cothros, & Mattar, 2003; Ostry et al., 2002). Thus, reduced sEMG activity with external focus relative to internal focus or control conditions suggests that the learning process is facilitated by an external focus. (That is, an external focus serves as a “short-cut” to more expert-like behavior in terms of both movement quality and effect).

Energetic data. Two recent studies (Schücker, Hagemann, Strauss, & Völker; 2009; Schücker, Buttfield, Strauss, Hagemann, & Focke, 2011) have demonstrated that the focus of attention during running can significantly affect metabolic efficiency as well, possibly as a result of the effects of attention on muscle recruitment. Schücker et al. (2009) reasoned that if an external focus of attention led to a savings in muscle recruitment in discrete tasks like jumping or dart throwing, these savings might scale up to improved metabolic efficiency in a continuous task like treadmill running. To test this prediction, the authors had trained runners run at a consistent pace on a treadmill under three different attentional focus conditions while measuring subjects' oxygen consumption. Both of the internal focus conditions, focusing on breathing (a non-motoric internal focus) and focusing on stride length (a motoric internal focus), led to increased oxygen consumption compared to an external focus (focusing on the optic flow of the simulated environment).

In their follow-up study, Schücker et al. (2011) sought to understand what motor control mechanisms could explain attentional focus differences in oxygen consumption during running. Again, runners had to focus their attention on three different aspects of the run while kinematics and surface electromyographic activity were measured. Subjects ran on a treadmill at a constant pace across conditions. Analysis of the kinematic data revealed a decrease in stride rate and an increase in vertical oscillation of the sacrum when focusing on the running movement compared to focusing on breathing or the simulated running environment. These changes in the subjects' running mechanics equate to a less efficient running style, which means that an internal focus on the running movement shifted these trained runners away from their optimal (or at least better) running mechanics. Analysis of the electromyographic data was non-conclusive, but is confounded by the changes in the running mechanics (i.e., because the running mechanics changed across attentional focus conditions, comparing the muscle activity between conditions is essentially comparing the muscle activity of different movements). Thus, it is not entirely surprising that the sEMG data from Schücker et al. (2011) did not replicate the pattern of reduced muscle recruitment with an external focus of attention.

Kinematic data. Perhaps most problematic for the constrained action hypothesis to explain in its current form is the finding of increased kinematic variability with an external focus of attention coincident to improved performance (Lohse et al., 2010). In their study of dart-throwing, Lohse et al. found that an external focus of attention led to significantly greater variability in the shoulder angle at the moment of release, lead to significantly reduced sEMG activity in the triceps muscle of the throwing arm, and lead to significantly improved accuracy (as measured by radial error from the bulls-eye). Increased variability during an external focus of attention would be similar to ‘‘functional variability” that is characteristic of expert performance (Lee, Lishman, & Thompson, 1982; Müller & Loosch, 1999; Voigt, 1933). Studies of functional variability demonstrate that variation in the result, or movement outcome, is considerably smaller than the variability of its components. This anisotropic difference in motor variability suggests that the motor system preserves the planned outcome or effect, while allowing variation in redundant dimensions of the movement (Bernstein, 1967). In their review, Wulf and Prinz (2001) also suggested that adopting an external focus of attention may facilitate compensatory variability during movement to preserve the movement effect, whereas focusing on the movements themselves may reduce movement variability but at the expense of the movement outcome.

Current theories of attention in motor control do not directly address these findings of changes in movement variability, muscle recruitment, or metabolic cost, and thus they cannot explain how such effects might mediate the influence of attention on performance. Therefore, the specific aim of this dissertation was to develop a more mechanistic theory of attention in complex motor tasks that could explain physiological changes at the neuromuscular level and, furthermore, that these changes would scale up to explain behavior changes in performance.

In order to achieve this goal, research on the focus of attention needs to be integrated with larger theories of motor control and learning (especially with optimal control theories of motor learning, which make specific predictions about kinematic variability and how patterns of variability relate to the structure of motor control). The general proposal of this dissertation (explained in detail below) is that attention regulates motor control by changing which dimensions of the movement that are controlled—goal dimensions with an external focus or bodily dimensions with an internal focus. To understand how attention can shift control of the motor system and thereby improve or impair performance, research on optimality in motor control is reviewed in the next section. Following this review, the chapter will conclude with a detailed explanation of a new hypothesis for the role of attention in motor control and an explanation of the four experiments designed to test this hypothesis (the results of which make up Chapters 2-5 of this dissertation).

Optimality in Motor Control – Variability and Expertise

In some classical conceptions of motor control, movement variability is treated exclusively as a source of error. In such theories, variability arises from a lack of calibration in the motor system's ability to predict the appropriate parameters for a movement (Schmidt, 2003; Schmidt & Lee, 2005). In most of these theories however, variability is only measured in the movement outcome, whereas studies that focus on movement quality find growing evidence that the trial-to-trial variation (or cycle-to-cycle variation in continuous tasks) is not merely a function of a noisy motor system, but is actually a product of the motor system compensating for an error in one parameter (e.g., a specific shoulder angle) with a coordinated change in another parameter/s (e.g., adjustments of the elbow and wrist). Thus, studying movement variability offers insight into the control and coordination of a motor act (Wolpert & Ghahramani, 2000). This principle of compensatory variability stems in part from signal dependent noise in the motor system. That is, the larger the magnitude of a motor command, the more variable it is (Harris & Wolpert, 1998; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Todorov, 2002). This Gaussian noise in individual parameters prevents exact movements being repeated from trial to trial. Thus, the motor system needs to learn the functional relationships between movement parameters in order to make compensatory adjustments to accurately control the movement outcome.

A classic example of this principle in motor control research comes from motion analysis of a hammer swings (Bernstein, 1967), in which the contact point of the hammer is very consistent, but the motion paths of shoulder and elbow are variable. Such patterns have been observed in a wide range of tasks, including reaching (Haggard, Hutchinson, & Stein, 1995), grasping (Cole & Abbs, 1986), pointing (Tseng, Scholz, & Schöner, 2002), writing (Wright, 1990), postural control (Scholz & Schöner, 1999), and even skiing (Vereijken, van Emmerick, Whiting, & Newell, 1992). Importantly, this anisotropic variability is more pronounced in the movement of experts than novices (Schorer et al., 2007; Vereijken et al., 1992; Wilson, Simpson, van Emmerick, & Hamill, 2008). By anisotropic, I mean that the distribution of variability is directionally dependent (as opposed to isotropic, in which variability is equivalent in all directions). In the case of expert movement, this anisotropy means that variation in goal-relevant dimensions is reduced compared to other dimensions in the action space.

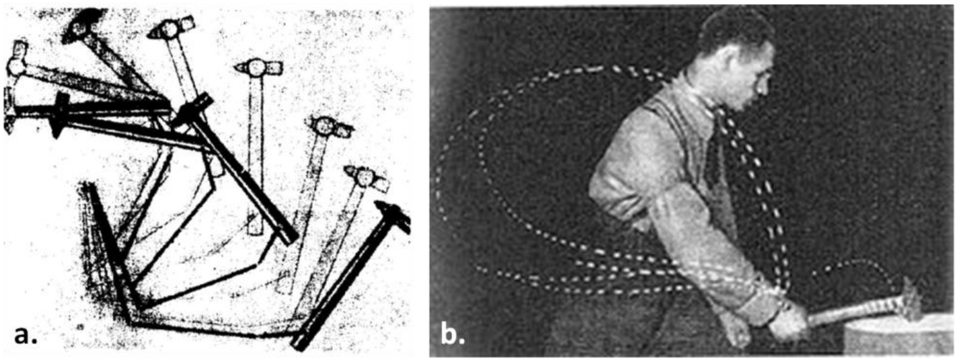

Figure 3. *Early studies of variability in human movement science showed that elemental parameters, such as the motion paths of the wrist, elbow, and shoulder, displayed greater variability than the final contact point of the hammer, suggesting anisotropic and goal-oriented control in expert movements. Figures adapted from Bernstein (1967).*

A prominent theory that models motor control using anisotropic variability is the *uncontrolled manifold* (UCM) hypothesis. The UCM analyzes movement variability along goal-relevant and irrelevant dimensions in order to understand the coordination of movement. Essential to this hypothesis is the fact that the motor system has many more degrees of freedom than it needs to complete any given movement and thus is said to have *redundancy*. Redundancy refers specifically to having more elements than necessary to solve a task, resulting in the existence of multiple possible solutions for a given motor problem (Todorov, 2004).

Latash, Scholz, and Schöner (2002) described the UCM hypothesis to address this problem of motor redundancy. According to this hypothesis, an UCM is a sub-space (manifold) within a larger multi-dimensional space (with different dimensions corresponding to the different degrees of freedom in the action). Often, a goal-relevant dimension emerges orthogonal to bodily dimensions in the action space (shown in Figure 4, below). Thus, when a multi-dimensional system changes its state within a UCM for a particular performance variable (e.g., total force produced by a set of fingers), this performance variable is kept at a constant value while the values of the individual dimensions change. As long as the system does not leave the UCM, the hierarchically higher controller (e.g., central nervous system) does not need to interfere and, in that sense, elemental dimensions (e.g., the force of individual fingers in the set) do not need to be controlled as long as the system remains within the manifold. If the system leaves the UCM and shows an appreciable error in the performance variable, the controller will intervene to correct the movement (Latash, 2008). The UCM approach has been applied to several motor tasks such as maintaining quiet standing, finger force production, bimanual pointing, sit-to-stand movements, and pistol shooting (Domkin, Laczko, Jaric, Johansson, & Latash, 2002; Latash, Scholz, Danion, & Schöner, 2001; Scholz, Kang, Patterson, & Latash, 2003). Applying the UCM in this way allows researchers to uncover coordination strategies of apparently redundant motor systems and uncover the functional purposes that variability plays in those motor tasks.

An example of the UCM is shown in Figure 4. This figure depicts the action space of a hypothetical task in which the goal is to produce a certain total force (say, 35 N) with two fingers (see Todorov & Jordan, 2002, for a computational analysis of an isomorphic task). The individual contributions of the fingers can vary (e.g., one finger can produce 10 N and the other 25 N), provided that variation in each finger is accommodated by an adjustment in the other. Thus, the goal-relevant dimension is the sum of the two forces, corresponding to the positive diagonal in action space, whereas the difference between the forces (the negative diagonal) is an irrelevant, or redundant, dimension in the action space.

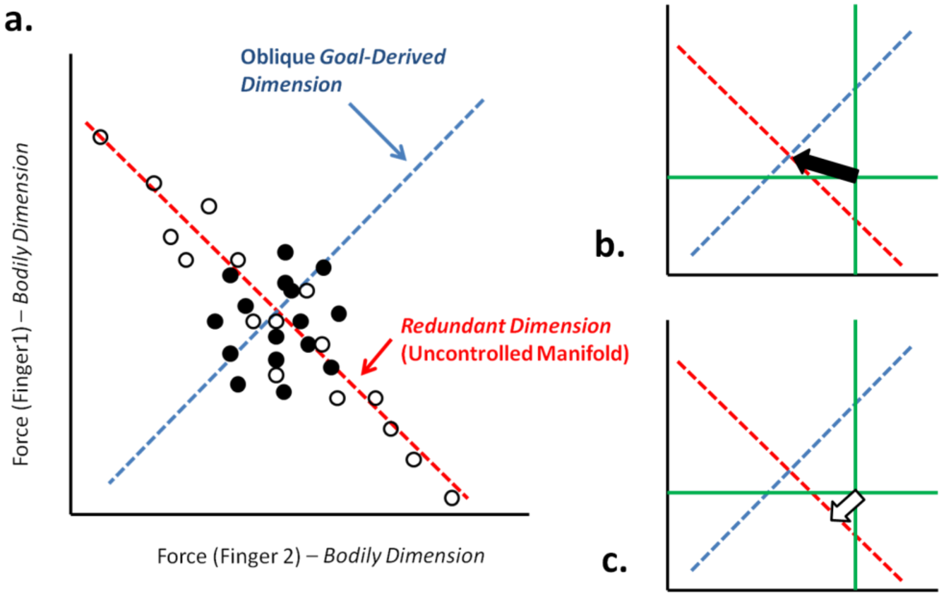

Figure 4*. (a) Hypothetical data points showing results of two alternative control structures for producing force with two fingers. The task goal is defined only by the sum of the two forces. Open circles correspond to anisotropic, goal-oriented control, showing how compensatory variability (in the bodily dimensions) can reduce variability in the goal-relevant dimension, as postulated by an optimal control framework. Solid circles correspond to isotropic, global suppression of movement variability that ultimately leads to increased variability in the goal dimension. (b) Shows an individual trial in which an error has been made (the the total of the two finger forces represented by the intersection of the green lines) and error is being controlled isotropically. (c) Shows an individual trial in which an error has been made (the the total of the two finger forces represented by the intersection of the green lines) and error is being controlled anisotropically, returning the total force to the nearest point on the UCM.*

Optimal control theory predicts any perturbation in one finger to be corrected by both fingers (e.g., a deviation of +2 N in one finger induces corrections of -1 N in both fingers), to bring the system back to the nearest point on the uncontrolled manifold (Figure 4.c; see Diedrichsen, 2007, for empirical confirmation of this prediction). That is, any error in the goal dimension is corrected using the minimal necessary control signals. The result of this control strategy is that the distribution of forces across trials exhibits less variability along the goal-relevant than the irrelevant dimension (illustrated by the open circles in Figure 4.a). An alternative strategy is to control each finger separately (e.g., trying to make each finger produce

17.5 N every time, Figure 4.b), which would decrease their individual variabilities, but would increase variability in the goal dimension (filled circles in Figure 4.a). Thus, optimal, goal-oriented control predicts anisotropic error distributions, characterized by correlations among bodily dimensions that reduce variability in the goal dimension.

A good demonstration of this type of goal-oriented, anisotropic control comes from studies comparing the variability—performance relationship in experts and novices. Somewhat paradoxically, experts can actually show increased trial-by-trial variation in movement patterns while simultaneously showing superior performance in the movement outcome. This phenomenon has been referred to as functional variability, to capture the idea that variability is somehow enabling improved performance (Müller & Loosch, 1999).

For instance, Schorer, Baker, Fath, and Jaitner (2007) explored kinematic variability in the throwing motion of handball players in three dimensions across a range of skill levels (from beginner to national-team level). Cluster analysis revealed that novices and intermediate players had only two stable movement patterns that principally differed only according to the direction of the throw (e.g., one stereotyped pattern for a shot to the high left and another to the low right). In contrast, experts' throwing motions clustered into roughly four different patterns, none of which could be assigned to a specific throwing direction. This absence of correspondence between throwing direction and movement pattern suggests that experts use varying movement patterns to produce similar flight trajectories. This finding suggests that experts have learned "multiple correct solutions" (Todorov, 2004), exploiting redundant degrees of freedom to reliably produce a specific shot with variable throwing mechanics.

One explanation of these findings of functional variability is that experts control variation primarily in goal-relevant dimensions of the movement, while allowing redundant dimensions to vary (i.e., increased variability in dimensions of the movement that do not affect the outcome). Suppressing error in task-relevant dimensions (such as the flight path of a ball), while allowing variation in redundant dimensions (such as the specific joint angles of the throwing arm) can lead to increased variability of individual bodily dimensions while at the same time reducing variability in the outcome. The result of this control strategy is the functional variability observed in human movement. However, from this perspective, the term "functional variability" is something of a misnomer. The strategy of selectively controlling goal-relevant aspects of the movement produces both increased variability in individual movement parameters and improved performance, but the variability itself is not the cause of the performance improvement. Furthermore, variability in goal-relevant dimensions will always impair performance. For variability to be functional, movement parameters cannot vary randomly, but must interact with and compensate for each other in a way that reduces variability in the outcome (i.e., goal-relevant dimensions of the action space; Lee, Lishman, & Thomson, 1982; Müller & Loosch, 1999; Schorer et al., 2007; Voigt, 1933; Wilson et al., 2008).

This reasoning leads to the prediction that in findings of functional variability, in either expertise studies or in studies on focus of attention (e.g., Lohse et al., 2010), the increased variability resides only in redundant dimensions, whereas variability in the goal dimension is actually reduced. Because the goal generally defines a dimension in action space that is oblique to individual bodily dimensions (i.e., the outcome depends on the combination of many effectors; see Figure 4 above), assessing variability in individual bodily dimensions may not reveal the full picture.

The strength of integrating optimal control theory with studies of attention is that optimal control theory explains how trial-by-trial variability in the details of movement can coexist alongside reliable, reproducible movement outcomes. Central to this approach is the assumption that the motor system is inherently noisy, so that exact movement patterns are not reproducible (Wolpert & Ghahramani, 2000). Thus, the motor system works to minimize expected error in the face of this noise. In cases of closed-loop control (as opposed to ballistic movement), the brain can adapt control signals in response to perturbations during the course of the movement, thus reducing final error. This is the critical link between optimal control theory and research on the focus of attention. The constraint action hypothesis, in its current form, posits that an internal focus of attention exerts a top-down constraint on the motor system, but does not specify what this constraint is. Given that an external focus of attention increases kinematic variability (Lohse et al., 2010), it is possible that attention shapes the control structure of the motor system. When attention is focused externally, implicit control mechanisms work to reduce error in the attended goal dimension by allowing compensatory variation in bodily dimensions. Conversely, when attention is directed internally, the coordination of the movement is controlled more externally, creating competition with compensatory implicit mechanisms and leading to a decrement in performance. The idea that attention has a regulatory function in the coordination of movement constitutes a very specific and testable reformulation of the constrained action hypothesis.

A New Hypothesis on the Role of Attention in Motor Control

Although there is considerable evidence that the focus of attention can improve or impair motor performance, current models of motor control do not include cognitive variables like attention and current hypotheses about the focus of attention are not well integrated with models of motor control. Thus, there is a clear need for a specific hypothesis about the role of attention in motor control. The principles of optimal control theory reviewed above, together with the effects of attention on variability, lead to a natural proposal that attention plays a regulatory role in the coordination of voluntary movement. Specifically, we propose that attention contributes to determining the control rule implemented by the motor system. This control rule does not necessarily correspond to the nominal, objective goal of the task. Instead, cognitive factors intervene to determine the effective, subjective goal of the individual. Thus, when attention is focused externally, on the objective task goal, the motor system works to optimize that goal. Variation along the goal dimension is thus minimized, whereas redundant dimensions are less controlled to allow functional variation. The relationships between bodily dimensions in the action space are likely learned through physical experience or at low levels may even be determined by neural synergies (Latash et al., 2007; Shim, Latash, & Zatsiorsky, 2003). This predicted pattern of variability is consistent with the predictions of optimal control theory, under the assumption that the control rule aligns with the focus of attention.

Conversely, when attention is focused internally on aspects of the movement such as joint angles or muscle tensions, the motor system treats those bodily dimensions as the goal, and it minimizes their variability even at a cost to objective performance. From the perspective of the UCM hypothesis, attention can be viewed as helping to determine which variables the motor system treats as task-relevant and which it treats as irrelevant or redundant. To test this hypothesis, we ran four experiments (Chapters 2-5 of this dissertation) that explored the effects of attention at fundamental levels of motor control (i.e., isometric force production) and in the performance of a more complex motor skill (i.e., novice subjects learning to throw darts accurately).

General Research Design and Methods

Hypothesis 1: Attention changes the control structure of the motor system.

If attention shapes the control structure of the motor system, there should be significant changes in the patterns of kinematic variability. An external focus of attention should lead to more anisotropic variation because error is being controlled in a goal-relevant dimension orthogonal to the elemental dimensions in the action space. Thus, this theory would predict that an external focus of attention will lead to improved performance (because error in goal-relevant dimensions is being reduced) while variation in redundant dimensions will increase (e.g., in the angle of shoulder and elbow), but importantly the co-variation between these redundant dimensions (or, at least a subset of these dimensions) should increase as well. Variation in elemental dimensions without increased co-variation would not be compensatory variation that helps achieve the task goal, but would instead be independent variability that is characteristic of an unskilled, uncoordinated movement.

This hypothesis is tested directly in **Chapter 4**. In this experiment, subjects were brought into the laboratory to throw darts in multiple training and testing sessions across a 2-week interval. During testing sessions, subjects threw darts under a range of internal and external foci while the motion of their throwing arm was recorded for later analysis. A number of kinematic variables were extracted from the video data so that the variability of these elemental dimensions could be analyzed.

However, because kinematics follow kinetics, it is important to understand how attention affects the recruitment of muscles and the generation of forces that underlie these kinematic effects. Thus, in Chapters 2 and 3, electrophysiological changes during isometric force production were studied as a function of attention. In **Chapter 2** (published as Lohse, Sherwood,

& Healy, 2011), subjects produced sub-maximal forces in an isometric plantar flexion task using their dominant leg. Subjects were instructed to produce 30 of their maximum voluntary contraction (30 %MVC) as accurately as possible, receiving verbal feedback on their accuracy from the experimenter after every trial. The focus of attention was manipulated within-subjects so that in counterbalanced phases subjects were instructed to focus either internally on the agonist muscle of their calf (in this case the soleus muscle of triceps surae) or externally on the force plate they were pressing against. During these contractions, sEMG was recorded from the soleus (agonist muscle) and tibialis anterior (antagonist muscle) and analyzed for changes in sEMG amplitude and the power spectral density of the sEMG waveform as a function of attention.

Chapter 3 used a similar task (isometric plantar flexion) while sEMG recordings were taken from soleus (agonist), gastrocnemius (syngerist), and the tibialis anterior (antagonist) of the dominant leg. In the first part of Chapter 3, subjects completed a task identical to Chapter 2, trying to produce force as accurately as possible, but at 30, 60, and 100 %MVCs. In the second part of Chapter 3, subjects completed fatiguing trials of much longer durations at 30, 60, and 100 %MVCs. The 30 and 60 %MVC trials were held for a 60-second duration while force was kept within +/- 5% of the target force with verbal feedback from the experimenter. The 100 %MVC trials were maintained until voluntary exhaustion and maximum forces could no longer be maintained (i.e., until *failure*). (Failure in this case was a drop below 95 %MVC of more than 1-s, or the third drop below 95 %MVC regardless of duration.) Due to the long nature of these trials, sEMG amplitude and power spectral density were analyzed as a function of attention after the data had been binned into deciles for each subject on each trial. The time to failure and ratings of perceived exertion were also calculated on the 100 %MVC trials to get both an objective and subjective measure of fatigue.

Hypothesis 2: The focus of attention affects performance, but not learning.

Previous work on the focus of attention suggests that the optimal focus of attention during *performance* changes as a function of expertise; novices benefit from a more proximal focus, where as experts benefit from a more distal focus (Bell & Hardy, 2009; Wulf & Su, 2007). Thus, the optimal focus appears shift more externally as a skill is learned, but some researchers have suggested that attention can have significant effects on *learning* itself, because the advantage of an external focus only emerges late in training (McNevin et al., 2003; Wulf et al., 1998; Wulf & McNevin, 2003; Wulf, McNevin, & Shea, 200) or on subsequent retention and transfer tests (Lohse, 2012; Totsika & Wulf, 2003). Under this reasoning, adopting an external focus of attention during training expedites the learning process in addition to improving performance.

There is often a great deal of difficulty, however, in effects on performance from true effects on learning. This problem largely occurs because learning is not directly measurable, instead being inferred from changes in performance over time. Thus, to confirm an effect on learning, experimenters must be certain that factors other than learning have not influenced the performance being measured or be able to adequately control for these factors. For studies on the FOA, this problem arises because if subjects are adopting the same focus during testing as they are during training, then it is not clear whether subsequent improvement is attributable to the focus used previously or the focus during performance (a limitation acknowledged by Wulf, 2007b). To date, most studies of the focus of attention have not controlled for the focus adopted during testing, preferring instead to allow subjects to self-select how their attention is directed.

As Lohse (2012) noted however, there is a strong correlation between the focus that subjects train with and the focus adopted during testing. This correlation between training and testing focus creates a confounding for interpreting any benefits of attentional focus to learning.

Thus, **Chapter 5** used dart-throwing task was used in which novice subjects were brought into the lab and trained to throw darts under different attentional focus conditions before retention and transfer testing. The unique aspect of Chapter 5 was that attentional focus was manipulated during retention and transfer tests. Again, previous work on the effects of attentional for learning have used retention and transfer tests where the focus of attention is not manipulated by the experimenter (that is, no explicit focusing instructions or feedback are given by the experimenter; Lohse, 2012; Maddox et al., 2000, Shea & Wulf, 1999; Wulf et al., 2000; Wulf, Shea, & Park, 2001), thus creating a confounding between training focus and testing focus; the advantage found during retention and transfer testing could be attributable to the focus adopted during training or to the re-investment of this focus during testing.

To resolve this confounding, in Chapter 5, subjects trained under either external or internal focus conditions in the dart throwing task and then received either identical or opposite attentional focus instructions during delayed retention and transfer testing. Half of the subjects retained the training focus (groups EE and II), whereas half switched to the opposite focus during the testing session (groups EI and IE). Using a cross-over design, the effects of attention on the learning process could be more accurately measured. If an external focus of attention improves learning beyond improving performance, the prediction would be that subjects who trained with an external focus of attention would do better during the testing session regardless of the focus they adopted during the testing session (EE and EI do better than IE or II). Conversely, if attention affects performance more than it affects learning of a motor skill, the prediction would be that the focus adopted during training would matter very little during testing and the focus adopted during testing would have a much larger effect (EE and IE do better than EI or II).

Furthermore, in Chapter 5 we were also interested in assessing how subjects were able to adapt internal models of the dart throwing task by manipulating the dynamics of the throwing arm (see Kawato & Wolpert, 1998; Wolpert et al., 2001). In order to change the dynamics of the throwing arm, a 1.0 kg weight was add to the forearm (below the wrist) at different points in the experiment. Functionally, adding this weight changes a subject's level of expertise because the motor system must now adapt to these new dynamics. For half of the subjects, training and retention testing took place without a weight being added to the throwing arm, and then the weight was added during the transfer test. For the other half of subjects, the weight was added immediately for the training session, remained on the for the retention test, and was only removed for the transfer test. The introduction and removal of this additional weight allows us to test the potential effects of attention on updating a subject's internal model of the throwing arm. By crossing the presence of the weight with the different attentional focus conditions and sessions, there are eight experimental conditions in Chapter 5. Subjects who were *unweighted* during training and retention testing and had an external focus at training and test (UEE); unweighted and had an external focus during training but shifted to an internal focus at test (UEI); unweighted and had an internal focus during training and test (UII); unweighted and had an internal focus during training but shifted to an external focus at test (UEI). There were for parallel conditions four subjects who wore the weight during training and retention testing, but then removed the weight for the transfer test (WEE, WEI, WII, WIE).

Chapter 2: Neuromuscular Effects of Shifting the Focus of Attention in a Simple Force Production Task

> *"All that is left to us is to create the psychic states that these physical processes originate from, and from which they unfold, in agreement with our aims, following rules and mediated by processes all of which elude our consciousness."*
>
> – Rudolf Herman Lotze, (Lotze, 1852, p. 288)

Bernstein (1967) hypothesized that the goal of a task serves as an invariant property in the regulation of movement, and that other parameters of movement will interact with each other in order to maintain that goal. As we gain more experience, our movements do not necessarily become more rigid, because skilled performance requires us to interact effectively with a range of environments and conditions, detect important information, and time our responses appropriately. In this way, effective motor learning results in movement patterns that are adaptable to the environment, to the specific requirements of a task, and to endogenous variables (like motivation and fatigue) while the goal of the task remains invariant (Davids, Bennett, & Newell, 2006). That is, as learners gain motor skill, rather than becoming more robotic and rigid, they learn the invariant features of the movement (those parameters that must be precise for the movement to be successful) and allow other features to vary (permitting the movement to be successful in different environments, at different speeds, with different forces, etc.).

Research on the focus of attention in motor learning and performance supports the role of the task goal in regulating and organizing movement (for a review see Wulf, 2007). In general, these experiments attempt to bias a subject's focus of attention to either an external focus (i.e., focusing on the goal of the task or the outcomes of movement) or an internal focus (i.e., focusing on one's own body during movement) (Wulf & Shea, 1999). Consistently, when subjects are biased toward an external focus of attention, they perform better than internally focused subjects (Emanuel, Jarus, & Bart, 2008; Lohse, Sherwood, & Healy, 2010; Marchant, Clough, Crawshaw, & Levy, 2009; Wulf, McNevin, Fuchs, Ritter, & Toole, 2000) and often better than control groups (Marchant, Greig, Scott, & Clough, 2006; Wulf & Su, 2007; Wulf, Zachry, Granados, & Dufek, 2007), suggesting that subjects might spontaneously adopt an internal focus of attention, particularly when the task is novel. One explanation for attentional focus effects is the *constrained action hypothesis* (Wulf, 2007), which posits that when subjects adopt an internal focus of attention, action is constrained because explicit processing overrides automatic control mechanisms that have the capacity to control movement effectively and efficiently. The constrained action hypothesis has been criticized, however, for not being integrated with larger theories of motor learning and control (Oudejans, Koedijker, & Beek, 2007), and because the precise mechanisms that constrain action need to be specified (Raab, 2007).

Theoretically, research on the focus of attention is in line with Bernstein's (1967) hypothesis, and this idea has been further elaborated in the ideo-motor principle (Stock & Stock, 2004) and the common coding principle (Prinz, 1990; Wulf & Prinz, 2001). Both of these theories state that voluntary behavior is exclusively planned in terms of the intended sensory consequences for any goal directed motor act (Hoffman, Stöcker, & Kunde, 2004). Thus, because movements are encoded based on their outcomes, introducing an internal focus on one's own movement might change the higher level representation of the task in motor programming (although the nominal "goal" of the task is still the same), leading to deleterious effects on performance. In fact, research on "choking" (a sudden, catastrophic decrease in performance) under increased pressure to succeed indicates that a shift to an internal focus of attention is responsible for the sudden drop in performance. This research shows that when the pressure to perform increases, both subjects in the laboratory and experts in the real world start to explicitly monitor their behavior, disrupting learned motor skills, and impairing performance (Baumeister, 1984; Beilock & Carr, 2001; Lewis & Linder, 1997; Wan & Huon, 2005).

Although the advantage of an external focus of attention is well established, only recently have studies started going beyond behavioral measures of performance to analyze how the focus of attention affects the quality of the movement itself. Recent studies have examined the stability/variability of movement patterns (Lohse et al., 2010) and electrophysiological measures such as surface electromyography (Lohse et al., 2010; Marchant et al., 2006; Vance, Wulf, Töllner, McNevin, & Mercer, 2004; Wulf, Dufek, Lozano, & Pettigrew, 2010; Zachry, Wulf, Mercer, & Bezodis, 2005).

All of these studies have used surface electromyography (sEMG) to measure muscular activity in the upper limbs: Lohse and colleagues (2010) measured the biceps and triceps brachii during dart-throwing with the dominant hand. Marchant and colleagues (2006) measured activity in the biceps and triceps brachii during an isokinetic biceps curl, which is similar to Vance and colleagues (2004), who measured the biceps and triceps brachii in an unconstrained biceps curl (Experiment 1) and then replicated their findings in a biceps curl with fixed time intervals (Experiment 2). Zachry and colleagues (2005) investigated activity in the dominant arm during basketball free-throw shooting, using sEMG to analyze the biceps, triceps, deltoid, and the flexor carpi radialis (although the only significant effects of attention were found in recruitment of the biceps and triceps brachii).

Across these studies the general findings are the same; an external focus of attention improved movement efficiency (i.e., reduced sEMG activity) and also improved the outcome. In these studies, an external focus of attention led not only to improved accuracy (or force production in the case of the biceps curl), but also to reduced sEMG activity (expressed as an integrated root mean square error of the EMG waveform) compared to when subjects were focusing internally. This result suggests that an external focus of attention leads to more economic movement than does an internal focus of attention. sEMG activity with an external focus was also reduced relative to a control phase in which subjects received no instructions (Lohse et al., 2010; Marchant et al., 2006). In the study by Lohse et al. (2010), however, the control phase always preceded the focus conditions, so this effect is confounded with order.

In line with the findings of decreased muscle activity, there is also some evidence of increased functional variability in the movement pattern (Lee, Lishman, & Thompson, 1982; Müller & Loosch, 1999) with an external focus of attention (Lohse et al., 2010). These results suggest that an external focus of attention functionally unlocks degrees of freedom (Vereijken, van Emmerick, Whiting, & Newell, 1992) in the movement by reducing stiffness (through reduced muscle recruitment), which increases variability in task-irrelevant dimensions of the movement pattern in order to improve the movement outcome (Scholz & Schöner, 1999; Todorov, 2004; Todorov & Jordan, 2002).

All of these studies analyzed the magnitude of activation in the sEMG (expressed as either percentage of a subject’s maximum voluntary contraction (%MVC) or as the integral of the rectified sEMG waveform). Beyond the magnitude of activation in the muscle however, the frequency characteristics of the contraction also need to be considered. Vance et al. (2004) found smaller mean power frequencies (MNF) in early trials (but not on average across all trials) with an external focus of attention. This finding suggests that, at least in early trials, there are fewer motor units being recruited with an external focus of attention because of the incremental nature of muscle contraction (i.e., “the size principle” of muscular contraction; Olsen, Carpenter, & Henneman, 1968). Lohse et al. (2010) failed to replicate this finding in a dart throwing task, instead finding very similar MNF with internal and external focus. (Although the MNF with an external focus tended to be lower than with an internal focus, there was no significant difference.) Thus, there is some evidence of a trend for reduced MNF with an external focus of attention. These conclusions must be treated with caution, however, because both of these studies used dynamic contractions (i.e., contractions in which the length of the muscle is changing while generating force). During dynamic contractions, muscle morphology, the relative location of the recording electrodes to the muscle’s innervation zone, and the relative depth of active motor units are all changing, so it becomes impossible to make definitive statements about what physiological changes the MNF represent (Farina, 2006; Farina, Merletti, & Enoka, 2004; Merletti, Rainoldi, & Farina, 2001).

Thus, although previous research on the focus of attention clearly demonstrated a reduction in muscle activity and improved performance with an external focus of attention, the effects of an external focus of attention must be demonstrated in a task that uses isometric contractions (where the length of the muscle is not changing) before strong claims about underlying physiological changes can be made. Also, no analysis in previous studies has statistically connected increases in muscle activity with errors in performance. These studies have used independent analyses that show an internal focus of attention leads to decreased performance and to increased muscle activity, but have not explored the relationship between performance and muscle activity.

Therefore, in the current study we aimed to address these two gaps in the literature by doing detailed sEMG analysis using an isometric force production task under internal focus, external focus, and free focus (uninstructed focus) conditions. We used an isometric plantar flexion task with the subject’s dominant leg. We chose to use isometric plantar flexion because, as previously mentioned, most previous sEMG research has used dynamic contractions which makes analysis of the frequency of the sEMG signal very difficult to interpret. Also, previous focus of attention studies have used the upper extremities and replicating these effects in lower extremities is important for generalizing to applied research (e.g., studies of balance and falling in elderly and patient populations; Landers, Wulf, Wallmann, & Guadagnoli, 2005; Masters, MacMahon, & Pall, 2004; Wong, Masters, Maxwell, & Abernathy, 2008; Wulf, Landers, Lewthwaite, & Töllner, 2009).

The goal of the task was to produce 30% of the subject’s maximum force. By constraining the task to a single joint, the goal of this study is to show how attentional focus effects on performance can be explained by patterns of muscle recruitment in detail. For electrophysiological measures, we recorded sEMG from the lateral aspect of the soleus and the midline of the tibialis anterior. We predicted that an external focus of attention would lead to more accurate performance, and also to less sEMG activity, and to a reduction in the average power spectral frequency (expressed as both the mean power frequency, MNF, and median power frequency, MDF) compared to an internal focus condition.

Method

Participants

Data were collected from 12 subjects, 2 of whom were left footed and 10 of whom were right footed (identified by self report). Subjects always used their dominant foot in the experiment. Six of the subjects were male and six were female. Subjects were recruited through introductory psychology classes and participated in the experiment to fulfill course credit requirements.

Apparati and Measurements

A custom built force-plate was mounted to an angled platform so that the face of the plate was at a 55° angle relative to the ground. The force-plate was divided into anterior and posterior sections (separate strain gauges in each section), and subjects pressed against the posterior section of the plate (which was the closest to the floor). Prior to testing each subject, the force plate was recalibrated to a known mass to prevent inaccurate measurement through drift. Each subject was seated in a chair against a wall (to prevent movement backwards), and the force-plate was positioned so that for all subjects their heel was on the floor and their thigh was resting flat in the chair with their foot flat against the force-plate (in this way the knee was always bent, but to varying degrees for each subject). The force-plate was then supported by weights to prevent movement of the apparatus. To stabilize the position of the lower leg, subjects were required to maintain upper-leg contact with the chair (no lifting of the knee) and heel contact with the floor on all trials. Subjects were also instructed to look straight ahead at a fixation point on the opposite wall during the experiment (preventing visual attention from being directed to the foot or apparatus). Subjects' gaze was verified/controlled by the experimenter, who was present with the subject throughout the experiment.

For the EMG recording, the dominant leg was fitted with pairs of circular EMG electrodes (Ag/AgCl$^-$ electrodes) on the surface of the skin at the mid-line belly of the tibialis anterior (antagonist muscle) and the lateral aspect of the soleus (agonist muscle; because the knee was bent the soleus was the agonist during plantar flexion and not the gastrocnemius, Rasch, 1993) at an elevation approximately at the middle of the lower leg. Electrodes had a 1-cm diameter and were placed approximately 1 cm apart. The surface of the skin was shaved, prepared using an alcohol wipe with a mild abrasive; EMG electrodes were coated with conductive gel and then affixed using adhesive collars. A GB Instruments GMT 312 ® multimeter measured the resistance between EMG electrodes; if the resistance was greater than 5,000 Ωs, the area was cleaned again and the electrodes were reattached. An electrical common for each electrode pair was attached to the ear lobe. EMG data were collected using Biopac ® MP100 hardware at a 1000 Hz sampling rate and analyzed using Biopac AcqKnowledge software.

The raw sEMG signal was converted to a root mean square error, RMSE, which some research suggests is a more accurate index of physiological changes than measures of raw amplitude (Basmajian & De Luca, 1985; De Luca, 1997) and has been used in previous studies on the focus of attention (Lohse et al., 2010; Zachry et al., 2005). Prior to the main experiment we recorded each subject's maximum voluntary contraction (MVC) in both the tibialis anterior (dorsi-flexion) and soleus (plantar flexion). Maximum force was calculated as the average of three plantar flexion MVCs. Maximum sEMG activity in the soleus was calculated as the average RMSE in the same three plantar flexion MVCs. Maximum sEMG activity in the tibialis anterior was calculated as the average RMSE in three dorsi-flexion MVCs. Muscle activity during the experiment was then normalized to maximum activity during a subject's MVC to express activity as a percentage of maximum (%MVC) for each muscle. During the plantar flexion MVCs we were able to record the subject's maximum force as the average of the peak forces during three MVCs. Thirty percent of this average maximum force served as the subject's target force for the rest of the experiment. A 30 %MVC target was chosen for two reasons: (1) a low %MVC target should help reduce effects of fatigue in the experiment, and (2) a low %MVC should be more representative of motor unit recruitment, whereas a higher %MVC would have a greater influence on rate coding within an active motor unit (Enoka & Fuglevand, 2001; Gydikov & Kosarov, 1974; Macefield, Fuglevand, & Bigland-Ritchie, 1996).

We also analyzed the power spectrum of the sEMG signal for a 3-s window, thus avoiding ramp contractions and only analyzing stable plateaus during a trial. We analyzed both the mean power frequency (MNF) and the median power frequency (MDF) of the sEMG signal by computing a Fast Fourier Transform (FFT), which was windowed using a Hamming function. The FFT was then squared and integrated. From this integrated waveform, the frequency (Hz) corresponding to the *mean* power (V) between 1 and 250 Hz was selected as the MNF; the frequency corresponding to the *median* power between 1 and 250 Hz was selected as the MDF. The 1 – 250 Hz window is a common restriction to filter out very low and very high frequency artifacts (Lohse et al., 2010; Vance et al., 2004). Prior to the FFT, a 60-Hz notch filter was used on the raw waveform to reduce the influence of line frequency in the data.

Increases in the power spectral density are indicative of increased motor unit recruitment because recruitment of larger motor units with faster conduction velocities shifts the MNF and MDF upwards (Arendt-Nielsen, Mills, & Forster, 1989; Farina, Fosci, & Merletti, 2002; Lindstrom, Magnusson, & Peterson, 1970; Solomonow et al., 1990). The MNF and MDF, however, are insensitive to increased discharge rates and therefore are only diagnostic of increased motor unit recruitment during isometric contractions (Lago & Jones, 1977; Van Boxtel & Schomaker, 1984).

Design

The experiment was divided into a practice phase, two experimental phases, and a free focus phase. All subjects completed all phases, and during each phase subjects completed five blocks of four trials. The goal on each trial was to generate 30% of the subject's maximum force. Subjects received no visual feedback during the experiment. They were required to look straight ahead (which also prevented them from looking at their foot or the apparatus) and received verbal feedback from the experimenter after each trial (e.g., "Over by .5 lbs", "Under by 1.2 lbs"). On each trial, subjects would receive a go signal from the experimenter and push against the force platform, trying to generate 30% of their maximum force and maintain that force over 4 s and then receive a stop signal from the experimenter. Thus, over time, the force would ramp up after the go signal; when the force reached plateau this level would be maintained for 4 s; and the force would ramp down after the stop signal. All accuracy and electrophysiological measures were calculated in the final 3 s of this 4-s plateau. Absolute error (AE; our main measure of subjects' accuracy) was calculated by taking the absolute value of the average force across the 3-s window minus the subject's target force. Constant Error (CE) was calculated as the signed value of this difference, rather than the absolute value.

Subjects received 2 min of rest between phases. The practice phase was always the first phase of the experiment and served to familiarize subjects with the experiment; however, no explicit instructions on how to focus attention were given. In all phases, subjects were instructed to look straight ahead and to try and be as accurate as possible.

Phases 2 and 3 were experimental phases. Phases 2 and 3 were counterbalanced between subjects with internal focus and external focus instructions given by the experimenter (i.e., 6 subjects had internal first and the other 6 had external first). For the external focus, subjects were told, "Mentally focus on the push of your foot against the platform, because the platform is recording the force that you produce in this experiment. If you produce too much force, try to focus on pushing against the platform less. If you produce too little force, try to focus on pushing against the platform harder." This instruction was accompanied by the experimenter physically pointing to the platform. Between each block, subjects were reminded of their focus through feedback, "You were under by X.X lbs, try to focus on pushing harder against the platform."

The instructions for the internal focus condition were identical, only instead of "the push of your foot against the platform" subjects were told to focus on "pushing with the muscle of their calf," and instead of being told to focus on "pushing against the platform" more/less, subjects were told to focus on "contracting the muscle" more/less. Also, instead of being reminded that the platform was recording the force they produced, in the internal focus condition, subjects' were told to focus on the muscle of the calf, "because this is the muscle producing the force in this experiment." A plantar flexion motion was demonstrated by the experimenter pointing toward his posterior calf (toward the soleus and gastrocnemius muscles). Thus, subjects' attention was directed toward the soleus muscle of the dominant leg in the internal focus condition. All subjects in a given condition received identical instructions from the same experimenter.

The fourth phase always served as a free focus condition, where, as in the practice phase, subjects were not given explicit instructions on how to focus their attention, and were simply told to be as accurate as possible. If subjects asked about how they should focus, the instructions were repeated and subjects were encouraged to focus on whatever they felt would make them the most accurate. At the completion of the free focus phase subjects were given a post test survey in which we assessed what subjects were focusing on during the free focus phase and whether subjects felt they performed better in either the external or the internal focus condition.

Analysis

Because the only experimental phases were the second and third phases (i.e., the external and internal focus phases), only these phases were examined for the effects of focus of attention on accuracy and electrophysiological measures. The practice and free focus phases were always the first and fourth phases, respectively, and are therefore confounded with order. For the overall design, there are two within-subject variables of phase (external and internal) and block (5 blocks per phase) and one between-subjects variable of order (internal then external or external then internal). There are dependent variables of error (both AE and CE), the variability of force produced, the %MVC in the soleus and tibialis anterior, and the MNF/MDF in both the soleus and the tibialis anterior. Each dependent variable was analyzed separately using a 2 x 5 x 2 mixed-factorial ANOVA.

To see if there was a significant relationship between %MVC in the tibialis and %MVC in the soleus, %MVC in the tibialis was regressed onto %MVC in the soleus within each subject. From these within-subject linear regressions, we took the beta-weights (slopes) from the regression equation and performed a one-sample *t*-test comparing the beta-weights for all subjects to zero (Judd, McClelland, & Ryan, 2009). A non-significant result would suggest no relationship between activity in the antagonist and the agonist; a significant result would suggest a non-zero relationship between activity in the antagonist and the agonist. What we were most interested in was whether or not the strength of this relationship would change as a function of attentional focus. After finding a significant positive relationship between soleus activity and tibialis activity, we conducted an ANOVA to see if the strength of these beta-weights interacted with focus of attention. That is, an Order x Phase mixed factorial ANOVA was performed using subjects' beta-weights from the %MVC soleus ~ %MVC tibialis linear regression.

To connect changes in performance with changes in electrophysiological measures, within-subject linear regressions were constructed regressing subjects' AE onto a measure of cocontraction. Cocontraction was calculated by dividing a subject's %MVC in the tibialis by the %MVC in the soleus. As such, increases in the cocontraction ratio suggest increases in antagonist activity relative to agonist activity. From these within-subject linear regressions, we took the beta-weights (slopes) from the regression equation and performed a one-sample *t*-test comparing the beta-weights for all subjects to zero (Judd et al., 2009). A non-significant result would suggest no relationship between AE and cocontraction; a significant result would suggest a non-zero relationship (either positive or negative) between AE and cocontraction. We were also interested in whether or not this relationship would change as a function of attentional focus. Thus, after finding a significant main effect for cocontraction on AE, we conducted an ANOVA to see if the strength of these beta-weights interacted with focus of attention. That is, an Order x Phase mixed factorial ANOVA was performed using subjects' beta-weights from the Cocontraction ~ AE linear regressions.

The free focus phase was analyzed separately from the experimental phases to see if the subjects' self-reported focus of attention led to effects behaviorally similar to our attempts to experimentally induce a focus of attention. A Block x Order x Reported FOA mixed-factorial ANOVA was conducted for each dependent variable in the free focus phase.

For all analyses, only significant results are reported in the results section, nonsignificant results are reported only if the authors thought that these results were germane to the hypotheses of the experiment; all other effects were nonsignificant.

Results

Figure 5 shows raw data from three sample subjects that summarize the effect of shifting the focus of attention on neuromuscular coordination in the soleus, tibialis anterior, and on isometric force production. These subjects were selected because they showed a large behavioral effect of increased AE in the internal focus condition. Comparing the external focus to the internal focus, there is a clear effect of increased cocontraction; there is a substantial increase in activity of the tibialis anterior relative to the activation of the soleus. Statistical analyses of these effects are presented next. (Means in the result section are presented with ± between-subjects standard error.)

Behavioral Performance (Error and Variability)

In terms of absolute error (AE), there was a significant main effect of phase, $F(1,10) = 5.87$, $p = .035$, $\eta_p^2 = .38$, showing reduced error in the external phase (11.29 ±1.09 N) compared to the internal phase (14.01 ±0.94 N). See Figure 6a. This effect was not found for constant error (CE), $F(1,10) < 1$, where CE did not significantly change between the external phase (-3.69 ±1.14 N) and the internal phase (-4.71 ±1.28 N). The difference in these accuracy measures suggests that although subjects are generally undershooting the target (mean CE = -.2.62 ±1.19 N), overshoots and undershoots in the raw data are cancelling each other out, making AE a better indicator of subjects' accuracy (mean AE = 13.21 ±0.87 N). Thus, only AE was used in further analyses. There was a significant interaction of phase and order, $F(1, 10) = 6.68$, $p = .027$, $\eta_p^2 = .40$. This significant interaction showed that error in the internal focus condition was much greater when the internal focus condition was completed first.

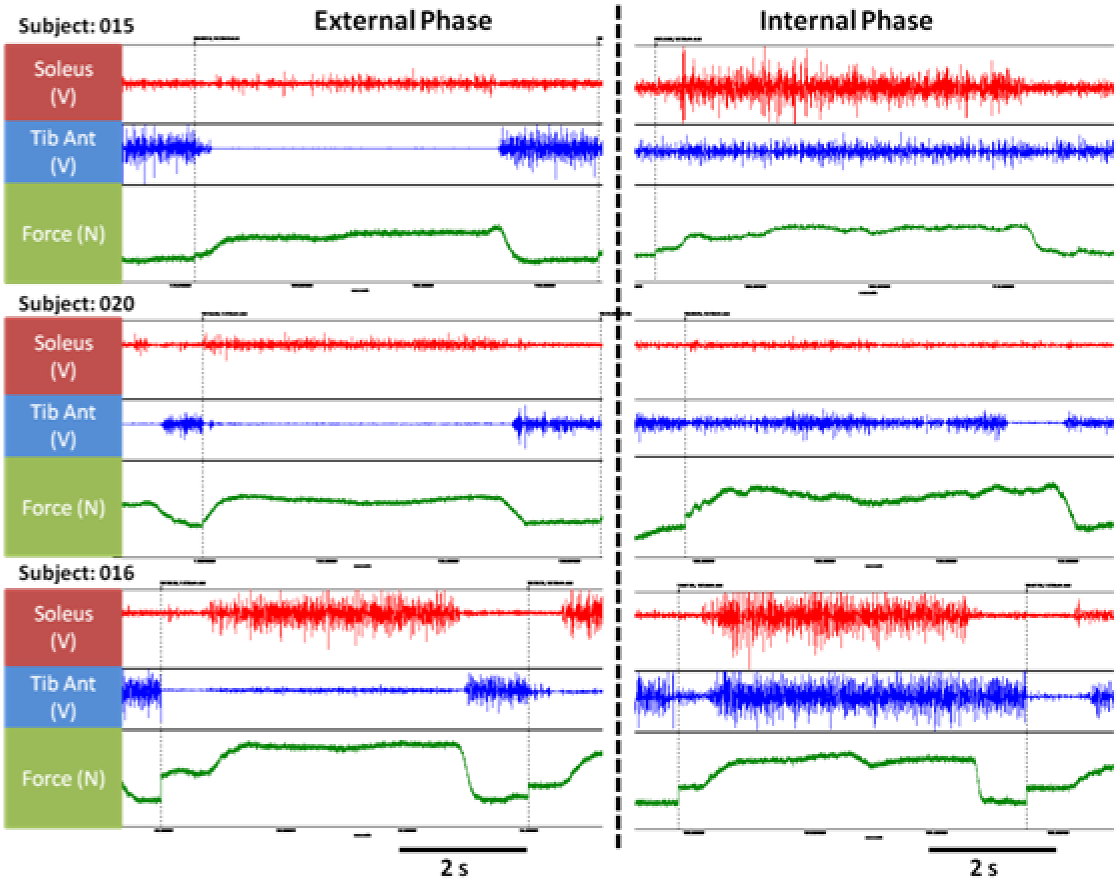

***Figure* 5.** *Example raw data from three subjects (who showed strong behavioral effects of shifting the focus of attention), showing representative trials from the external phase (on the left) and the internal phase (on the right). sEMG activity in the soleus, sEMG activity in the tibialis anterior, and force are shown as a function of phase and time for a single trial.*

Completing the external focus prior to the internal focus reduced absolute error during the internal focus condition. The opposite effect was less strong, however, because completing the internal focus condition prior to the external focus condition conferred a much smaller advantage in performance. This interaction of phase and order is shown in Figure 6b. There was a significant main effect of block, $F(4, 40) = 3.60$, $p = .013$, $\eta_p^2 = .26$, such that error decreased substantially from the first block of trials (15.47 ±1.29 N) to the second (13.52 ±1.73 N), third (12.36 ±0.85 N), fourth (10.45 ±1.63 N), and fifth blocks (10.14 ±1.03 N); error in the fifth block was also significantly less error than the second block (Tukey's HSD, *p's* < .05). There was no significant interaction of phase and block, *F*(4,40) < 1, suggesting that the rate of improvement was similar in both the internal and external focus conditions, although the advantage for the external condition did not emerge until the second block. See Figure 6a.

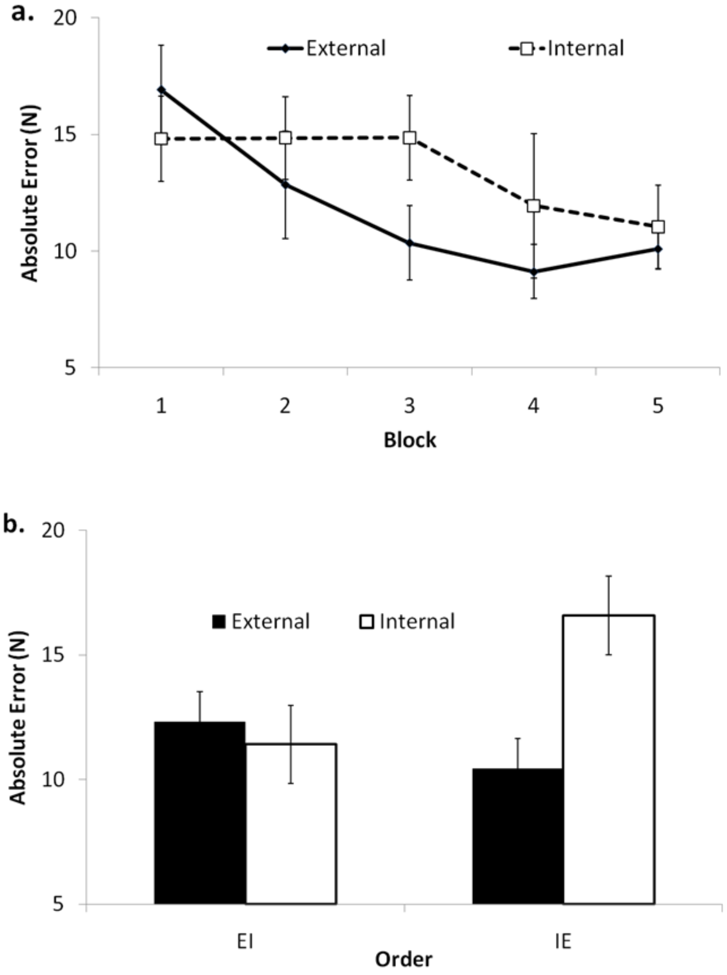

Figure 6. *(a) Absolute in error (in N) as a function of the focus adopted during the experimental phases and block. (b) Absolute error as a function of experimental phase and order (either external first/internal second (EI), or internal first/external second (IE)). Bars show between-subjects standard error.*

Variability in the force produced (expressed as the standard deviation of force across the 3 s recording window) did not change as a function of phase, *F*(1,10) = 1.49, *p* = .25, η_p^2 = .15. Variability reduced slightly from the external (8.27 ±0.85 N) to the internal (8.85 ±0.96 N) phase, but this difference was nonsignificant.

EMG Measures (%MVC and MDF/MNF)

Looking first at the %MVC measure of EMG amplitude, there was a significant main effect of phase for the tibialis anterior overall, *F*(1,10) = 6.18, *p* = .032, η_p^2 = .38. Activity was much greater in the internal focus phase compared to the external focus phase. See Figure 7. In the soleus however, there was no effect of phase, *F*(1,10) < 1. Thus, there was comparable soleus activity in the external and internal focus phases, whereas in the tibilais anterior, activity nearly tripled during the internal focus phase.

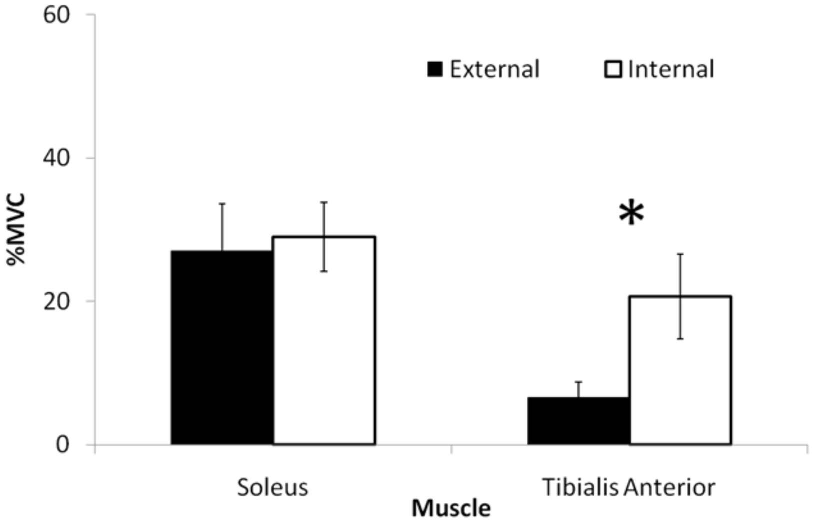

Figure 7. *sEMG activity, expressed as a percentage of the maximum voluntary contraction (%MVC) for the soleus and the tibialis anterior as function of phase. Bars show between-subject standard error. * denotes a significant (p < .05) effect.*

Next, changes in the power spectral density of the EMG waveform were analyzed by studying the MNF and MDF. Again, significant effects were found in the antagonist muscle, the tibialis anterior, but not in the agonist muscle, the soleus. In the tibialis anterior there was a significant main effect of phase, $F(1,10) = 7.62$, $p = .020$, $\eta_p^2 = .43$, as there was a significant increase in MDF from the external focus phase to the internal focus phase. In MNF however, the effect of phase was not significant, $F(1,10) = 2.75$, $p = .128$, $\eta_p^2 = .21$, although MNF tended to be lower with an external focus compared to an internal focus. See Figure 8.

There were no significant effects of phase in the soleus for either MDF, $F(1,10) < 1$, or MNF, $F(1,10) < 1$. The power spectral density was comparable for soleus activity in the external and internal phases. See Figure 8.

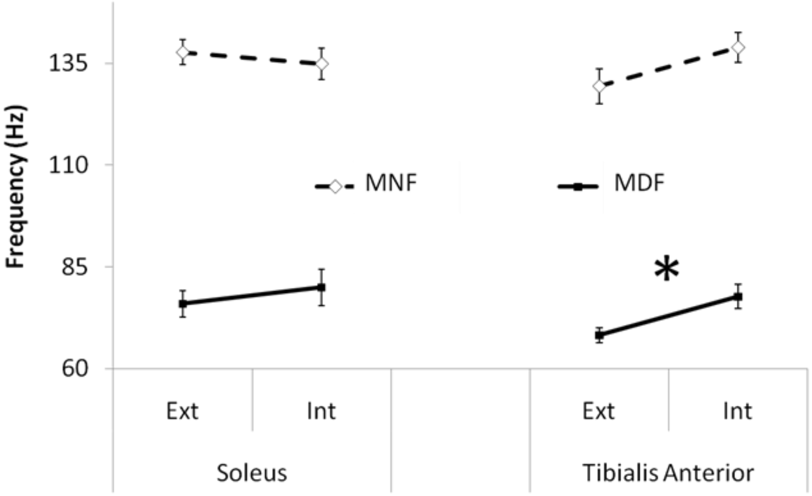

Figure 8. *The MNF (dashed line) and MDF (solid line) for both the soleus and the tibialis anterior as a function for phase. Bars show between-subject standard error. * denotes a significant (p < .05) effect.*

Regression Analyses

Regressing %MVC in the tibialis onto %MVC in the soleus within each subject produced 24 beta-weights (one slope and one intercept for each subject), which were then used in one-sample *t*-tests to see if this relationship was significantly different from zero across subjects. The intercepts were not significantly different from zero, $t(11) < 1$. Analysis of the slopes showed that there was a significant positive relationship between the activity in the soleus (agonist) and activity in the tibialis (antagonist), $t(11) = 2.85$, $p = .016$, $\eta_p^2 = .42$. The point estimate of the slope for the overall regression line was .95, meaning that when trying to produce 30% of their maximal force, a 100% increase in subjects' soleus activity was accompanied by a 95% increase in subjects' tibialis activity. Interestingly, this relationship between agonist and antagonist activity interacted with subjects' focus of attention. Analyzing the beta-weights from the within-subjects regressions, there was a significant effect of phase, $F(1,10) = 6.78$, $p = .026$, $\eta_p^2 = .40$, such that the strength of the agonist-antagonist relationship increased from the external focus condition ($m_{\text{beta slope}} = .28$, $CI_{95\%} = .020 < m_{\text{beta slope}} < .541$) to the internal focus condition ($m_{\text{beta slope}} = 1.62$, $CI_{95\%} = .390 < m_{\text{beta slope}} < 2.85$). The significant effect of focus of attention demonstrates that the level of cocontraction increased significantly with an internal focus of attention.

Regressing the cocontraction ratio (tibials activity divided by soleus activity) onto AE within each subject produced 24 beta-weights (one slope and one intercept for each subject), which were then used in a one-sample *t*-test to see if this relationship was significantly different from zero across subjects. The intercept was significantly different from zero, $m_{\text{beta intercept}} = .507$, $CI_{95\%} = .067 < m_{\text{beta intercept}} < .947$, $t(11) = 2.56$, $p = .027$, $\eta_p^2 = .39$, but did not change as a function of phase, $F(1,10) = 1.98$, $p = .189$, $\eta_p^2 = .17$. For the slopes, there was a significant positive relationship between the degree of cocontraction and absolute error, $t(11) = 2.40$, $p = .035$, $\eta_p^2 = .34$. The mean beta-weight across subjects was $m_{\text{beta slope}} = .011$, $CI_{95\%} = .001 < m_{\text{beta slope}} < .024$, meaning that for every one Newton increase in AE there was a .011 unit increase in the cocontraction ratio. As such, increased cocontraction is significantly correlated with increased AE. In analyzing the beta-weights from the within-subject regressions, there was not a significant effect of phase, $F(1,10) = 1.86$, $p = .202$, $\eta_p^2 = .15$, suggesting that there is the same positive relationship between cocontraction and AE in both the internal and external focus conditions.

Post-test Surveys and Analysis of the Free Focus Phase

Post test surveys revealed that during the free focus phase, 4 subjects adopted a purely external focus of attention, 3 subjects adopted a purely internal focus of attention, and 5 subjects adopted a mixture of the two (reported using different foci on different trials, or some balance of internal and external focus across trials). Although there was no significant difference in the performance of these groups in any measure, the externally focused group tended to have a lower mean AE than the internal or mixed focus groups. For a summary of performance in the free focus condition, see Table 1. Similarly, there was a trend for subjects adopting an external focus or a mixed focus to have less antagonist activity (%MVC) than subjects reporting an internal focus of attention. This same trend was found for both MDF and MNF in the tibialis anterior; subjects who reported using an external focus had somewhat lower MDF and MNF, consistent with the within-subject analysis. There was no effect of FOA for soleus activity (as either %MVC, MDF, or MNF) during the free focus phase.

Table 1. *Mean values of AE, %MVC, MDF, and MNF for the soleus and tibialis anterior muscles during the free focus phase as a function of subjects' reported FOA. Standard errors are given in parentheses.*

		Soleus			Tibialis Anterior		
FOA	AE (N)	%MVC	MDF (Hz)	MNF (Hz)	%MVC	MDF (Hz)	MNF (Hz)
External	9.11	30.0	78.79	140.19	6.9	69.43	130.10
	(1.38)	(.13)	(9.45)	(8.72)	(1.1)	(10.15)	(12.46)
Internal	10.01	21.1	75.48	126.97	19.0	81.54	142.60
	(1.69)	(.16)	(11.57)	(10.68)	(1.3)	(12.43)	(15.27)
Mixed	10.54	36.4	83.45	138.09	3.7	79.24	142.52
	(1.29)	(.12)	(8.63)	(.79)	(1.0)	(9.27)	(11.38)

Results of the analyses of the free focus phase show trends consistent with experimentally induced effects in the external and internal focus conditions. However, analyses of the free focus phase suffer from a lack of statistical power (i.e., rather than a within-subject test with 12 subjects, during the free focus phase the analysis becomes a between-subjects test with 12 subjects divided among three groups). Thus, although these trends are congruent with the within-subject analysis of phase, future studies would require more subjects to address FOA effects as a between-subjects variable.

Subjects also showed metacognitive awareness of which attentional focus yielded their best performance. Subjects who reported being more accurate in the external focus phase (n = 8) did have smaller errors with an external focus (10.09 ±1.02 N) relative to an internal focus (13.65 ±1.73 N). Similarly, subjects who reported being more accurate in the internal phase (n = 4), did have slightly smaller errors with an internal focus (10.01 ±1.55 N) relative to an external focus (12.36 ±1.17 N). However, these subjects who were more accurate in the internal phase had all completed the external phase prior to completing the internal phase. Therefore, it is unclear if their improved performance with an internal focus of attention is a unique individual difference (i.e., some people would perform better with an internal focus) or if it is an effect of order (i.e., these subjects already completed the external phase, and thus benefited from having practiced the task with an external focus when the time came to adopt an internal focus).

Discussion

This is the first study to address the focus of attention with an isometric task, and analysis of the behavioral data and the electrophysiological data helps to illuminate why shifting one's focus of attention internally has such profound negative effects on performance (Baumeister, 1984; Beilock & Carr, 2001; Lewis & Linder, 1997; Wan & Huon, 2005). Simply verbally prompting subjects to internally focus on their leg muscles, rather than on the platform they were pushing against, increased error in this isometric force production task and led to significantly greater cocontraction of the soleus and tibialis anterior. This result confirms our hypothesis that an internal focus of attention would lead to less efficient neuromuscular coordination. Interestingly, changes in motor unit recruitment were only observed in the antagonist muscle (tibialis), and not the agonist muscle (soleus), even though attention was specifically directed to the agonist muscle. There was also a significant effect of order, such that completing trials using the external focus instructions prior to the internal focus instructions improved performance during the internal focus phase. However, there were no order effects in any of the sEMG measures.

This order effect on accuracy might be attributable to improved learning and transfer that result from training using an external focus of attention. In a subsequent study, Lohse (2010) used the same isometric force production task with the same external/internal focus instructions and found that training with an external focus of attention improved performance on retention and transfer testing 1 week later. Thus, completing the external focus phase might have led to improved learning of the task that subjects were then able to apply to the internal focus phase, which enhanced their performance.

An internal focus of attention led to greater motor unit recruitment in the tibialis anterior (see Figure 3), while also producing increased error. Looking at the sample raw data makes the effects of an internal focus of attention on the antagonist muscle fairly clear (see Figure 1); an internal focus of attention led to inefficient neuromuscular coordination. Averaging across all subjects, the tibialis anterior shows minimal activity in the external focus condition (6.0 %MVC on average); however in the internal focus condition the level of activity is more than triple (20.7 %MVC on average). These effects of attention on cocontraction in the leg muscles have important implications for applied research on postural stability (Landers et al., 2005; Masters et al., 2004; Wulf et al., 2009), which has demonstrated, for instance, that elderly individuals with a history of falls are more likely to internally focus and attempt to explicitly control their balance (Wong et al., 2008), and suggests that attention might play a role in increasing the cocontraction that has been observed in postural control by elderly individuals (Benjuya, Melzer, & Kaplanski, 2004).

Significantly greater muscle activity in the antagonist muscle with an internal than with an external focus of attention is further explained by within-subject linear regressions, because not only did average AE and average cocontraction increase during the internal focus phase, but there was a significant positive correlation between AE and cocontraction, suggesting that in this task cocontraction is an inefficient and ineffective strategy. This is an intriguing result that merits further investigation and would suggest that increased cocontraction causes increased error;

however, underlying third variables might be affecting the error-cocontraction relationship. For instance, it is unclear whether cocontraction is affecting only performance on a given trial or whether cocontraction affects learning from the previous trial and impairs subjects' ability to appropriately correct errors in force production on following trials (also see Lohse, 2010, for an experimental study of FOA affecting learning in isometric force production).

Not only was the increase in muscle activity found as an increase in the %MVC from the external to the internal focus condition, but also there was some evidence of an upward shift in the power spectral density. In the tibialis anterior, MDF was significantly higher in the internal focus condition compared to the external focus condition. This result must be treated with caution, however, because there were no significant effects of attentional focus on MNF (although the trend was in the predicted direction). The increases in the power spectral density (a significant increase in MDF and a trend to increase in MNF) both are indicative of increased motor unit recruitment, because motor units are recruited based on the size principle (Andreassen & Arendt-Nielsen, 1987; Henneman, 1957). That is, smaller motor units with slower conduction velocities are always recruited before larger motor units with faster conduction velocities (Desmedt & Godaux, 1977). Thus, the recruitment of larger motor units means that more motor units are being recruited, and this addition creates a corresponding upward shift in the MNF and MDF (Arendt-Nielsen et al., 1989; Farina et al., 2002; Lindstrom et al., 1970; Solomonow et al., 1990).

From these results we can conclude that an internal focus of attention hurts accuracy because an internal focus changes the pattern of muscle activation that underlies the movement necessary to perform the action. In the case of this isometric plantar flexion task, an internal focus of attention reduced the efficiency of movement at both an intermuscular level and an intramuscular level. Efficiency was reduced at an intermuscular level because an internal focus led to increased cocontraction between the soleus and tibialis. Efficiency was reduced at an intramuscular level because an internal focus led to increased motor unit recruitment within the antagonist muscle, the tibialis. This unnecessary motor unit recruitment in the antagonist muscle is much less efficient than the recruitment pattern during an external focus, when the antagonist is relatively inactive. This finding is particularly interesting because it shows that high level cognitive mechanisms like attention can have very significant impacts on neuromuscular coordination. Although motor unit recruitment is clearly not under conscious control, this study and a few others (Diedrichsen, 2007; Hunter, Ryan, Ortega, & Enoka, 2002) have begun to show that high-level cognitive representations of the task can influence motor control in significant ways.

Importantly, the neuromuscular effects of shifting the focus of attention were demonstrated when subjects were given explicit instructions on how to focus their attention, but also data collected during the free focus phase were congruent with these significant effects (shown in Table 1). After coding subjects' reported FOA during the free focus phase, there was a clear trend that subjects who reported using an external FOA were somewhat more accurate and had less cocontraction than subjects who reported using and internal FOA. However, because reported FOA was a between-subjects variable (whereas the analysis of phase to explore FOA was a within-subject variable), the comparison of reported FOAs has very low statistical power and none of these effects were significant. It is very promising, though, that the effects of subjects' self-reported FOA are congruent with the experimentally induced FOA, and future studies should address this question with larger groups of subjects.

Post test surveys also revealed that subjects were generally aware of which attentional focus led to their best performance. Although most subjects preferred and were more accurate using the external focus of attention, a minority of subjects preferred and were more accurate using the internal focus of attention. This finding is not definitive however, because those subjects who were more accurate with the internal focus of attention also completed the internal phase after the external phase, creating a confounding effect of order. However, these differences in accuracy and subjects' different self-reported preferences should invite future research on individual differences in the focus of attention.

Particularly, further research is needed to see how the focus of attention interacts with skill level. The conceptual structures of novices relative to experts are very different (McPherson, 2000; Shack & Mechsner, 2006; Vallacher, 1993), and it is reasonable to assume that the appropriate attentional focus for one skill level might not be appropriate for a different skill level. In fact, there is some debate on this point in the literature already, with some researchers claiming that an internal focus of attention might be more beneficial for novices (Perkins-Ceccato, Passmore, & Lee, 2003); however, most tasks showing an advantage for an external focus of attention show that novices also benefit from an external focus (e.g., Lohse et al., 2010; Marchant, Clough, & Crawshaw, 2007; Wulf, Gärtner, McConnel, & Schwarz, 2002; Wulf et al., 2000; Wulf & Su, 2007). A shift in attention from internal to external could also explain why the level of co-contraction might decrease with motor learning (Osu et al., 2002).

Conclusion

In summary, this experiment demonstrated an advantage for an external focus of attention in an isometric force-production task. Manipulating verbal instructions to bias attention toward the force-plate a subject was pushing against improved a subject's accuracy, and also had substantial effects on muscle activity in the antagonist muscle, the tibialis anterior, but surprisingly no effects on muscle activity in the agonist muscle, the soleus. The tibialis anterior showed increased activity as a %MVC, and importantly increased MDF. Because of the isometric nature of the task, MDF provides a more accurate representation of the physiological changes that occur with a shift in the focus of attention; whereas previous research has used dynamic contractions to study these electrophysiological changes, which prevents strong conclusions about physiological changes from being made. Increased MDF in this isometric force-production task clearly shows that an internal focus of attention leads to increased motor unit recruitment in the antagonist muscle. This finding resolves previous ambiguity in sEMG research on the focus of attention and is consistent with the hypothesis that an internal focus of attention artificially constrains an action by reducing movement efficiency. These results are important because they provide a specific mechanism for constraining movement within the constrained action hypothesis (Wulf, 2007), implicating cocontraction as a factor that disrupts movement efficiency and effectiveness. These results also add an important new dimension to the ideo-motor principle (Stock & Stock, 2004).

Discussion of ideo-motor theory is largely theoretical, using conceptual explanations that are not grounded in biological motor control. For instance, William James suggested that action occurs when an individual, "think[s] of the movement purely and simply, with all brakes off; and presto! it takes place with no effort at all" (James, 1890, p. 527). Although James' reference to "brakes" is metaphorical and conceptual, this metaphor is particularly apt because increased cocontraction does serve as a very real, mechanical "brake" that increases joint stiffness and constrains action when subjects are internally focused. This increased joint stiffness functionally "locks" degrees of freedom (i.e., reducing movement variability for a given degree of freedom in a joint) and is characteristic of novice motor behavior (Bernstein, 1967; Vereijken et al., 1992). Thus, research on the focus of attention has very important implications for human performance, demonstrating that an external focus of attention can be induced through verbal cues and that an external focus leads to increased neuromuscular efficiency, through reduced cocontraction. This reduced cocontraction might underlie functional variation (i.e., fluidity) that is characteristic of expert performance (Lee et al., 1982; Lohse et al., 2010; Müller & Loosch, 1999). In this way, verbal cues can be used to make performance more expert-like or novice-like by biasing attention either externally or internally, respectively.

As research on the focus of attention continues to demonstrate, even subtle differences in the structure of a task, such as the specific wording of instructions or feedback that a subject is given, can have profound effects on behavior and the underlying physiology. Thus, instructors, coaches, therapists, and performers themselves need to be aware of how these differences affect performance and should develop effective strategies to keep the performer's attention focused externally on the goal of the task. Internally focusing on one's own movements constrains the motor system and leads to inefficient movements that are not only less accurate, but also less efficient at the neuromuscular level.

Chapter 3: Thinking about Muscles: The Neuromuscular Effects of Internally Focused Attention in Accuracy and Fatigue

“The central nervous system knows nothing of muscles, it only knows movements.”

– John Hughlings Jackson, FRS, British neurologist (Jackson, 1889)

Over the past decade, considerable research has been done in the field of motor behavior to explore the effects of attention on the acquisition and performance of motor skills. Detailed reviews of this literature can be found elsewhere (see Lohse, Wulf, & Lewthwaite, 2012; Wulf, 2007a, 2007b), but in general, this research has found that performance is improved by directing attention externally to the effect of a movement on the environment (e.g., focusing on the lower corner of the goal in football or the flight of the ball in golf) compared to focusing attention internally on the motion of the body itself (e.g., focusing on the motion or placement of the legs in football or the swing of the arms and trunk in golf). Furthermore, a number of studies have shown an external focus of attention, induced through instructions and feedback by the experimenter, improves performance relative to control conditions in which attention is not directed either externally or internally (Landers, Wulf, Wallmann, & Guadagnoli, 2005; McNevin & Wulf, 2002; Wulf & McNevin, 2003; Wulf, Weigelt, Poulter, & McNevin, 2003). Similarly, the advantage of focusing externally holds true for both healthy populations and clinical populations. Patients with musculoskeletal injuries (Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007), patients recovering from stroke (Fasoli, Trombly, Tickle-Degen, & Verfaellie, 2002), and Parkinson’s disease patients have all been shown to benefit from externally focused attention (Landers et al., 2005; Wulf, Landers, Lewthwaite, & Töllner, 2009).

It is important to note that in these studies, subjects' overt, or visual, attention is controlled and what is manipulated is subjects' covert, or mental, attention.

The exact mechanisms that underlie the effects of attention on skilled performance are not known, but it has been suggested that focusing attention internally creates top-down constraints on the coordination of movement, although it is not clear how these top-down constraints manifest in terms of biomechanical changes (this position is referred to as the *constrained action hypothesis*; Wulf, 2007a, 2007b). Recently, research on neuromuscular coordination (Lohse, Sherwood, & Healy, 2011) and movement variability (Lohse, Jones, Healy, & Sherwood, 2011; Hossner & Erhlenspeil &, 2010) has suggested physiological mechanisms that might explain how action is physically constrained. These studies suggest attention acts to allocate precision along different dimensions within the motor system, increasing movement precision in the attended dimension. That is, when attention is directed externally and the goal of the action is being attended to, the motor system works to optimize performance by reducing variation in the goal dimension (see Todorov & Jordan, 2002). However, when attention is directed internally and one's own body/mechanics are being attended to, the motor system works to optimize function by reducing variation in bodily dimensions (e.g., locking degrees of freedom). By focusing internally and penalizing variation in these bodily dimensions, attention effectively reduces the motor system's ability to make compensatory adjustments and performance can suffer as a result (Lohse et al., 2011; Hossner & Erhlenspeil, 2010).

Related work on muscle activity as a function of attention suggests that an internal focus of attention reduces movement efficiency by increasing the magnitude of muscle activation during the movement (i.e., the energetic cost of the movement) without improving the movement outcome (often making the outcome even worse). Two studies have shown that an internal focus of attention during submaximal force production in elbow flexion leads to increased sEMG activity in the elbow flexor muscles (Marchant, Greig, & Scott, 2009; Vance, Wulf, Töllner, McNevin, & Mercer, 2004), even though the outcome of the movement was identical (i.e., the same amount of force was always produced, but it was produced inefficiently with an internal focus). A study of maximal force production in the form of a vertical jump also found that center of mass displacement was greater while sEMG activity in the musculature of the legs was reduced as a function of focusing externally (Wulf, Dufek, Lozano, & Pettigrew, 2010). Other studies have similarly found that an external focus of attention increases displacement in vertical and broad jumping, but without sEMG measurements (Porter, Ostrowski, Nolan, & Wu, 2010; Wulf, Zachry, Granados, & Dufek, 2007).

In our own research, we have studied accuracy in force production and found that focusing externally not only increases accuracy in the production of sub-maximal forces, but that an external focus of attention also leads to reduced cocontraction between agonist and antagonist muscles in plantar flexion (evaluated at 30 %MVC; Lohse, Sherwood, & Healy, 2011). Reduced cocontraction means that focusing externally generates more efficient patterns of muscle recruitment for a given level of force. Furthermore, training with an external focus of attention in this task significantly improves performance on delayed retention and transfer testing in force production (albeit without sEMG analysis; Lohse, 2012).

Although there is growing evidence to suggest that focusing attention externally increases the efficiency of force production through efficient patterns of muscle recruitment, no previous work has evaluated different intensities or levels of force production within a single experiment, and no previous work using sEMG has studied the effects of attention on muscular fatigue. These are important questions to address because potential interactions exist between the focus of attention and the magnitude of the force being produced. For instance, efficient muscle recruitment is reasonably predicted to be more important for the generation of maximal forces, where any unnecessary antagonist muscle activation will reduce the net force and the agonist muscles are already at their contractile limit. Empirically studying fatigue is also an important step forward in this research because, based on findings indicating that maximal (Marchant et al., 2009) and sub-maximal (Lohse, Sherwood, & Healy, 2011) forces are produced with more efficient muscle recruitment when an external focus is adopted, one would predict that individuals should be able to maintain force levels longer, or increase the level of force for a given period of time, with an external focus of attention. Recently, two studies have provided behavioral evidence that an external focus of attention increases the time to failure in an isometric "wall-sit" task (Nolan, 2011; Lohse & Sherwood, 2011). Neither of these studies made any objective physiological measurements of fatigue, although perceived exertion was been found to be significantly higher with an internal focus of attention (Lohse & Sherwood, 2011). Thus, in the present study, we conducted two experiments to explore the efficiency and accuracy of force production at different %MVCs (Experiment 1) and to explore the effects of attention on muscular fatigue at different %MVCs (Experiment 2). Both experiments used an isometric plantar-flexion task and experimental protocol similar to that used by Lohse, Sherwood, & Healy (2011).

Experiment 1

Only a few experiments have studied the effects of attention on force production (for a review see Marchant, 2010), but from previous work on maximum force production (Marchant et al., 2009; Wulf et al., 2010) we know that at maximum forces an external focus of attention leads to lower sEMG activity than an internal focus of attention. At sub-maximal forces (30 %MVC), when accuracy is being measured, an external focus of attention leads to less cocontraction between the agonist and antagonist muscles and also to more accurate force production (Lohse, Sherwood, & Healy, 2011). Thus, Experiment 1 was designed to evaluate the effects attentional focus at 30, 60, and 100 %MVC in an isometric plantar flexion task while taking sEMG recordings from the soleus (agonist), gastrocnemius (synergist), and tibialis anterior (antagonist) of the dominant leg. We hypothesized that an internal focus would disrupt intermuscular coordination between the soleus and the tibialis anterior. If this prediction is correct, we should observe that (*a*) an external focus of attention leads to more accurate and more efficient force production overall, but also that (*b*) the advantage of an external focus of attention would be greater for higher %MVCs because better inter-muscular coordination is needed to generate maximum forces. That is, if the goal is to generate 30 or 60 %MVC, antagonist activity can be overcome by increases in agonist activity to generate the appropriate net force. However, at 100 %MVC, any unnecessary antagonist activity will reduce the net force. The hypothesis that attention directly influences intermuscular coordination would explain behavioral findings on fatigue and add a new theoretical dimension to the constrained action hypothesis.

Method

Participants. Data were collected from 12 healthy and physically active subjects, all of whom were right footed (identified by self report). Subjects always used their dominant foot in the experiment. Six of the subjects were male and six were female. Subjects were recruited through classes in the Department of Integrative Physiology and participated in the experiment to fulfill course credit requirements.

Apparati and measurements. A custom built force-plate was mounted to an angled platform so that the face of the plate was at a 55° angle relative to the ground. The force-plate was divided into anterior and posterior sections (separate strain gauges in each section), and subjects pressed against the posterior section of the plate (which was the closest to the floor). Prior to testing each subject, the force plate was recalibrated to a known mass to prevent inaccurate measurement through drift. Each subject was seated in a chair against a wall (to prevent movement backwards), and the force-plate was positioned so that for all subjects their thigh was resting flat in the chair and their heel was on the floor, with their foot flat against the force-plate (in this way the knee was always bent, at angle of 110° ± 5° for each subject). The force-plate was then supported by weights to prevent movement of the apparatus. To stabilize the position of the lower leg, subjects were required to wear a thigh strap (maintaining upper-leg contact with the chair) and to maintain heel contact with the floor on all trials. Subjects were also instructed to look straight ahead at a fixation point on the opposite wall during the experiment (preventing visual attention from being directed to the foot or apparatus). Subjects' gaze was verified/controlled by the experimenter, who was present with the subject throughout the experiment.

For the sEMG recording, the dominant leg was fitted with pairs of circular EMG electrodes (Ag/AgCl- electrodes) on the surface of the skin at the mid-line belly of the tibialis anterior (antagonist muscle), the lateral aspect of the soleus (agonist muscle) and the medial head of the gastrocnemius (synergistic muscle). Because the knee was bent, the soleus was the agonist during plantar flexion and not the gastrocnemius (Rasch, 1993). Electrodes had a 1-cm diameter and were placed approximately 1 cm apart. The surface of the skin was shaved and prepared using an alcohol wipe with a mild abrasive; sEMG electrodes were coated with conductive gel and then affixed using adhesive collars. A GB Instruments GMT 312 ® multimeter measured the resistance between EMG electrodes; if the resistance was greater than 5,000 Ωs, the area was cleaned again and the electrodes were reattached. An electrical common for each electrode pair was attached to the ear lobe. EMG data were collected using Biopac ® MP100 hardware at a 1000 Hz sampling rate and analyzed using Biopac AcqKnowledge software.

Prior to analysis, the raw sEMG data were high-pass filtered (5 Hz cut-off) and converted to a root mean square error (RMSE) and then low-pass filtered (250 Hz cut-off). This method of integration was chosen because some research suggests RMSE is a more accurate index of physiological changes than other types of rectification (Basmajian & De Luca, 1985; De Luca, 1997) and these methods have been used in previous studies of the focus of attention (Zachry, Wulf, Mercer, & Bezodis, 2005).

Prior to the main experiment we recorded each subject's maximum voluntary contraction (MVC) in both the tibialis anterior (through dorsi-flexion) and soleus and gastrocnemius (through plantar flexion). Maximum sEMG activity in the soleus and gastrocnemius was calculated as the average RMSE in three plantar flexion MVCs. Maximum sEMG activity in the tibialis anterior was calculated as the average RMSE in three dorsi-flexion MVCs. Muscle activity during the experiment was then normalized to maximum activity during a subject's MVC to express activity as a percentage of maximum (%MVC) for each muscle.

During the plantar flexion MVCs, subjects' maximum force was recorded as the average of the peak forces during the three MVCs. From this average maximum force, we calculated three different target forces: 30, 60, and 100 %MVC. Subjects completed 10 trials at each %MVC during the course of the experiment. Subjects' goal on every trial was to generate the target %MVC.

Design and procedure. The experiment was divided into six blocks for each subject by crossing the variable of target force (30, 60, and 100 %MVC) with the variable of attentional focus (external or internal). Both the order of %MVC targets and the order of attentional foci were fully counter-balanced across subjects. All subjects completed 10 trials at each %MVC target with each attentional focus. Subjects received 2 min of rest between each block of trials. Target %MVCs were blocked together (e.g., all 30 %MVC trials were completed in either an external-internal order or an internal-external order, and then the next target %MVC would be completed in the same order).

Subjects were informed at the beginning of a block of trials which %MVC they were aiming for, how to focus their attention, and what the %MVC translated to in pounds of force. Subjects were told that the goal on each trial was to generate "X.X lbs of force," based on the %MVC. Subjects received no visual feedback during the experiment. They were required to look straight ahead (which also prevented them from looking at their foot or the apparatus) and received verbal feedback from the experimenter after each trial (e.g., "Over by .5 lbs", "Under by 1.2 lbs").

On each trial, subjects would receive a go signal from the experimenter and push against the force platform, trying to generate the target %MVC and maintain that force over 4 s and then receive a stop signal from the experimenter. Thus, over time, the force would ramp up after the go signal; when the force reached plateau this level would be maintained for 4 s; and the force would ramp down after the stop signal. All accuracy and electrophysiological measures were calculated in the final 3 s of this 4-s plateau. Absolute error (AE; the main measure of subjects' accuracy) was calculated by taking the absolute value of the average force across the 3-s window minus the subject's target force. Constant Error (CE) was calculated as the signed value of this difference. sEMG measurements were based on electrophysiological activity in the soleus, gastrocnemius, and tibialis anterior in this 3-s window.

Attentional focus was manipulated by giving subjects subtly different sets of verbal instructions and feedback (based on instructions from Freedman, Maas, Caligiuri, Wulf, & Robin, 2007; Lohse, Sherwood, & Healy, 2011). For the external focus condition, the experimenter would demonstrate the plantar flexion motion and point toward the force platform. Subjects were told, "Mentally focus on the push of your foot against the platform. If you produce too much force, try to focus on pushing against the platform less. If you produce too little force, try to focus on pushing against the platform harder." Between each block, subjects were reminded of their focus through feedback, "You were under by X.X lbs; try to focus on pushing the platform harder." Thus, in the external focus condition, attention was directed toward the *platform*.

In the internal focus condition, the experimenter would demonstrate the plantar flexion motion and point towards the experimenter's own soleus (below the gastrocnemius). The instructions for the internal focus condition were identical, except instead of the platform, subjects were told to, "Mentally focus on the contraction of the muscle in your calf. If you produce too much force, try to contract this muscle less. If you produce too little force, try to contract this muscle more." Between each block, subjects were reminded of their focus through feedback, "You were under by X.X lbs; try to focus on contracting the muscle more." Thus, in the internal focus condition, attention was directed toward the *agonist* muscle of the calf. Verbal feedback about accuracy and attentional focus reminders were given after every trial in all conditions.

These instructions were designed so that attention was directed to the platform (in the external focus condition) or the agonist muscle (in the internal focus condition) so that in both conditions attention would be directed to task-relevant sources of information. Previous studies of the focus of attention have been criticized for internal focus conditions with low task relevance (see Hommel, 2007; Künzell, 2007), thus we tried to equate these foci on task relevance, making the only critical difference the external/internal distinction.

Analysis. For the dependent variables of AE, CE, and sEMG activity, a 2X3X10 repeated-measures ANOVA was used with factors of Focus (external versus internal), Target (30, 60, or 100 %MVC), and Trial (trials 1-10 for each Focus by Target block). These effects are summarized in Table 2. Only the significant results of this analysis are presented, all other effects were not significant (*p* > .05). Post-hoc tests reported in the results section used a Šidák adjustment to correct for multiple comparisons.

Results and Discussion

Behavioral data (AE and CE). Analysis of AE in the force revealed a main effect of attentional focus, such that AE was lower when subjects were externally focused compared to when they were internally focused. There was also a significant effect of target; the magnitude of AE increased with the magnitude of the target %MVC. Šidák post-hoc tests revealed that the magnitude of AE for the 30, 60, and 100 %MVC targets were all significantly different from each other (*p*s < .01). This effect is likely the result of signal-dependent noise, with variability scaling to the magnitude of force produced (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Finally, there was a significant main effect of trial, showing that, on average, AE reduced across trials. Because of the large number of tests required for post-hoc testing with a 10-level variable, we thought it was better to simply look at this effect as a trend, with most subjects' improvement in AE occurring in the first two trials. These effects for AE are shown in Figure 9.

Table 2. List of significant effects by dependent variable in Experiment 1.

Effect	AE	CE	%MVC
Focus	$F(1,11) = 5.40$, $p = .04$	$F(1,11) = 4.01$, $p = .07$*	$F(1,11) = 5.35$, $p = .04$
Target	$F(2,22) = 84.86$, $p <.001$	$F(2,22) = 92.96$, $p < .001$	$F(2,22) = 48.73$, $p < .001$
Trial	$F(9,99) = 4.95$, $p < .001$	$F(9,99) = 3.21$, $p < .01$	-*n.s.*-
Focus X Trial	-*n.s.*-	$F(9,99) = 2.74$, $p < .01$	-*n.s.*-
Muscle	--	--	$F(1,11) = 155.15$, $p < .001$
Muscle X Target	--	--	$F(4,44) = 35.30$, $p < .01$
Muscle X Focus X Target	--	--	$F(2,22) = 5.67$, $p = .01$

Note. The dependent measures of absolute error (AE) and constant error (CE) were all analyzed using 2 X 3 X 10 repeated measures ANOVAs with factors of focus (external v. internal), target (30, 60, or 100% of maximum force), and trial (trials 1-10). Normalized EMG activity (%MVC) had an additional factor of Muscle (soleus v. tibialis anterior). The gastrocnemius was omitted from the analysis because of its minimal contribution.

* = significant when tested in the a priori direction.

n.s. = 'Not significant', used to denote an effect that was not significant for that variable, but was significant for others. All unreported effects were not significant ($p > .05$).

Analysis of CE revealed a main effect of attentional focus that approached significance, (if tested in the hypothesized direction however, $p = .035$), showing a trend for subjects to have CE closer to zero when externally focused compared to when internally focused. The significant effect of attentional focus for AE, which changes to marginally significant for CE, suggests that although subjects are generally undershooting their target force, positive and negative errors are cancelling each other out, making the measure of AE more representative of subjects' performance.

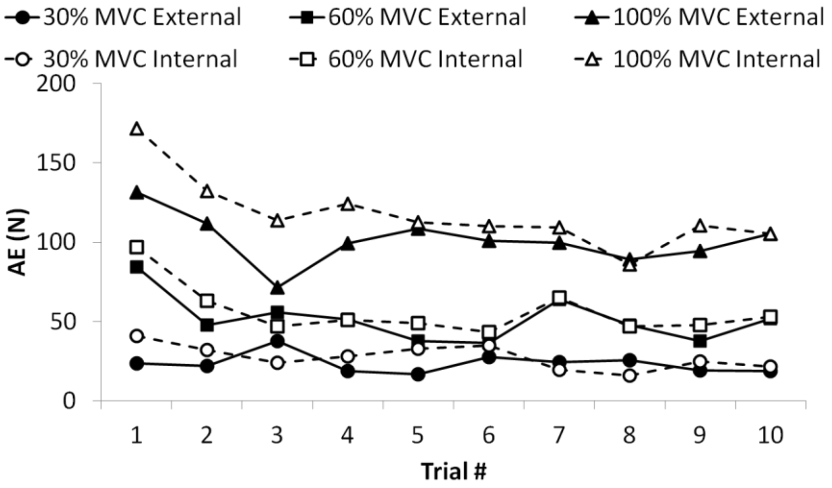

Figure 9. *Absolute error (AE) as a function of target force, attentional focus, and trial.*

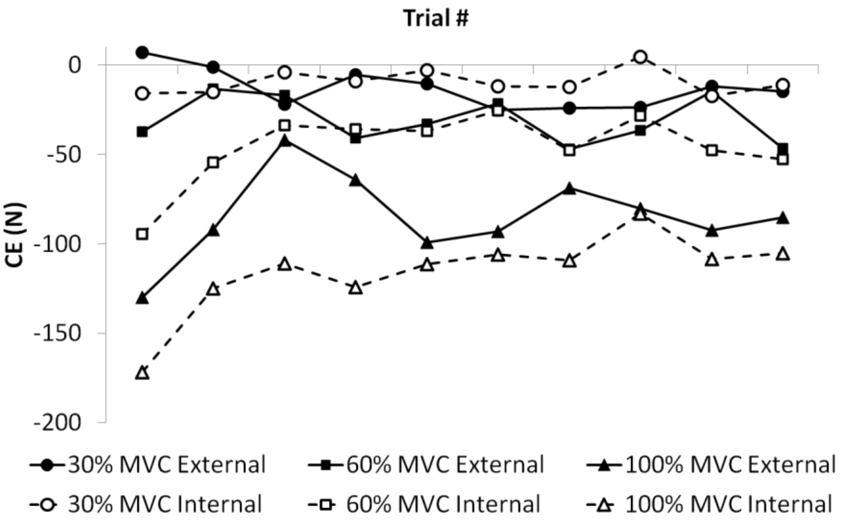

Figure 10. *Constant error (CE) as a function of target force, attentional focus, and trial.*

For CE there was also a significant effect of target, which showed smaller CE for smaller magnitudes of force. Šidák post-hoc tests showed that CE for the 30, 60, and 100 %MVC were all significantly different from each other (*p*s < .01). Again, there was a main effect of trial, which we describe as a trend; early trials tended to be more negative than later trials. Similar to AE, this effect of trial suggests that most of the performance improvement in this task took place in the first few trials. However, there was also a significant Focus x Trial interaction, which further showed that the largest difference between the external and internal focus conditions was in early trials. These effects for CE are shown in Figure 10.

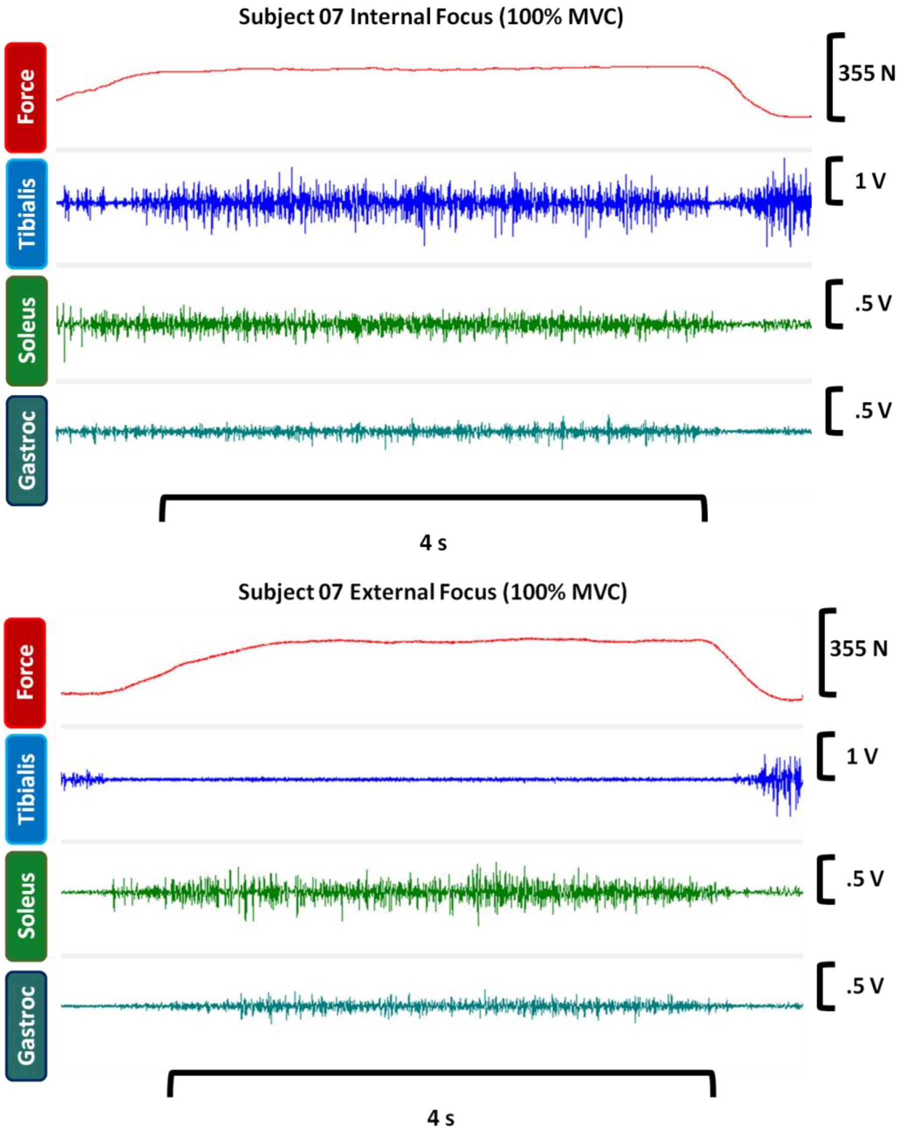

Figure 11. *Force and sEMG from the last trial of the internal and external focus blocks for Subject 07 in Experiment 1. In both cases, the subject was trying to produce a target force of 100 %MVC. The cocontraction depicted is representative of the pattern found across subjects; Subject 07's data was chosen because this subject showed a large behavioral effect of attentional focus on accuracy.*

Electromyographic data (sEMG). In order to analyze sEMG data, the basic repeated-measures ANOVA (with factors of focus, target, and trial) was expanded to included a two-level factor of muscle (the agonist muscle, the soleus, versus the antagonist muscle, the tibialis anterior). Again, because the knee was substantially bent during the isometric plantar flexion task, the gastrocnemius becomes a synergist muscle. Thus, the gastrocnemius was omitted from statistical analysis, but data from the gastrocnemius is presented in the figures for the sake of completeness. Representative sEMG data from a single subject are provided in Figure 11. Qualitative analysis of these data suggests that an internal focus of attention did indeed lead to increased cocontraction compared to an external focus of attention.

In statistical analysis of the soleus and the tibialis anterior, there was a significant main effect of muscle. The level of activity in the soleus (normalized to maximum recorded activity in the soleus during plantar-flexion) was significantly greater than activity in the tibialis (normalized to maximum recorded activity in the tibialis during dorsi-flexion). There was also a significant main effect of target and a muscle by target interaction, showing that although activity in both muscles increased at higher target forces, activity in the soleus scaled more linearly to the target force. See Figure 12.

Importantly, there was a significant main effect of attentional focus. This main effect demonstrates that the external focus of attention led to lower levels of activity overall (33 %MVC on average) compared to an internal focus of attention (37 %MVC on average). However, there was also a significant Muscle X Focus X Target interaction. This interaction is shown in Figure 4. For the soleus, activity was greater in the internal focus relative to the external focus condition at both 30 and 60 %MVC targets, but this relationship changed for the

100 %MVC target. At maximum forces, an internal focus of attention led to reduced activity in the agonist muscle compared to the external focus condition. In the tibialis anterior, however, an internal focus always led to greater activation, compared to an external focus, even as the magnitude of the target force increased.

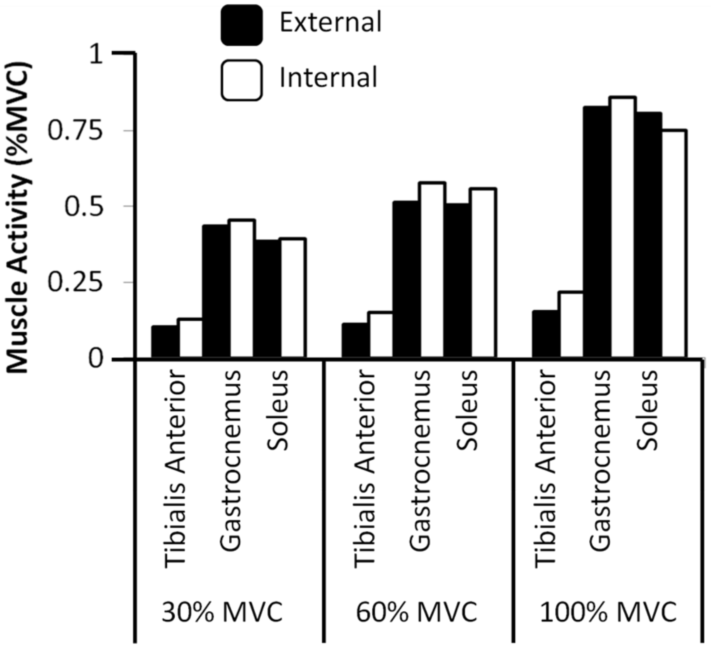

Figure 12. *sEMG activity normalized to a percentage of the maximum voluntary contraction (%MVC) as a function of muscle, attentional focus, and target force.*

Relating Cocontraction to Accuracy. This interaction of focus, target, and muscle fits well with the accuracy data, which shows that subjects were making their largest errors for the 100 %MVC target when internally focused. Underlying these effects on accuracy, subjects were also contracting their soleus less and their tibialis more when internally focused in the 100 %MVC condition. To test the relationship between increasing cocontraction with increasing error, we first calculated an index of cocontraction by dividing activity in the tibialis by activity in the soleus on every trial; this cocontraction ratio is referred to as CCN. Secondly, within each subject, we correlated CCN with AE in each Focus X Target block to get Pearson's R-values representing the relationship of cocontraction to AE. These R-values were transformed using a Fisher's Z-transformation (Fisher, 1915) so that they could be analyzed statistically. These transformed values were significantly different from zero [$Z_{average} = 0.31$, $t(10) = 4.04$, $p = .002$], showing that cocontraction on a given trial was significantly and positively correlated with error on that trial. The relationship between cocontraction and AE did not change significantly as a function of focus, $F(1,10) < 1$, or target, F(1,10) < 1. An identical analysis was conducted correlating CCN with CE within each subject, again the cocontraction relationship was significantly non-zero [$Z_{average} = -0.48$, $t(10) = 4.71$, $p < .001$], showing that increased cocontraction was not just related to larger errors on a given trial, but to large negative errors in particular. Again, the relationship between cocontraction and CE did not change significantly as a function of focus, $F(1,10) < 1$, or target, F(1,10) < 1.

Summary

The results of Experiment 1 show that an external focus of attention led not only to more accurate force production overall, especially in early trials, and that these effects were robust across a range of forces. Furthermore, not only was an external focus of attention more accurate (for both AE and CE), it was more efficient. Analysis of the sEMG data showed that, on average, an external focus of attention led to more efficient patterns of muscle recruitment because it reduced cocontraction relative to an internal focus of attention (which led to significant and unnecessary recruitment of the antagonist muscle). This effect on cocontraction was particularly high for the internal focus condition during the 100 %MVC trials. Correlation analysis showed that increased cocontraction on a given trial was significantly correlated with increased error and with negative errors specifically, which makes sense, given increased activity in the antagonist muscle.

Experiment 2

In Experiment 2, we used the same force production paradigm as Experiment 1 to study the effects of attention on fatigue in the isometric plantar flexion task. Instead of 4 s trials for all MVCs, Experiment 2 used 60 s trials for 30 and 60 %MVC targets, and 100 %MVC trials continued until subjects failed to maintain the target force. Previous behavioral studies have demonstrated that an external focus of attention increases resistance to fatigue in more complex movements (such as multi-joint weight lifting; Marchant, Greig, Bullough, & Hitchen, 2011) and in multi-joint isometric tasks (Lohse & Sherwood, 2011; Nolan, 2011). In our simpler, single joint isometric task however, we equated attentional focus conditions on accuracy and force produced in order to study efficiency specifically. To equate conditions in this way, accuracy criteria were established for each target force, and subjects were given continuous verbal feedback about their accuracy from the experimenter. Thus, we predicted no differences between internal/external focus in terms of movement effects, but predicted that an internal focus of attention would again lead to increased cocontraction as was observed in Experiment 1.

Method

Participants. Data were collected from 12 subjects, 11 of whom were right footed (identified by self report). Subjects always used their dominant foot in the experiment. Five of the subjects were male and seven were female. Subjects were recruited through classes in the Department of Integrative Physiology and participated in the experiment to fulfill course credit requirements.

Apparati and measurements. Identical apparati and measurements were used in Experiment 2. Subjects completed three plantar-flexion MVCs and three dorsi-flexion MVCs prior to testing. The average of the peak forces from those plantar-flexion MVCs was treated as a subject’s maximum force; 100, 60, and 30 %MVC targets were calculated from this average. sEMG data from the soleus and gastrocnemius were normalized to the average activity recorded during the three plantar-flexion MVCs. sEMG data from the tibialis anterior were normalized to the average activity recorded during the three dorsi-flexion MVCs.

Analysis of the sEMG power spectral density was introduced as a new measure in Experiment 2. We analyzed both the mean power frequency (MNF) and the median power frequency (MDF) of the sEMG signal by computing a Fast Fourier Transform (FFT) within 500 ms epochs of the raw sEMG signal (windowed using a Hamming function; data was not filtered prior to spectral analysis). The FFT was then squared and integrated. From this integrated waveform, the MDF was the frequency at which 50% of the total power within the epoch was reached. The MNF was the frequency at which the average power within the epoch was reached. Increases in the power spectral density are indicative of increased motor unit recruitment. The recruitment of larger motor units with faster conduction velocities shifts the MNF and MDF upwards (Arendt-Nielsen, Mills, & Forster, 1989; Farina, Fosci, & Merletti, 2002; Lindstrom, Magnusson, & Peterson, 1970; Olsen, Carpenter, & Henneman, 1968; Solomonow et al., 1990). The MNF and MDF, however, are insensitive to increased discharge rates and therefore are most diagnostic of increased motor unit recruitment during isometric contractions (Lago & Jones, 1977; Van Boxtel & Schomaker, 1984) whereas %MVC is a more general measure of the neural drive supplied to the muscle.

For all biomechanical measurements (i.e., force produced, %MVC for each muscle, and MDF/MNF for each muscle), data was averaged across epochs to create ten decile bins for each trial. Binning data into deciles was done to normalize the time of each trial for statistical analysis.

The psychological measurement of perceived exertion (using a 20 point scale; Borg, 1998) was collected at the end of the 100 %MVC trials. Similarly, the time to failure was also calculated for 100 %MVC trials. Time to failure was defined as the time from when a subject's force entered the target bandwidth to the time when the subject's force left the target bandwidth. 30 and 60 %MVC trials had a fixed duration of 60 s which all subjects were able to maintain.

Design and procedure. The experiment was divided into six trials for each subject by crossing the variable of target %MVC (30, 60, and 100%) with the variable of attentional focus (external or internal); subjects completed one trial with each focus-target pair. Both the order of %MVC targets and the order of attentional foci were fully counter-balanced across subjects. Subjects received 2 min of rest between 30 and 60 %MVC trials. Following 100 %MVC trials, subjects were allowed to rest for four times the duration of the trial or a minimum of five minutes (whichever was longer) to reduce the effects of fatigue between trials. Target %MVCs were blocked together (e.g., all 30 %MVC trials were completed in either an external-internal order or an internal-external order, and then the next target %MVC would be completed in the same order).

Subjects were informed at the beginning of a block of trials which %MVC they were aiming for, how to focus their attention, and what the %MVC translated to in pounds of force. On each trial, subjects would receive a go signal from the experimenter and push against the force platform, trying to generate the target %MVC and maintain that force for 60 s (at 30 & 60 %MVC targets) or until failure (at 100 %MVC targets).

Attentional focus was manipulated by giving subjects the same sets of verbal instructions and feedback used in Experiment 1. During the trial, subjects were reminded of their focus through feedback every 15 s. In the external focus condition, subjects were reminded "Mentally focus on the platform, maintaining your force.” Thus, in the external focus condition, attention was directed toward the *platform*. In the internal focus condition, subjects were reminded, “Mentally focus on the muscle, maintaining the contraction.” Thus, in the internal focus condition, attention was directed toward the agonist *muscle*.

In order to maintain accurate levels of force in all conditions and for the duration of each trial, continuous verbal feedback on accuracy was given by a second experimenter (approximately every 5 s). A target bandwidth was calculated for each trial centered on the subjects’ target force (30, 60, or 100 %MVC) and ± 5% of the target force. On 100 %MVC trials, there was no upper-bound imposed on subjects’ force, meaning that subjects had to produce >95% of their previously recorded maximum, but could exceed the recorded maximum, if possible. If subjects’ force was within the bandwidth, feedback was simply “That’s good”. If subjects’ force started to exceed the bandwidth, they were told, “Less.” If subjects’ force started to fall below the target bandwidth, they were told, “More.” On the 30 and 60 %MVC trials, subjects maintained force for 60 s and then received a stop signal from the experimenter. On the 100 %MVC trials, subjects maintained the target force for as long as possible. A 100% trial ended when a subject dropped below the target bandwidth for more than 1-s or dropped below the target bandwidth more than three times. (It should be noted that for all subjects, they were able to maintain the target force until complete failure, so no trials were ended due to repeated drops in force.)

Analysis. Because biomechanical measures of efficiency were the principle interest of Experiment 2, we used continuous feedback and accuracy requirements to equate the other characteristics of subjects’ performance. Indeed, the focus of attention led to no significant differences in the level of force produced, the standard deviation of force produced, the time to failure in 100 %MVC trials, or RPE for 100 %MVC trials (*p*s > .05). This suggests that the experimental protocol was successful in creating identical force/accuracy requirements in both the internal and external focus conditions. Equating attentional focus conditions on their effectiveness in this way allows us to interpret the biomechanical measures more purely as efficiency.

For the dependent variables of %MVC (sEMG amplitude normalized to each subjects maximum amplitude) and MDF/MNF (power spectrum measures indicating the relative number of active motor units) a 2X2X3X10 repeated-measures ANOVA was used with factors of muscle (the soleus versus the tibialis anterior), focus (external versus internal), target (30, 60, or 100 %MVC), and decile (data averaged into 10 bins for each trial). These effects are summarized in Table 3. Only the significant results of this analysis are discussed, all other effects were not significant (*p* > .05).

Table 3. List of significant effects by dependent variable in Experiment 2.

Effect	%MVC	MDF	MNF
Muscle	$F(1,11) = 74.73$, $p < .001$	$F(1,11) = 59.75$, $p < .001$	$F(1,11) = 7.21$, $p = .02$
Target	$F(1.35,14.88) = 35.41$, $p < .001$ GG, $\varepsilon = .67$	$F(2,22) = 6.07$, $p < .01$	$F(2,22) = 6.05$, $p < .01$
Decile	-*n.s.*-	$F(2.24,24.61) = 5.17$, $p = .01$ GG, $\varepsilon = .25$	$F(3.43,37.76) = 8.24$, $p < .001$ GG, $\varepsilon = .38$
Muscle X Focus	$F(1,11) = 5.97$, $p = .03$	-*n.s.*-	-*n.s.*-
Muscle X Target	$F(1.24,13.63) = 24.02$, $p < .001$ GG, $\varepsilon = .62$	-*n.s.*-	-*n.s.*-
Muscle X Decile	$F(2.13,23.45) = 17.29$, $p < .001$ GG, $\varepsilon = .24$	$F(2.41,23.5) = 8.55$, $p < .01$ GG, $\varepsilon = .24$	-*n.s.*-
Muscle X Focus X Decile	-*n.s.*-	$F(2.24,24.65) = 3.98$, $p = .02$ GG, $\varepsilon = .25$	-*n.s.*-
Focus X Target X Decile	$F(18,198) = 1.72$, $p = .04$	-*n.s.*-	-*n.s.*-
Muscle X Focus X Target X Decile	$F(18,198) = 1.83$, $p = .02$	-*n.s.*-	-*n.s.*-

Note. The dependent measures of normalized muscle activity (%MVC), median power frequency (MDF), and mean power frequency (MNF) were all analyzed using 2 X 2 X 3 X 10 repeated measures ANOVAs with factors of muscle (soleus v. tibialis), focus (internal v. external), target (30, 60, 100% of maximum force), and decile (data from each trial was binned into 10 intervals to normalize for time).

GG = Greenhouse-Geisser correction for violating sphericity (based on Maulchy’s test). Epsilon (ε) was used to adjust weights in degrees of freedom for tests of significance. Corrected degrees of freedom are displayed in the table above.

n.s. = ‘Not significant’, used to denote an effect that was not significant for that dependent variable, but was significant for others. All unreported effects were not significant ($p > .05$)

Results and Discussion

Representative data from a single subject are given in Figure 13, showing two 100 %MVC trials (one externally focused and one internally focused). Qualitative analysis of the EMG data shows high levels of cocontraction between the soleus and the tibialis anterior, especially early in the trial, and greater cocontraction for the internal focus. It is important to note that although this particular subject shows a large difference in the time to failure, there was no significant effect of attentional focus on time to failure across subjects.

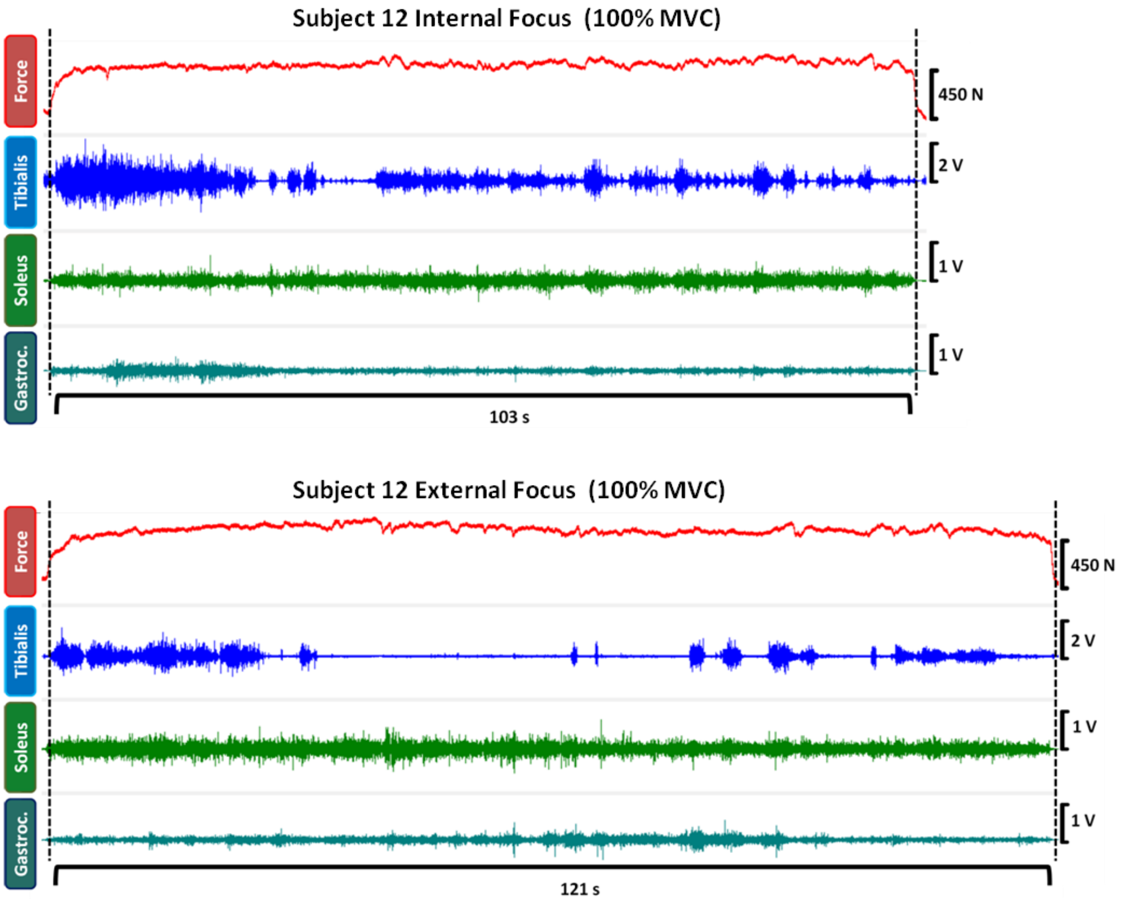

Figure 13. *Force and sEMG from the 100 %MVC trial for Subject 12 in Experiment 2 for both an external and internal focus of attention. In both cases, the subject was trying to maintain 100 %MVC for as long as possible and was given identical feedback about the force being produced. Early cocontraction with an internal focus is representative of the pattern found across subjects; Subject 12's data was chosen because this subject showed a large behavioral effect of attentional focus on time to fatigue.*

Again, there were no significant effects of attentional focus on any of the behavioral dependent variables (i.e., force produced, standard deviation of force produced, time to failure, or ratings of perceived exertion). These behavioral results are summarized in Table 4. This lack of significant differences suggests that the accuracy requirements and the feedback given successfully equated the internal and external focus conditions in terms of the movement effect, making our biomechanical measures a more pure index of movement efficiency. (Although there was a trend for higher levels of force to be produced during externally focused trials.)

Table 4. Summary of behavioral data in Experiment 2 as function of attentional focus and target force.

	External Focus			Internal Focus		
Dependent Variable	30%	60%	100%	30%	60%	100%
Time to Failure (s)	*na*	*na*	107.7 ± 57.4	*na*	*na*	98.9 ± 47.9
RPE	*na*	*na*	14.1 ± 4.95	*na*	*na*	14.5 ± 3.47
Force SD (N)	8.05 ± 2.15	13.25 ± 5.05	21.71 ± 5.98	9.69 ± 3.97	13.61 ± 5.36	23.17 ± 7.05
Force (%MVC)	30.4 ± 0.02	58.7 ± 0.01	1.09 ± 0.11	30.2 ± 0.01	58.7 ± 0.03	1.03 ± 0.08

Note. Cells show the mean ± the standard deviation for each dependent variable as a function of attention focus (external versus internal) and target force (30, 60, or 100 %MVC). The dependent measures include time to failure (which was only collected for 100 %MVC trials, 30 and 60 %MVC trials were always 60 s), ratings of perceived exertion on a 20 point scale (RPE), the standard deviation of force produced (SD), and the level of force produced normalized to each subjects maximum force during a voluntary contraction (%MVC).

Amplitude analysis (%MVC). A significant effect of muscle showed, not surprisingly, that average activity in the soleus (64 %MVC) was much greater than activity in the tibialis (9 %MVC). Also, the significant muscle by target interaction showed that activity in the soleus scaled to the target force (31.6, 52.9, and 108 %MVC for the 30, 60, and 100% targets, respectively) more linearly than activity in the tibialis (6.6, 5.6, and 14.9 %MVC, respectively). Most importantly, there was a significant muscle by focus interaction that showed a significant increase in cocontraction with an internal focus of attention. During internally focused trials when attention was directed to the muscle, activity in the tibialis was greater (9.9 %MVC) relative to activity in the soleus (60.3 %MVC), than it was during externally focused trials when attention was directed to the platform (8.2% and 62.6 %MVC), on average.

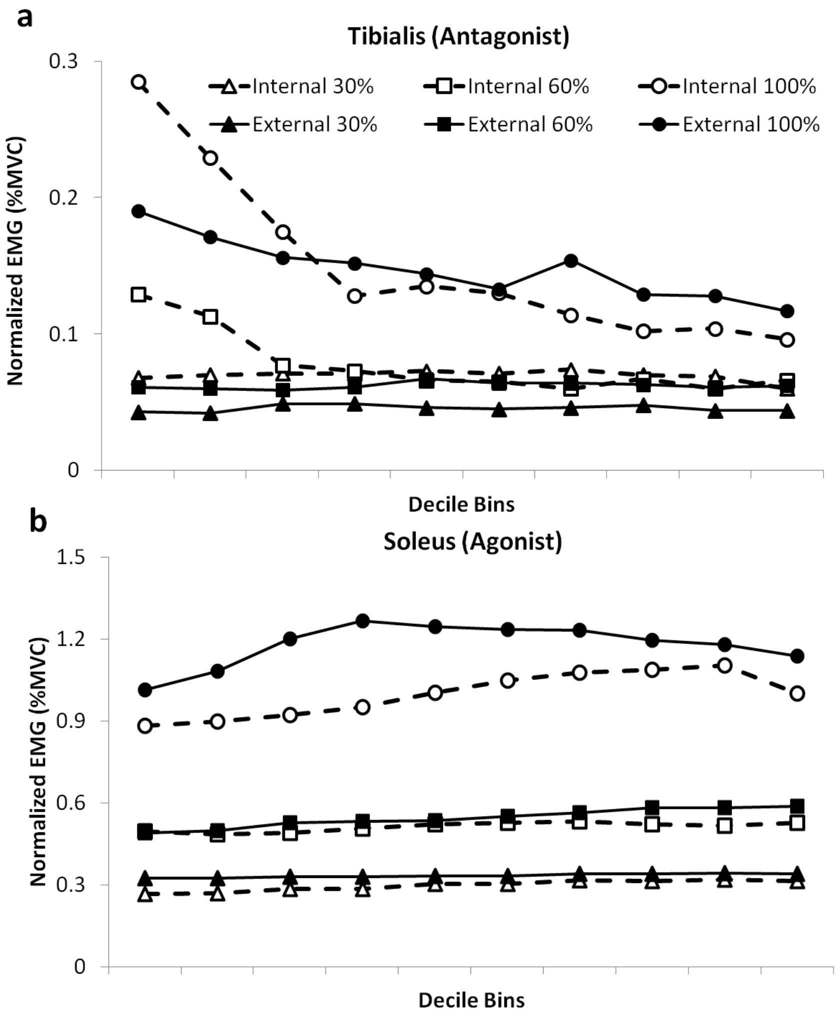

Figure 14. *Normalized sEMG activity (%MVC) as a function of attentional focus, target force, and decile for both the tibialis anterior (panel A) and the soleus (panel B).*

The data are not as simple as an increase in cocontraction with an internal focus of attention, however. There were also significant three-way (focus by target by decile) and four-way (muscle by focus by target by decile) interactions, shown in Figure 14. These interactions with decile show how the cocontraction effect changed as a function of time and level of force produced. At lower levels of force (30 %MVC) there was a nonsignificant increase in tibialis activity with an internal focus relative to an external focus in the first and last decile. As the level of force increased however (60 %MVC), an internal focus led to significantly greater levels of tibialis activity in the first decile (Tukey's LSD *p* = .01), but not in the last decile (*p* = .11). Similarly, at maximum forces (100 %MVC), an internal focus of attention led to significantly greater tibialis activity compared to an external focus in the first decile (Tukey's LSD *p* = .02) but not the last decile (*p* = .27). In the soleus however, this pattern of effects changed. Attentional focus had no significant effect on soleus activity at 30, 60, or 100 %MVC targets, and the level of soleus activity was stable across time.

Power spectrum analysis (MDF/MNF). Analysis of the power spectral density across time shows the effects of fatigue on motor unit recruitment (higher MDF/MNF translates to a greater number of active motor units). For both MDF and MNF, there were significant effects of muscle, target, and decile. These effects on frequency show that there were relatively more active motor units in the soleus (91.9/144.1 Hz; MDF/MNF) than in the tibialis (52.7/121.7 Hz) and that more motor units were recruited with increasing levels of force produced (65.6/128.7; 72.4/132.2; 78.9/137.5 Hz for 30, 60, and 100%MVC targets averaging across muscles).

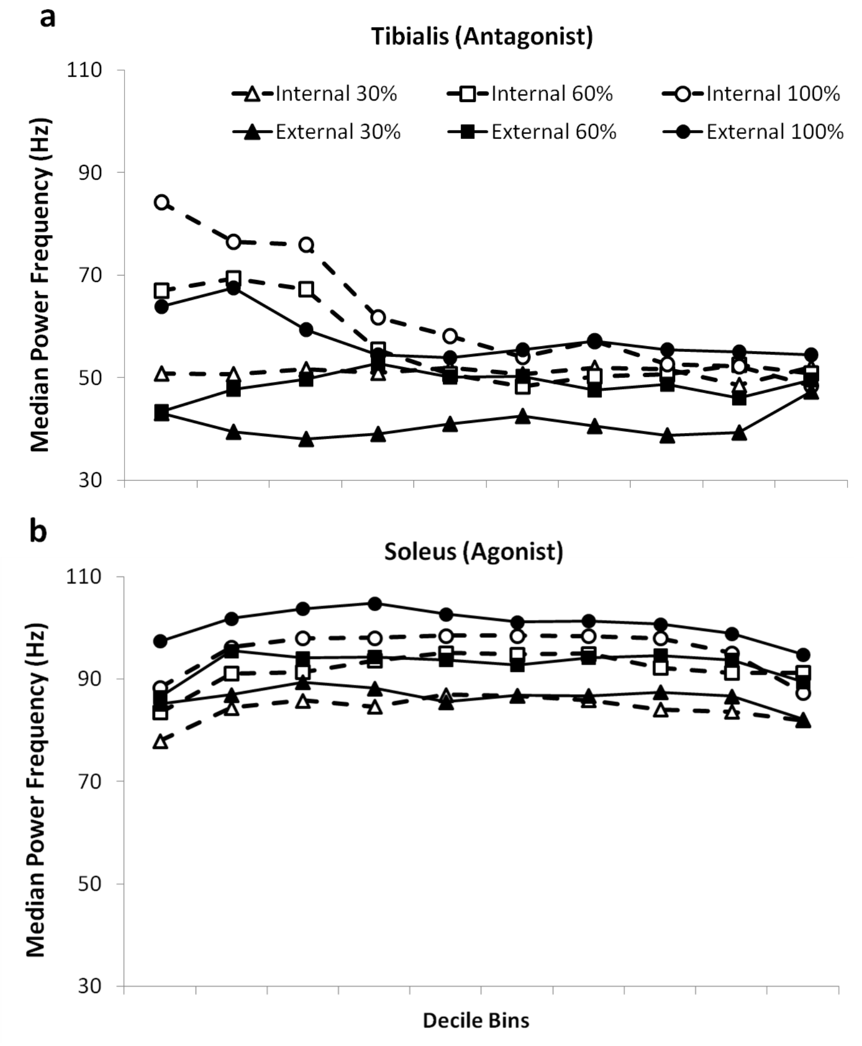

Figure 15. *Median Power Frequency (MDF) as a function of attentional focus, target force, and decile for both the tibialis anterior (panel A) and the soleus (panel B).*

With respect to time, there was a significant effect of decile, but this effect was complicated by significant two-way (muscle by decile) and three-way (muscle by focus by decile) interactions. (These interactions are shown for MDF in Figure 15.) In the tibialis anterior, an internal focus of attention relative to an external focus led to significantly greater MDF in the first decile (Tukey's LSD *p* = .01), but not in the last decile (*p* = .99). In the soleus, however, an internal focus of attention led to significantly lower MDF in the first decile (Tukey's

LSD *p* = .02), but not in last decile (*p* = .38). (Although the data for MNF followed these general trends, the two and three-way interactions between muscle, focus, and decile were only significant for MDF.)

Summary

In Experiment 2, subjects were required to maintain a constant level of force for 60 s (in the 30 and 60 %MVC target conditions) or until failure (100 %MVC condition). Behaviorally, the focus of attention did not significantly affect the time to failure, perceived exertion, or amount of force produced. Neuromechanically, however, the focus of attention had significant effects on the efficiency with which force was produced. An internal focus of attention disrupted efficient intermuscular coordination early in the fatigue trials by increasing cocontraction. This increase in cocontraction was primarily the result of unnecessary increases in antagonist muscle activity, which is particularly interesting because attention was actually directed toward the agonist muscle. Parallel to the results of Experiment 1, this increase in cocontraction was more pronounced at higher levels of force (cocontraction at 30% < 60% < 100 %MVC) which suggests that attention interacts with the magnitude of the motor signal.

It is also interesting that, in Experiment 2, the effects of attention were strongest at the beginning of the trial even though subjects were receiving attentional focus instructions throughout the trial (approximately every 15 s). One potential explanation of this diminishing effect is that subjects shifted their attention externally as the trial continued, despite experimenters' instructions to focus internally. Another possibility is that an internal focus simply leads to more explicit, conscious calibration of the agonist/antagonist relationship that takes more time to adjust than the more implicit calibration which results from an external focus. Thus, given enough time, an internal focus will allow effective force production as subjects consciously adjust the “feeling” of the contraction, but at the expense of efficiency early in the contraction.

General Discussion

Experiments 1 and 2 both generally showed that cocontraction between the agonist and antagonist muscles increased with an internal focus of attention. The full interpretation is more nuanced, however. It appears the level of cocontraction increases with the magnitude of the force produced and seems to be strongest at the beginning of the contraction, at least when force needs to be maintained over time. Interestingly, even though subjects are getting identical feedback about their accuracy and always trying to be as accurate as possible, the ancillary goal to focus, “on the muscle” or “on the platform” has significant effects on neuromuscular efficiency (shown in both Experiments 1 & 2) and these changes can disrupt movement effectiveness (i.e., the correlations between error and cocontraction in Experiment 1). Changes in neuromuscular coordination as a function of attention have important implications for basic research in motor behavior and for applications to rehabilitation and athletics.

Implications for Basic Research: A Neurophysiological Framework

From the perspective of basic research, these changes in intermuscular coordination are fascinating and help us understand the neurophysiological mechanisms that underlie the constrained action hypothesis (Wulf, 2007a; Wulf & Prinz, 2001). To paraphrase the quote by Jackson (1889) at the beginning of this paper, human beings do not generally attempt to control movement based on the actions of individual muscles or even joints, but instead through the desired sensory consequences of the movement (e.g., I don’t need to consciously coordinate the sequence of muscle activations to grab my coffee; Consciously, I decide to take a drink). This notion of effect-based control of voluntary movements has been explored at the psychological/

computational level (e.g., ideomotor theory; James, 1890; Stock & Stock, 2004) and at the algorithmic level (e.g., control through forward and inverse models; Wolpert & Kawato, 1998). Importantly, the current findings on attention in inter-muscular coordination suggest it is not only the nominal goal of the task (e.g, "generate 350 N of force") but also attention that shapes the control structure of the motor system (e.g., "*how* do we generate 350 N of force?"). The finding that attention affects the control structure of the motor system is not a new finding (e.g., Wulf, McNevin, & Shea, 2001), but what is new about the current studies is an understanding of how attention affects motor control at the most basic neuromechanical level of motor unit recruitment.

Increases in cocontraction around a joint increase the stiffness of the joint and are characteristic of motor control early in the learning process (Gribble, Mullin, Cothros, & Mattar, 2003; Osu, Franklin, Kato, Gomi, Domen, Yoshioka, & Kawato, 2002). Increases in joint stiffness might underlie the "freezing degrees of freedom" seen in the kinematics of novice movements, as opposed to expert movements, which are much more fluid (Bernstein, 1967; Schorer, Baker, Fath, & Jaitner, 2007; Vereijken, van Emmerick, Whiting, & Newell, 1992; Wilson, Simpson, van Emmerick, & Hamill, 2008). This fluidity in kinematics emerges because experts have learned to exploit redundant degrees of freedom in the movement pattern, controlling variability in only the most goal-relevant dimensions (Haggard, Hutchinson, & Stein, 1995; Lee, Lishman, & Thomson, 1982; Müller & Loosch, 1999; Scholz, Schöner, & Latash, 2000; Schorer et al., 2007; Voigt, 1933; Wilson et al., 2008). Similar research on the focus of attention shows that an internal focus of attention functionally locks degrees of freedom, (Lohse, Jones, Sherwood, & Healy, 2011; Hossner & Erhlenspeil, 2010) and that high levels of anxiety, which can lead to internally focused attention, similarly create more rigid movement patterns (Beilock & Gray, in press; Higuchi, Imanaka, & Hatayama, 2002; Pijpers, Oudejans, Holsheimer, & Bakker; 2003). These kinematic variability data, combined with electrophysiological data on cocontraction, suggest that an internal focus of attention might lead the motor system to spuriously increase joint stiffness in order to decrease variability in the movement pattern even at the expense of the effectiveness of the movement.

Chapter 4: Attention and Movement Variability

> *"It appeared important to me to demonstrate that a movement could not be understood in terms of some nuance in operation of a single impulse, but that it is the result of simultaneous co-operative operation of whole systems of impulses, while the structure of this system—its structural schema—is important for the understanding of the result."*
>
> – Nikolai Bernstein (1967, p. 36)

One of the most important features of human movement is variability. Variability is important because it allows for movement patterns to be effectively adapted to the environment, to the specific requirements of a task, or to endogenous variables (like motivation and fatigue), while the goal of the task remains invariant (Bernstein, 1967; Davids, Bennett, & Newell, 2006). However, variability can be both promising and problematic, because from a motor-control perspective humans have many more degrees of freedom than are needed to accomplish any single task. The problem of so many additional degrees of freedom has been referred to as the "redundancy problem", because the same movement outcome can be achieved in many different ways (i.e., there are multiple correct solutions to most movement problems; see Todorov, 2004). Recently, optimal control theories of motor learning and control have quantified and modeled how the nervous system takes advantage of these redundancies to optimize performance (Latash, Scholz & Schöner, 2002; Todorov & Jordan, 2002). These theories account not only for measures of performance on average, but also trial-by-trial variability in performance (Loeb, Brown, & Cheng, 1999), which has received less emphasis in previous theories of motor control.

The current study investigates the role of movement variability in mediating the effects of attention on motor outcomes. Previous research on attention in motor learning and control has generally found that when subjects are instructed to focus externally on the goal of a task, they consistently perform better than when instructed to focus internally on their own body mechanics (for reviews, see Lohse, Wulf, & Lewthwaite, in press; Wulf, 2007a). The benefits of an external focus of attention (FOA) with respect to the outcome of movement have been demonstrated in a wide variety of dynamic and isometric tasks, including golf (Bell & Hardy, 2009; Wulf & Su, 2007), basketball free-throw shooting (Zachry, Wulf, Mercer, & Bezodis 2005), dart throwing (Lohse, Sherwood, & Healy, 2010), volleyball serves and soccer kicks (Wulf, McConnel, Gärtner, & Schwarz, 2002), and force production (Lohse, Sherwood, & Healy, 2011; Marchant, Grieg, & Scott, 2009). However, only recently have studies begun examining how attention affects properties of the movement itself, such as muscle recruitment (Lohse et al., 2011; Vance, Wulf, Töllner, McNevin, & Mercer, 2004; Zachry et al., 2005), energetic cost (Schücker, Hagemann, Strauss, & Völker, 2009), and movement kinematics (Lohse et al., 2010). We suggest that analyzing movement variability is critical to understanding the effects of attention, because it provides insights into what aspects of the movement are being controlled (Wolpert & Ghahramani, 2000).

One finding from recent research on attention and motor variability is that external FOA actually increases variability of the movement pattern across trials, even though it reduces error in the movement outcome (Lohse et al., 2010). Although this finding may seem paradoxical, it is consistent with findings of *functional variability* in research on expertise effects in motor control, whereby experts often exhibit greater movement variability, concomitant with better performance. Functional variability can be explained within optimal control theory as a consequence of coordination among effectors, whereby effectors compensate for perturbations in each other's dynamics to reduce overall error (Todorov & Jordan, 2002). Thus, there is a tradeoff between minimizing variability of the outcome and of the dynamics of individual effectors. When the goal of the motor system is to control some external outcome variable (e.g., the landing position of a dart), the optimal control strategy produces increased correlations among effectors, at the expense of increasing their individual variances.

These previous findings lead to the present proposal that attention regulates motor control by helping to determine the control strategy of the motor system. In internal FOA conditions, we hypothesize that bodily dimensions such as muscle activations or joint angles are directly controlled, minimizing their individual variabilities. This control strategy indirectly reduces error or variability in the outcome, but not as effectively as does controlling the outcome directly. Under external FOA, we hypothesize the target of control is the outcome itself. This control strategy leads to improved performance, by allowing individual effectors to compensate for each other in service of reducing variability in the outcome. As a byproduct of this coordination, the variabilities of individual effectors increase, as do their intercorrelations (as explained in more detail below). Thus, the present theory makes predictions for how FOA affects performance (outcome variability), variability across trials of individual bodily dimensions such as joint angles or muscle tensions, and the correlation structure among bodily dimensions.

This theory of attention in motor control is grounded in optimal control theory and is consistent with models of attention in other domains, including learning and perception. After reviewing these connections, as well as previous research on FOA in motor control, we report an experiment testing the theory in a dart-throwing task. Results show that more-external FOAs produce improved performance as well as increased movement variability. Critically, external FOA also strengthens the correlation structure among the movements of individual joints, indicating that their increased variabilities are consequences of coordination, which presumably acts to reduce variability of the outcome. These results support the proposal that attention can alter the control structure that guides movement, and more broadly, they argue for a central role of cognitive variables in low-level motor control.

The Effects of Focus of Attention on Motor Control

Research on FOA suggests that instructions or feedback directing subjects' attention externally (to the effect of an action on the environment) significantly improves performance relative to focusing internally (to the mechanics of the body itself). For instance, when shooting a basketball, subjects do better when mentally focused externally on the back of the rim compared to internally on the motion of the wrist, even though visual attention (i.e., gaze direction) is the same in both conditions (Zachry et al., 2005). Furthermore, a number of previous studies have shown focusing externally to improve performance relative to control conditions where no attentional instructions are given (Freudenheim, Wulf, Madureira, Pasetto, & Corrêa, 2010; Hodges & Franks, 2000; Landers, Wulf, Wallmann, & Guadagnoli, 2005; McNevin & Wulf, 2002; Wulf & McNevin, 2003; Wulf, Weigelt, Poulter, & McNevin, 2003). The advantage of focusing externally also holds in clinical studies of motor performance following stroke (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002), in Parkinson's disease patients (Landers et al., 2005; Wulf, Landers, Lewthwaite, & Töllner, 2009), or following musculoskeletal injury (Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007).

Similarly, Mechsner, Kerzel, Knoblich, and Prinz (2001) found that focusing on the goal of a bi-manual coordination task allowed subjects to produce movement patterns that were almost impossible for them to produce when focused on controlling the movement itself. In one of their experiments, subjects performed bimanual, circular hand movements. In this bimanual coordination task, there is a strong tendency toward symmetrical movement of the hands, and unequal frequencies (e.g., 5:4 or 4:3 frequency ratios) are very difficult to maintain and almost impossible for novices to perform (Kelso, 1995). The clever manipulation in this experiment was that subjects grasped handles obstructed from their vision below a table, and rotating these handles rotated flags that were within view above the table. The gear ratio between the flags and the handles could be manipulated so that a 4:3 frequency rotation in hand movement would produce synchronized flag movement. Subjects were able to stably produce the 4:3 frequency ratio in hand movements in this condition. Thus, being able to focus on controlling a stable perceptual pattern allowed subjects to produce a coordinated movement that would otherwise be quite difficult. There was also anecdotal evidence that attention directed to the hands disrupted movement control and degraded the intended movement pattern (Mechsner et al., 2001, p. 72).

Currently, the dominant explanation in the literature of impaired performance resulting from an internal FOA is the *constrained action hypothesis* (Wulf, 2007b), which posits that an internal FOA increases explicit monitoring of otherwise implicit motor behaviors, thus slowing processing and hurting performance (see also Beilock & Carr, 2001). The constrained action hypothesis has been criticized, however, for not being integrated with larger theories of motor control (Oudejans, Koedijker, & Beek, 2007) and because the precise mechanisms that constrain action need to be better specified in order to make the hypothesis testable (Raab, 2007). For instance, in its current form, the constrained action hypothesis does not make predictions about the details of movement under internal versus external focus conditions. One reason the constrained action hypothesis does not address movement details is that the majority of studies on FOA have been limited to the effects of attention on motor outcomes (e.g., accuracy, balance, speed), and little work has been done to explore the effects of attention on the kinematic and dynamic properties of movement itself.

One recent study on dart throwing that did examine movement kinematics (Lohse et al., 2010) found that performance was significantly increased by verbal cues in instructions directing subjects' attention to the flight of the dart (external focus) compared to the motion of the arm (internal focus). Additionally, biomechanical analysis showed that external FOA increased trial-by-trial variability in the shoulder angle of the throwing arm at the moment of release. One possible cause of this increased variability is reduced rigidity in the motion due to decreased muscle stiffness, as indicated by significantly reduced surface electromyographic (sEMG) activity in the muscles of the throwing arm in the external condition. Similar studies exploring the effects of attention on muscle recruitment have generally found that external FOA produces more efficient muscle recruitment during dynamic tasks (Marchant, Greig, & Scott, 2009; Wulf, Dufek, Lozano, & Pettigrew, 2010) and reduced cocontraction between agonist-antagonist muscle pairs in isometric tasks (Lohse et al., 2011), which is consistent with the finding of increased variability of individual joints, because reducing cocontraction reduces joint stiffness.

These changes in movement variability and joint stiffness likely play an important role in mediating the influence of attention on performance, but they lie outside the scope of current theories. Thus, the aim of the current study was to develop a more mechanistic theory of attention in complex motor tasks, by integrating research on FOA with optimal control theories of motor control and learning. We propose below that attention regulates motor control by changing which aspects of the movement are controlled—goal dimensions with an external focus or bodily dimensions with an internal focus. To motivate how such shifts of the control policy can affect both performance and patterns of movement variability, we next review research on the role of movement variability in skilled and optimal performance.

Variability in Expertise and Optimal Control

One interesting finding regarding the relationship between movement variability and performance comes from studies comparing experts to novices. Somewhat paradoxically, experts can show increased trial-by-trial variation in movement patterns while simultaneously showing superior performance in the movement outcome. This phenomenon has been referred to as functional variability, to capture the idea that variability is somehow enabling improved performance (Müller & Loosch, 1999).

For instance, Schorer, Baker, Fath, and Jaitner (2007) explored kinematic variability in the throwing motion of handball players in three dimensions across a range of skill levels (from beginner to national-team level). Cluster analysis revealed that novices and intermediate players had only two stable movement patterns that principally differed in the direction of the throw (e.g., one stereotyped pattern for a shot to the high left and another to the low right). In contrast, experts' throwing motions clustered into roughly four different patterns, none of which could be assigned to a specific throwing direction. This absence of correspondence between throwing direction and movement pattern suggests that experts use varying movement patterns to produce similar flight trajectories. This finding suggests that experts have learned "multiple correct solutions" (Todorov, 2004) to reliably produce a specific shot with variable throwing mechanics.

One explanation of these findings of functional variability is that experts control variation in only goal-relevant dimensions of the movement, while allowing redundant dimensions (i.e., aspects of the movement that do not affect the outcome) to vary. By dimensions, we mean directions within the abstract movement space comprising all possible movement patterns.

Evidence for this type of selective control is seen in anisotropic patterns of variability, wherein redundant dimensions show greater trial-by-trial variation than goal-relevant dimensions. A classic example in the motor control literature comes from motion analysis of expert hammer swings (Bernstein, 1967), in which the contact point of the hammer on the target is very consistent, but the motion paths of shoulder and elbow are variable. Such patterns have been observed in a wide range of tasks, including reaching (Haggard, Hutchinson, & Stein, 1995), grasping (Cole & Abbs, 1986), pointing (Tseng, Scholz, & Schöner, 2002), writing (Wright, 1990), postural control (Scholz & Schöner, 1999), and even skiing (Vereijken, van Emmerick, Whiting, & Newell, 1992). Importantly, anisotropic variability is more pronounced in the movement of experts than novices (Schorer et al., 2007; Vereijken et al., 1992; Wilson, Simpson, van Emmerick, & Hamill, 2008).

Scholz and Schöner (1999) offer a formal framework for addressing the relationship between anisotropic variability and control strategies. They define the *uncontrolled manifold* as the subspace, within the space of all possible movements, within which the movement is uncontrolled and hence allowed to vary. When the control strategy of the motor system is to control the task outcome directly, the uncontrolled manifold comprises the subspace of movements that are consistent with the task goal (Kang, Shinohara, Zatsiorsky, & Latash, 2004; Scholz & Schöner, 1999). Based on this definition, Scholz and Schöner (1999) proposed that trial-by-trial movement variability should be greater parallel than perpendicular to the uncontrolled manifold. Scholz, Schöner, and Latash (2000) tested this prediction in a study of quick-draw shooting, using kinematic analysis of pistol drawing and shooting motions. They reasoned that pitch (vertical deviation in the sagittal plane) and yaw (lateral deviation in the transverse plane) significantly influence the outcome of the shot, whereas roll (rotary deviation of the gun in the frontal plane) and the absolute position of the pistol in the line of the shot are largely irrelevant. Consistent with this task analysis and with the uncontrolled manifold hypothesis, pitch and yaw exhibited significantly less variability than did roll and absolute position.

This framework shows how the goal of any task defines a decomposition of movement space into dimensions that are relevant to the outcome and those that are irrelevant. If we consider the subspace of movements that are consistent with the task goal, then any variability perpendicular to this manifold is detrimental, whereas any variability within (i.e., parallel to) it contributes no error. We thus define a *goal-relevant dimension* as any dimension within movement space that is perpendicular to this subspace, that is, any dimension of the movement that affects the task outcome (such as the final landing point of a dart). A *redundant dimension* is any dimension of the movement that is parallel to the subspace and hence does not affect the task outcome. To be clear, by *dimension* we mean not a spatial direction, but a dimension within the abstract multidimensional space of possible movements, similar to a perceptual dimension within an abstract stimulus space. Importantly, because the outcome of most tasks depends on the combined actions of many effectors, a goal-relevant dimension will tend to lie at some oblique angle in the movement space defined by individual bodily dimensions (e.g., joint angles).[1]

Research in optimal control theory has provided a rational, quantitative basis for the prediction that movement variability should be greater along redundant dimensions than along

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[1] A technical complication is that the goal will in general be nonlinearly related to individual effectors, meaning the uncontrolled manifold is a curved hypersurface, not a linear subspace. We follow Scholz and Schöner (1999) in assuming a linear approximation to this surface in the region of the average movement pattern of each subject. This approach simplifies the data analysis below but is not a necessary assumption of the theoretical framework.

goal-relevant dimensions. Optimal control theory casts motor behavior in terms of statistically optimal control (for reviews see Latash et al., 2002; Latash, Scholz & Schöner, 2007; Todorov, 2004). According to this perspective, a control rule defines a movement variable to be either maximized or minimized (e.g., the goal in a vertical jump is to maximize center of mass displacement, whereas the goal of a balance task is to minimize sway). Lower levels of control (e.g., the activities of individual muscles or joints) then interact to implement the optimal solution to the control rule.

One strength of optimal control theory is that it explains how trial-by-trial variability in the details of movement can coexist alongside reliable, reproducible movement outcomes. Central to this approach is the assumption that motor dynamics are inherently noisy, so that exact movement patterns are not reproducible (Wolpert & Ghahramani, 2000). Thus, the motor system works to minimize expected error in the face of this noise. In cases of closed-loop control (as opposed to ballistic movement), the brain can adapt control signals in response to perturbations that arise during the course of the movement, thus reducing final error. However, because motor noise is positively dependent on muscle activation (Harris & Wolpert, 1998; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Todorov, 2002), optimal control conserves the corrective signals it generates, correcting only those perturbations that affect attainment of the task goal. This conservation strategy is referred to as the *minimal intervention principle* (Todorov & Jordan, 2002). Because of redundancy, there are generally many more degrees of freedom in the space of possible movements than in the constraints that define the task goal. That is, the task is underconstrained, meaning that variability in certain directions in movement space is irrelevant to the goal. Optimal control allows these irrelevant perturbations to accumulate, rather than correcting them at the cost of increasing motor noise. Consequently, optimal control theory predicts greater variability in task-irrelevant than in task-relevant aspects of the movement.

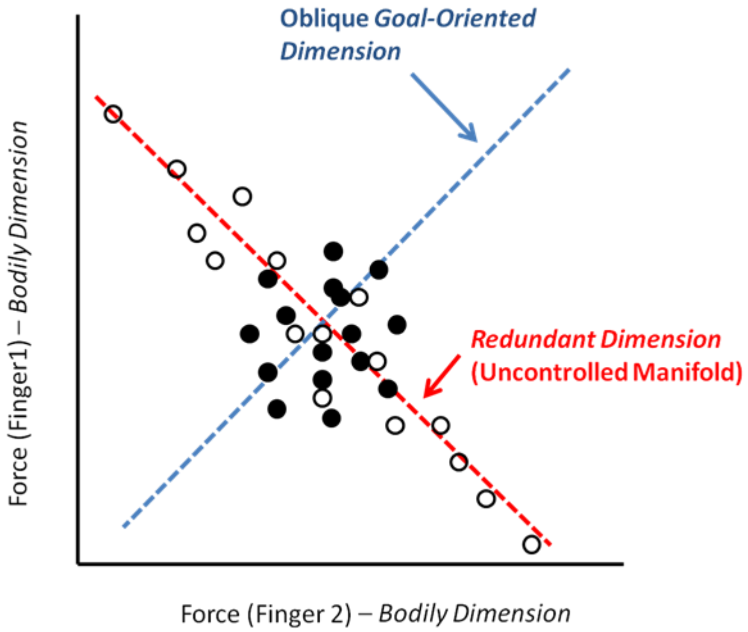

Figure 16. *Hypothetical data points showing results of two alternative control structures for producing force with two fingers. The task goal is defined only by the sum of the two forces. Open circles correspond to goal-oriented, externally focused control, showing how functional variability (in the bodily dimensions) can reduce variability in the goal-relevant dimension, as postulated by an optimal control framework. Solid circles correspond to movement oriented, internally focused control, producing global suppression of movement variability that ultimately leads to increased variability in the goal dimension.*

An example of this prediction from optimal control theory is shown in Figure 16. This figure depicts the action space of a hypothetical task in which the goal is to produce a certain total force (say, 35 N) with two fingers (see Todorov & Jordan, 2002, for a computational analysis of an isomorphic task). The individual contributions of the fingers can vary (e.g., one finger can produce 10 N and the other 25 N), provided that variation in each finger is accommodated by an adjustment in the other. Thus, the goal-relevant dimension is the sum of the two forces, corresponding to the positive diagonal in movement space, whereas the difference between the forces (the negative diagonal) is a redundant dimension. Optimal control theory predicts any perturbation in one finger to be corrected by both fingers (e.g., a deviation of +2 N in one finger induces corrections of -1 N in both fingers), to bring the system back to the nearest point on the uncontrolled manifold (see Diedrichsen, 2007, for empirical confirmation of this prediction in a bimanual movement task). That is, any error in the goal-relevant dimension is corrected using the minimal necessary control signals, in line with the minimal intervention principle. The result of this control strategy is that the joint distribution of forces across trials exhibits less variability along the goal-relevant than the redundant dimension (illustrated by the open circles in Figure 16). An alternative strategy to control each finger separately (e.g., trying to make each finger produce 17.5 N every time) would decrease their individual variabilities, but it would increase variability on the goal-relevant dimension (filled circles in Figure 16), leading to poorer performance. Thus, optimal, goal-oriented control predicts anisotropic error distributions, characterized by correlations among bodily dimensions that serve to selectively reduce variability on the goal-relevant dimension.

The preceding analysis helps to shed light on the phenomenon of functional variability. Suppressing variability in goal-relevant dimensions, while allowing variation in redundant dimensions, can lead to increased variability of individual bodily dimensions while at the same time reducing variability in the outcome. The result of this control strategy is the functional variability observed in human movement. However, from this perspective, the term “functional variability” is something of a misnomer. The strategy of selectively controlling goal-relevant aspects of the movement produces both increased variability in individual movement parameters and improved performance, but the increased variability itself is not the cause of the performance improvement. Furthermore, variability in goal-relevant dimensions will always impair performance. For variability to be functional, movement parameters cannot vary randomly, but must interact with and compensate for each other in a way that improves and reduces variability in the movement outcome (Lee, Lishman, & Thomson, 1982; Müller & Loosch, 1999; Schorer et al., 2007; Voigt, 1933; Wilson et al., 2008). This reasoning leads to the prediction that in findings of functional variability—in expertise studies and, as we propose in more detail below, in conditions of external FOA—the increased variability resides only in redundant dimensions, whereas variability in goal-relevant dimensions is actually reduced. Because the task goal generally defines a dimension in movement space that is oblique to individual bodily dimensions (i.e., the outcome depends on the combination of multiple effectors, as in Figure 16), assessing variability only along individual bodily dimensions may not reveal the full picture.

The Role of Attention in Motor Control

Although there is considerable evidence that the focus of attention can improve or impair motor performance, current models of motor control do not include cognitive variables like attention. The principles of optimal control theory reviewed above, together with the findings on effects of FOA, lead to a natural proposal regarding the role of attention in motor control. Specifically, we propose that attention contributes to determining the control rule implemented by the motor system. This control rule does not necessarily correspond to the nominal, objective goal of the task. Instead, cognitive factors intervene to determine the subjective goal of the subject. Attention can thus be viewed as helping to determine that subjective goal. From the perspective of the uncontrolled manifold hypothesis (Scholz & Schöner, 1999), attention can be viewed as helping to determine which aspects of the movement the motor system treats as task-relevant and which it treats as irrelevant or redundant.

According to this proposal, when attention is focused externally, on the objective task goal, the motor system works to optimize that goal. Variation along goal-relevant dimensions of the movement is thus minimized, while bodily dimensions vary more freely to implement the necessary coordination (e.g., open circles in Figure 16). This predicted pattern of variability is consistent with the predictions of optimal control theory, under the assumption that the control rule aligns with the nominal task goal. When attention is focused internally, on aspects of the movement such as joint angles or muscle tensions, the motor system treats those bodily dimensions as the goal, and it minimizes their variability even at a cost to objective performance (e.g., filled circles in Figure 16). Both of these patterns could be considered optimal, if the motor system is assumed to treat the attended dimensions in each case as defining the objective function to be optimized.

This theory of attention in motor control leads to the straightforward prediction that variability will be greater along unattended than attended dimensions of movement. Thus, attention can be viewed as acting to allocate precision among competing dimensions. At a computational level, this proposal is quite similar to theories of attention in other domains. For example, Goldstone (1994a) found evidence that increased attention to a stimulus dimension selectively improves discrimination along that dimension. Maddox and Dodd (2003) observed similar effects, which they successfully modeled using general recognition theory (Ashby & Townsend, 1986) under the assumption that perceptual noise is greater on unattended than attended dimensions. Thus, attention appears to regulate the precision of perceptual representations on different stimulus dimensions.

Similar ideas have been prominent in research on attention in learning. Classic research on animal discrimination learning found that attention to different stimulus dimensions controls how broadly animals will generalize learned associations along those dimensions (Sutherland & Mackintosh, 1971). Research on human category learning has supported the same conclusion, that category knowledge about one stimulus will be generalized to other stimuli differing greatly on unattended dimensions, but only to stimuli with small differences on attended dimensions (Jones, Maddox, & Love, 2005; Nosofsky, 1986). Modern approaches from statistics and machine learning (e.g., Jäkel, Schölkopf, & Wichmann, 2007, 2008) show that these effects of attention can be modeled using Gaussian similarity kernels (which determine pairwise similarity or generalization between stimuli), with greater dispersion along unattended than attended dimensions.

The findings and models in perceptual discrimination, conditioning, and categorization all fit with theories of similarity in which attention acts to weight different stimulus dimensions in determining overall similarity (Goldstone, 1994b; Medin, Goldstone, & Gentner, 1993; Nosofsky, 1986), with similarity seen as reflecting discriminability or tendency for generalization (or both). The present proposal regarding attention in motor control is consistent with this framework as well, under the assumption that deviations between actual and target movement trajectories are used to determine the need for correcting the movement. In this case, we suggest that deviations on different dimensions are weighted according to their level of attention, so that deviations on attended dimensions are corrected more strongly or consistently. Specifically, we propose that corrective signals are primarily driven by deviations in bodily dimensions in conditions of internal FOA and by deviations along goal-relevant dimensions in conditions of external FOA. Thus, whereas previous work suggests that attention serves to modulate the precision of stimulus representations along alternative dimensions, the present proposal suggests attention plays a complementary role in motor control, modulating the precision of movement along alternative (goal-based or bodily) dimensions.[2] This proposal leads to specific patterns of variability under internal and external FOA, which we test in the present experiment.

The Present Study – Attention as the Allocation of Precision

The main hypothesis of the current experiment was that attention influences the control structure of human movement, leading to increased precision for attended movement dimensions. From a theoretical standpoint this hypothesis has two major implications: (a) It provides a testable mechanism by which attention can affect movement (cf. Oudejans et al., 2007; Raab, 2007), and (b) if attention does significantly affect the coordination of movement, it would open the door for future research to explore the inclusion of attention and other cognitive variables in formal models of motor control.

The present study tested this hypothesis using a dart-throwing paradigm similar to that of Lohse et al. (2010), with novice participants. Each subject performed the task under four FOAs, ranging from purely internal (throwing arm) to purely external (dartboard), as well as a free focus condition. We tested the effects of attention on movement variability by recording seven biomechanical variables (joint angles and positions) at the moment of release on each trial. It was expected that the more internal FOAs would produce decreased variability in these bodily dimensions, whereas the more external FOAs would produce greater accuracy in the outcome (i.e., landing point of the dart). Most importantly, the superior performance under external FOA

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[2] As mentioned above, goal-relevant and bodily dimensions will generally lie at oblique (i.e., non-orthogonal) angles, and thus they are not in pure competition. Nevertheless, variability in goal-relevant dimensions should be less with external than internal FOA, and vice versa for bodily dimensions.

was predicted to arise from increased coordination among joints, implementing selective control along the goal-relevant dimension in movement space.

The outcome on each trial is likely a nonlinear function of the various bodily dimensions involved in the motion. However, under the assumption that this function is approximately linear in a local neighborhood around the mean movement (Scholz & Schöner, 1999), we can treat the goal as factorizing the movement space defined by the individual bodily dimensions (i.e., the space spanned by the seven biomechanical measures) into two linear subspaces: one defined by the goal-relevant dimension and the other defined by the redundant degrees of freedom in the motion.[3] To the extent that the biomechanical variables all play some role in affecting the outcome, the goal-relevant dimension will be oblique to all of the bodily dimensions. Therefore, if external FOA leads to selective control of the goal-relevant dimension relative to the redundant dimensions, the resulting pattern of anisotropic variability will be reflected in increased correlations among the bodily dimensions (as in the example of Figure 16). Thus, without knowing how the goal-relevant dimension is oriented in movement space—which depends on complex kinematics of the arm and dart—we can still test the effects of attention on selectively reducing variability on this dimension by comparing the correlations among bodily dimensions across the different focus conditions (as elaborated below). Thus, our specific predictions were that more-external foci would be associated with (a) increased trial-by-trial

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[3] Because all biomechanical measurements were made in the sagittal plane, they primarily affect the vertical position of the dart's landing point. Thus, even though the goal is defined by two variables (vertical and horizontal dart position), only one goal dimension is likely to lie within the movement space spanned by the bodily dimensions measured here. The dimensionalities of the goal-relevant and redundant subspaces are not critical to our prediction regarding correlations among bodily dimensions, but nevertheless we write in terms of a single goal-relevant dimension.

variance in the bodily dimensions and (b) increased correlations among the bodily dimensions, leading to (c) improved performance.

A secondary aim of this study was to test whether the optimal FOA changes for novice dart throwers as a function of practice. To test this hypothesis, subjects were brought into the lab in four separate sessions over the course of 2 weeks. In each session, subjects practiced and were tested on throwing with their dominant arm under five attentional foci distributed along the kinetic chain of the task: arm motion, release of the dart, dart trajectory, the dartboard, and a free focus condition. This approach of testing an ordered array of foci throughout learning allows detection of potential shifts in the optimal FOA as a function of practice. In the fourth and final session, after training and testing with the dominant arm, subjects also completed the same test of dart throwing with the nondominant arm. This approach allows a comparison of a skilled effector (the dominant arm, which has at that point received considerable practice) with an unskilled effector (the nondominant arm, which is assumed to be generally less skilled and has not had the benefit of specific practice in the dart-throwing task), allowing potential shifts in the optimal focus of attention to emerge as a function of skill with a given limb. Previous quasi-experimental research comparing the performance of experts and novices with varying FOAs has found that both groups benefit more from an external focus than an internal focus (Wulf & Su, 2007), but also that the optimal focus is more distal for experts than for novices (Bell & Hardy, 2009; Wulf, McNevin, Fuchs, Ritter, & Toole, 2000). This idea is consistent with the present theory of attention in motor control, because directly controlling an external goal requires knowing how it can be controlled. That is, subjects must learn an adequate model of the task dynamics in order to, in effect, identify what dimension (or submanifold) within movement space corresponds to that goal. Goals further down the kinetic chain of a task require more accurate or elaborate mental models, and novices lacking such models will be unable to benefit from focus on those goals.

Method

Participants

Data were collected from 15 subjects, 13 of whom were right-handed as identified by the Edinburgh Handedness Inventory (Oldfield, 1971). Nine of the subjects were male. Subjects were recruited through introductory psychology classes and participated in the experiment to fulfill course credit requirements. Subjects were naive to the hypotheses of the experiment.

Apparatus and Measurements

A commercially available competition bristle dartboard was set to a regulation height (1.73 m off the ground) and distance (2.37 m from the throwing line). Subjects threw regulation steel-tip darts weighing 22 g. Performance was defined as absolute error (AE) on each trial, measured as the linear distance from the center of the dartboard ("bulls-eye") to the dart using a hand-held tape measure.

A Canon Z950 MiniDV camera (30 frames per second capture rate) was placed perpendicular to the line of the throw, on the side of the subject's throwing arm, to capture movement in the sagittal plane. Video data were captured and analyzed using Dartfish ConnectPro motion-analysis software. To capture kinematic data in the video, reflective anatomical markers were placed on the throwing arm at the acromion process of the shoulder, the lateral epicondyle of the elbow, the ulnar styloid process of the wrist, and the first knuckle of the index finger (see Figure 17). From these anatomical locations, seven biomechanical variables were derived for characterizing the subject's position at the release point of each throw, defined as the first video frame in which the dart had clearly left the hand. These variables, displayed in Figure 17, were (A) the X and Y (i.e., horizontal and vertical) coordinates of the shoulder, (B) the angle of the shoulder (defined as the angle between the vertical axis, acromion process, and lateral epicondyle), (C) the angle of the elbow (defined as the angle between the acromion process, lateral epicondyle, and styloid process), (D) the wrist angle (defined as the angle between the lateral epicondyle, styloid process, and first knuckle of the index finger), and (E) the X and Y coordinates of the first knuckle of the index finger.

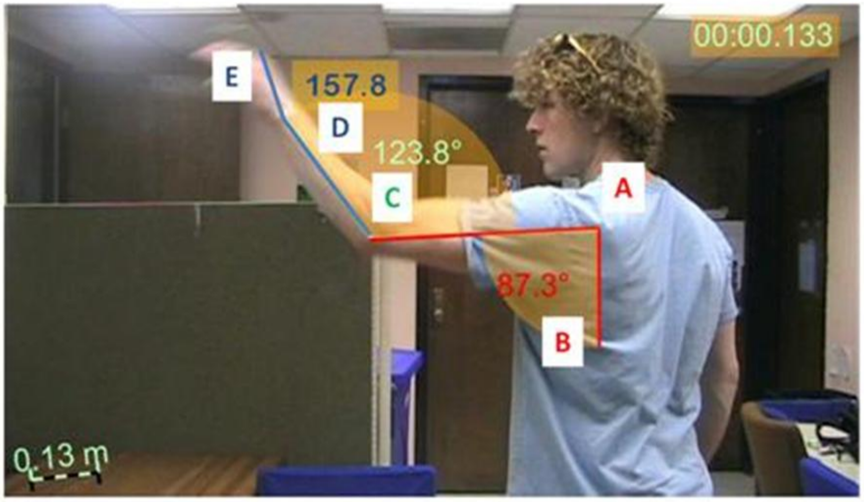

Figure 17. *A diagram of the biomechanical variables captured at the endpoint of the throwing motion. The endpoint was defined as the first frame in which the dart had clearly left the hand. A = shoulder X and Y coordinates (at the acromion process); B = shoulder angle (measured from the vertical axis to the acromion process to the lateral epicondyle); C = elbow angle (measured from the acromion process to the lateral epicondyle to the ulnar styloid process); D = wrist angle (measured from the lateral epicondyle to the ulnar styloid process to the first knuckle of the index finger); E = knuckle X and Y coordinates (at the first knuckle of the index finger).*

Design

The experiment was divided into four sessions, with two sessions in the first week and two sessions in the second week. Sessions were on different days each week based on subjects' availability. Each session consisted of 1-2 testing phases and 1-2 free practice phases, occurring in different orders depending on the session. During free practice, subjects were allowed to throw darts at the board at their own pace with no accuracy measurements, no collection of video data, and no instructions from the experimenter. During each testing phase, subjects completed 75 throws, 15 for each of five attentional foci, in a blocked ordering. The order of attentional foci was counterbalanced using a Latin Square across subjects, and a given subject always completed the foci in the same order within each session.

Procedure

Subjects were instructed and shown through experimenter demonstration to limit their throwing as much as possible to flexion and extension of the arm and wrist in the sagittal plane (i.e., no “side-arming” the throw). For all five FOA conditions, subjects were instructed to try to be as accurate as possible, and the bulls-eye was always the target during practice and testing. Subjects were required to maintain their gaze on the dartboard in all conditions, removing any confound of overt visual attention.

At the beginning of the first session, subjects were allowed six practice throws to familiarize themselves with the experiment setup. They then immediately began the first testing phase. Following testing, subjects were allowed 10 min of free practice. In the second and third sessions, subjects completed 10 min of free practice, then a testing phase, and then another 10 min of free practice. In the fourth session, subjects completed 10 min of free practice prior to a testing phase with the dominant arm. Following testing with the dominant arm in the fourth session, anatomical markers were placed on the subject’s nondominant arm and the subject was given six practice throws with the nondominant arm before beginning a testing phase with the nondominant arm.

For each FOA condition within each testing phase, the subject completed 5 blocks of 3 throws (trials) each. The subject was given three darts to throw in succession, to minimize disruption to the subject's posture within each block. At the end of every FOA condition (i.e., after every 15 throws), subjects were given a brief rest period during which they were allowed to sit. Accuracy measurements were taken by the experimenter after every block of 3 throws.

Testing was the only time that the experimenters collected accuracy or video data. The camera was always present during free practice as well as testing, but subjects were only filmed during testing, and subjects were aware of when they were being filmed. Only testing phases from Session 1 (referred to as Session 1D for consistency), Session 4 with the dominant arm (Session 4D), and Session 4 with the nondominant arm (Session 4N) were used for analysis. Data from Sessions 2 and 3 were collected but were omitted from the final analysis to limit the number of statistical tests used and to simplify the analysis.

In each FOA condition, subjects' mental attention was directed, through verbal instruction, to a different aspect of the throw: the motion of the arm, the release of the dart, the trajectory of the dart, or the board itself. The attentional foci thus ranged from the more internal and proximal to the more external and distal. In a fifth focus condition, subjects were allowed to direct their attention freely.

For the *arm* condition, subjects' attention was directed to the motion of the throwing arm. At the beginning of this condition in each testing phase, subjects were told: "Focus on the motion of your arm. When you make a mistake, or when you are off target, try to fix it by correcting the motion of your arm." In each subsequent block in this condition, subjects were reminded: "Be as accurate as possible, mentally focused on the movement of your arm."

The *release* condition directed subjects' attention to the release of the dart. In this condition, subjects were told: "Focus on the dart leaving your hand. When you make a mistake, or when you are off target, try to fix it by correcting the release of the dart." In each subsequent block in this condition, subjects were reminded: "Be as accurate as possible, mentally focused on the dart leaving your hand."

The *trajectory* condition directed subjects' attention to the flight of the dart. In this condition, subjects were told: "Focus on the flight of the dart into the board. When you make a mistake, or when you are off target, try to fix it by correcting the flight of the dart." In each subsequent block in this condition, subjects were reminded: "Be as accurate as possible, mentally focused on the flight of the dart."

The *board* condition directed subjects' attention to the target on the board. In this condition, subjects were told: "Focus on the bulls-eye. When you make a mistake or when you are off target, try to fix it by refocusing on the next trial." In each subsequent block in this condition, subjects were reminded: "Be as accurate as possible, mentally focused on the bulls-eye."

The uninstructed *free* focus condition served as a control condition, and subjects were simply encouraged to "be as accurate as possible." If subjects asked how they should focus, the instructions were repeated, and subjects were encouraged to focus on whatever they felt would yield the best performance.

In the rest period following the free focus condition in each testing phase, subjects were asked, "What, if anything, were you focused on during the last set of throws when we did not give you explicit instructions on how to focus?" Their verbal responses were coded as indicating focus on the arm, release, trajectory, or dartboard, based on subjects' references to these areas.

At the end of the fourth session, subjects were asked, for each arm, “Did you feel more accurate in one or more of the focus conditions compared to any other?” Subjects’ responses were transcribed by the experimenter and coded as indicating the arm, release, trajectory, dartboard, or none of these.

Analysis

For this experiment there are two groups of dependent variables: AE and the seven biomechanical variables (shoulder X, shoulder Y, shoulder angle, elbow angle, wrist angle, knuckle X, and knuckle Y). The measures of interest for the analysis were average error (AE), variability of each biomechanical variable, and the correlations between biomechanical variables. The first two of these were computed separately for each block of three trials. AE was computed by taking the mean AE across trials for each block. Trial-by-trial variability of each biomechanical variable was defined by taking its standard deviation within each block. (Analysis of *mean* biomechanical variables revealed no significant differences among sessions or focus conditions and is therefore omitted from the results.)

Correlations among the biomechanical variables were computed for each set of 5 blocks (i.e., the 15 trials for each FOA within each session) as follows. First, the variance-covariance matrix among all seven variables was computed separately for each block of 3 trials. Second, these matrices were averaged across the 5 blocks. Because subjects held and threw three darts at a time, we assumed within-block (co-) variance represents intrinsic variability in the movement, whereas between-block (co-) variance could reflect additional processes such as shifts in stance between blocks. The present approach captures only the former type of variability. The mean variance-covariance matrix was then converted to a correlation matrix (by dividing each row and each column by the square root of the corresponding diagonal entry). This process was repeated for each focus within each session, separately for every subject. The approach of averaging variances and covariances across blocks before converting to correlations was used because sample variance and covariance are unbiased estimators, meaning that the average of several estimates yields an unbiased estimate.

Mean AE and the standard deviations of the biomechanical variables were analyzed in separate mixed factorial ANOVAs, to assess effects of session and FOA. Correlation matrices of biomechanical variables were also compared across sessions and FOAs, in a manner described below. All post-hoc tests used Tukey's HSD.

Analysis of learning with the dominant hand. To assess learning and performance solely with the dominant hand, a series of 5x2x5x5 mixed factorial ANOVAs were constructed, with a between-subjects factor of order (the 5 orders used for counterbalancing the different attentional focus conditions) and within-subject factors of session (Sessions 1D vs. 4D), FOA (5 different attentional foci), and block (5 blocks per condition within each session). Eight such ANOVAs were performed, for AE and the standard deviations of each of the seven biomechanical variables.

Analysis comparing the dominant to the nondominant arm. To assess performance differences between the dominant and nondominant arms during Session 4, a series of 5x2x5x5 mixed factorial ANOVAs were constructed, with a between-subjects factor of order (5 different orders counterbalancing the different attentional focus conditions) and within-subject factors of session (Session 4D for the dominant hand vs. Session 4N for the nondominant hand), FOA (5 different attentional foci), and block (5 blocks per condition within each session). These ANOVAs paralleled the ones comparing Sessions 1D and 4D: one for mean AE and one for the standard deviation of each of the seven biomechanical variables. The comparison between

Sessions 1D and 4D and that between 4D and 4N are reported separately, rather than in a single analysis of all three sessions, because of qualitative differences in the two analyses, as described below.

Correlation analysis of biomechanical variables. The present theory predicts that, under external FOA, the joint distribution of biomechanical variables will be compressed along some oblique goal-relevant dimension that is most responsible for determining the task outcome (i.e., landing location of the dart). This selectively reduced variability on the goal-relevant dimension would produce a correlation structure among the variables, reflecting their increased coordination induced by the goal-based control strategy (see Figure 16). In contrast, internal FOA should induce a body-based control strategy that minimizes the separate variabilities of the biomechanical variables without regard for their coordination, leading to a weaker correlation structure. To test this prediction, an analytic method was devised for assessing the extent to which a multidimensional distribution is compressed along an unknown, oblique dimension.

The method generalizes the concept of Pearson correlation for two variables. In the case of two variables with a bivariate Gaussian distribution, Pearson correlation can be viewed as measuring how compressed their joint distribution is relative to an independent distribution. More precisely, if one considers the area taken up by the joint distribution (e.g., within a 95% confidence region) and compares it to an alternative distribution in which the variables are independent but their individual variances are unchanged, the ratio of areas can easily be shown to equal $1 - r^2$, where r is the Pearson correlation. Intuitively, $1 - r^2$ is the fraction of the total variance that remains once the dependence between the variables is taken into account. For example, when the correlation is near one, $1 - r^2$ is close to zero, reflecting the fact that the joint distribution is collapsed nearly to a line (which has zero area).

This approach generalizes to higher-dimensional distributions as follows. First, we consider the *n*-dimensional volume taken up by the distribution (again, defined, e.g., by a 95% confidence region, and assuming a Gaussian shape). Then we compare the empirical distribution to an alternative distribution in which the variables are all independent but their individual variances are unchanged. The volume ratio of these two distributions can be shown to equal the determinant of the empirical correlation matrix, which we denote by D. That is, D measures the fraction of the volume taken up by the distribution relative to what it would fill if the variables were independent. In the case of $n = 2$, the correlation matrix equals $[1\ r;\ r\ 1]$, and its determinant is $1 - r^2$. With $n > 2$, D depends on all the pairwise correlations, but it serves the same purpose of indicating how strongly the distribution is collapsed to some (arbitrary) hyperplane. If the joint distribution of biomechanical variables has low variance on some oblique goal-relevant dimension, meaning variability is largely constrained to the hyperplane defined by the redundant dimensions (as predicted for external FOA), then D will be closer to 0. If the biomechanical variables are more independent (as predicted for internal FOA, on the assumption that the motor system works primarily to reduce variance on individual bodily dimensions), D will be closer to 1. D thus measures the degree to which the motor system selectively limits variability on some oblique dimension, as opposed to independently controlling individual bodily dimensions.

The power of this analytic approach lies in that it does not require a priori knowledge of the goal-relevant dimension (i.e., of the complex kinematic relationship between bodily dimensions and task outcome), and that it is insensitive to scaling differences in the variances of individual bodily dimensions, instead depending only on their correlations. A counterpoint to this strength is that finding increased correlations only indicates compression along some oblique dimension(s), not necessarily corresponding to the task goal. However, finding increased correlations in conjunction with improved performance (as both predicted for external FOA) would provide strong converging evidence that external FOA acts by shifting control to goal-relevant dimensions.

Throughout the Results and Discussion section, only significant effects ($p < .05$) are reported, or effects that were germane to hypotheses of the experiment. All unreported effects were not statistically significant ($p > .05$). Mauchly's test for sphericity violation was performed for all within-subjects tests involving multiple degrees of freedom. Whenever the sphericity assumption failed at $p < .05$, a Greenhouse-Geisser (GG) correction was applied to the corresponding F test.

Results and Discussion

We begin by reporting the analyses comparing mean performance (AE) and variability of each biomechanical variable between sessions. Table 5 summarizes the principal results of these analyses. Following these results, analyses of intercorrelations among the biomechanical variables are reported. Finally, results are provided regarding subjects’ self-reports.

Learning and Performance with the Dominant Hand (Sessions 1D & 4D)

Absolute Error. Analysis of AE revealed a significant main effect of FOA, with performance tending to be better with more-external foci (see Figure 18). Post-hoc tests indicated that AE was significantly greater in the arm and release focus conditions than the trajectory focus condition (*p*s < .05), with the board and free focus conditions somewhere in between. The free focus condition had significantly less error than the arm focus condition ($p < .05$), but the free focus, board focus, and release focus were not significantly different from each other.

Table 5. *Summary of significant and marginal effects for 5x2x5x5 mixed factorial ANOVAs with a between-subjects factor of order and within-subject factors of session (Sessions 1D and 4D, or Sessions 4D and 4N), FOA (5 different attentional foci), and block (5 blocks per condition).*

	Accuracy	Biomechanical Variability					
	AE	Shoulder X	Shoulder Y	Shoulder Angle	Elbow Angle	Wrist Angle	Knuckle X	Knuckle Y
Session 1D compared to Session 4D	Focus, $F(4,40) = 5.51, p = .001, \eta_p^2 = .35$ Session, $F(1,10) = 8.49, p = .015, \eta_p^2 = .25$	Focus, $F(1.66,416.57) = 3.25, p = .072, \eta_p^2 = .25$*	*(no effects)*	Focus, $F(4,40) = 4.09, p = .007, \eta_p^2 = .29$	Focus, $F(2.34,23.43) = 3.38, p = .045, \eta_p^2 = .25$*	*(no effects)*	*(no effects)*	Session × Block, $F(4,40) = 3.039, p = .028, \eta_p^2 = .23$
Session 4D compared to Session 4N	Focus, $F(4,40) = 3.59, p = .013, \eta_p^2 = 27$ Session, $F(1,10) = 66.81, p < .001, \eta_p^2 = .87$	Session, $F(1,10) = 9.02, p = .013, \eta_p^2 = .47$ Block, $F(4,40) = 2.61, p = .049, \eta_p^2 = .21$	*(no effects)*	Session, $F(1,10) = 6.89, p = .025, \eta_p^2 = .41$ Session × Focus × Order, $F(16,40) = 2.61, p = .007, \eta_p^2 = .51$.	Session, $F(1,10) = 18.58, p = .002, \eta_p^2 = .65$	*(no effects)*	Session, $F(1,10) = 19.17, p = .001, \eta_p^2 = .66$	Session, $F(1,10) = 21.74, p < .001, \eta_p^2 = .69$

* - Denotes a Greenhouse-Geisser correction for sphericity violation.

Note. Only significant effects are reported (with the exception of the main effect of attentional focus on the shoulder X variable, which was marginal). All other effects were not significant ($p > .05$)

Mean AE did decrease from Session 1D (8.40 cm) to Session 4D (7.62 cm), and this improvement in performance was significant. The session × focus interaction was not significant, *F*(4,40) < 1, suggesting that the effects of FOA were similar early and late in training.

There was no significant effect of order, *F*(4,10) < 1, and order did not significantly interact with any other variables, suggesting that the order in which subjects completed the different phases did not have a significant impact on their accuracy.

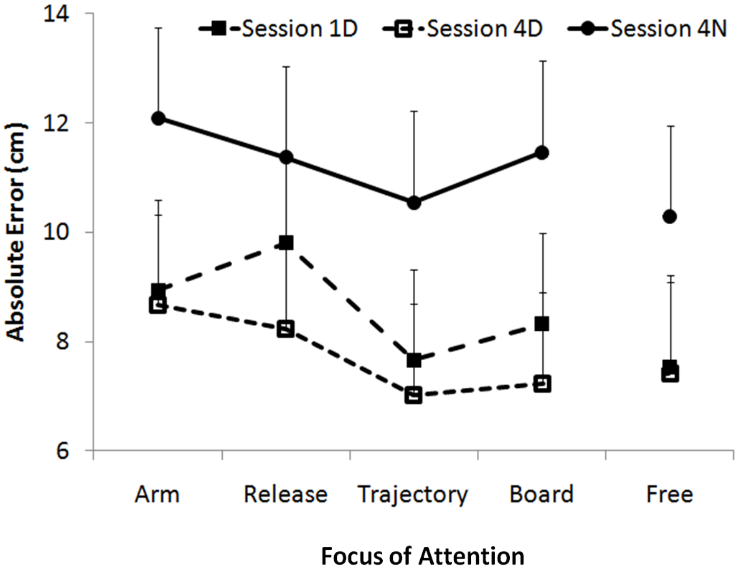

Figure 18. *Absolute error as a function of attentional focus and session. Error bars show within-subject standard error based on the mean squared error of the Subject X Session X Focus interaction (Loftus & Masson, 1994).*

Biomechanical variability. The effects of FOA and session on biomechanical variability (the standard deviation of each variable between trials) are shown in Figure 19. Analysis of the shoulder X coordinate standard deviation revealed a main effect of FOA that approached significance (*p* = .07) suggesting that variability in the shoulder X coordinate increased with more-external foci (GG correction, ε = .414).

Shoulder Y showed no significant effects, suggesting that shoulder Y variability was similar across FOAs and sessions.

Shoulder angle showed a significant effect of FOA. Post-hoc comparisons showed significantly greater variability in shoulder angle with a trajectory FOA compared to the arm and release FOAs (*p*s < .05), but no reliable differences among the other foci.

Elbow angle showed a significant effect of FOA (GG correction, ε = .589). Post-hoc comparisons showed that variability in elbow angle was significantly greater in the trajectory focus condition compared to the arm, release, and free focus conditions (*p*s < .05). Variability in elbow angle was also greater in the free focus condition compared to the arm focus condition (*p* < .05).

Wrist angle showed no significant effects, suggesting that variability in wrist angle was similar across FOAs and sessions.

Knuckle position data revealed no significant effect of FOA for either knuckle X or knuckle Y, *F*(4,40) < 1 for both variables. However, for variability in knuckle Y, there was a significant interaction of session and block, such that in Session 1D there was a reduction in variability across blocks (Block 1: 1.53 cm, Block 5: 1.18 cm), whereas in Session 4D variability was more stable across blocks (Block 1: 1.33 cm, Block 5: 1.39 cm).

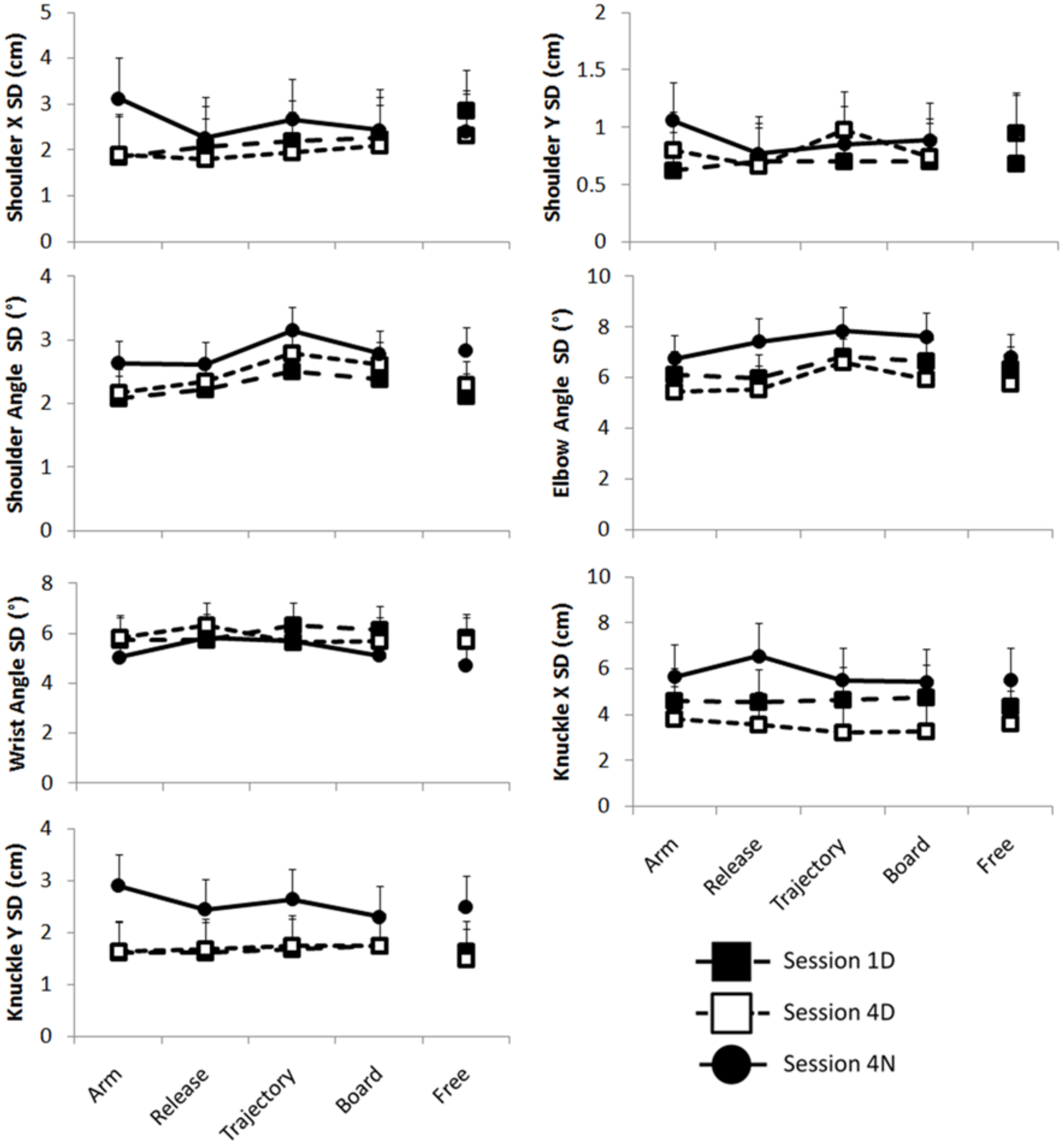

Figure 19. *Mean standard deviations (SD) of end-point kinematics (within each block of 3 trials) for the shoulder X coordinate, shoulder Y coordinate, shoulder angle, elbow angle, wrist angle, knuckle X coordinate, and knuckle Y coordinate as a function of attentional focus and session. Error bars show within-subject standard error based on the mean squared error of the Subject X Session X Focus interaction (Loftus & Masson, 1994).*

In summary, accuracy data showed that subjects significantly improved from Session 1D to Session 4D, and focusing externally (on the flight of the dart, but less so on the dartboard itself) significantly improved performance relative to the more internal focus conditions (i.e., focusing on the arm or the dart leaving the hand). In terms of variability, three of the seven biomechanical variables (shoulder X, shoulder angle, and elbow angle) showed marginal or significant effects of FOA. Post-hoc tests revealed consistent patterns of increasing variability with more-external foci (arm and release < trajectory focus, with less consistent results for the board focus).

Comparing Dominant and Nondominant Arms (Sessions 4D & 4N)

Absolute error. Comparing data from Session 4D with data from Session 4N allows comparison of a relatively skilled effector with an unskilled effector, within individuals. There was a large main effect of session, with mean AE in Session 4D significantly less than in Session 4N (see Figure 18). There was also a significant main effect of FOA, with post-hoc comparisons showing that AE during the free focus condition (averaged across dominant and nondominant arms) was significantly lower than during the arm focus condition ($p < .05$). The reduction in error in the trajectory focus condition compared to the arm focus condition was marginally significant ($p = .10$). The interaction of FOA and session was nonsignificant, $F(4,40) < 1$, suggesting that, taken across all five focus conditions, the advantage of focusing more externally was similar for the dominant and nondominant arms. However, closer inspection of the trajectory and board conditions suggests a sharp rise in error for the most external FOA with the nondominant arm that is not present in the dominant arm. Therefore, although the interaction is not statistically reliable, there is some suggestion that the more-skilled effector can benefit from a more external FOA than can the less-skilled one.

Biomechanical variability. The average variability of all seven biomechanical variables for Sessions 4D and 4N is shown in Figure 4. Shoulder X showed a significant increase in variability from Session 4D to Session 4N. There was also a significant effect of block, such that variability generally decreased across blocks.

Shoulder Y showed no significant effects, suggesting that variability in the vertical position of the shoulder was similar across sessions and FOAs.

Shoulder angle showed a significant effect of session, with greater variability in the nondominant arm compared to the dominant arm. There was also a significant interaction of session, focus, and order. The focus × order interaction itself may reflect an effect of position in the sequence of FOAs during testing, in which case the session × focus × order interaction may indicate differences between sessions in learning from the first FOA to the last. (It is also worth noting that this interaction was the only significant effect of order in any of the analyses.)

Elbow angle showed a significant effect of session, such that variability in the elbow was significantly greater with the nondominant hand compared to the dominant hand.

Wrist angle showed no significant effects, suggesting that variability in the wrist angle was similar across sessions and FOAs.

Knuckle X and knuckle Y both showed significant effects of session. There was significantly greater variability in both the horizontal and vertical positions of the knuckle with the nondominant arm compared to the dominant arm.

In summary, the comparison of Sessions 4D and 4N showed that subjects were significantly more accurate with their dominant arms than with their nondominant arms. Both arms benefited from more-external FOAs, although there was some indication that the dropoff in performance with the most external focus (dartboard) was more severe with the nondominant arm. In terms of biomechanical variability, there were no reliable effects of FOA,[4] but the nondominant arm was more variable than the dominant arm for five of the seven variables.

The comparisons of Sessions 1D and 4D and of Sessions 4D and 4N show an interesting contrast in the relationship between performance and biomechanical variability. Within the dominant arm (Sessions 1D and 4D), more-external FOAs led to increased movement variability and better performance. Between arms (Sessions 4D vs. 4N), the nondominant arm exhibited increased movement variability and worse performance. This contrast in the performance–variability relationship suggests variability can play two different roles in motor control. The increased variability found in the nondominant arm can be interpreted as a general lack of control, due to less robust or well-learned motor representations as compared to the dominant arm, leading to poorer performance. The increased variability found with more-external FOAs (in the dominant arm) appears to be qualitatively different in that it is concomitant with improved performance. Our hypothesis is that this variability arises because external attention shifts motor control from bodily to goal-relevant dimensions of the movement, which leads to coordination among effectors and improved performance. This interpretation is tested next, in the analysis of intercorrelations among joints.

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[4] There is a logical inconsistency between this finding and the finding of significant FOA effects in Sessions 1D and 4D. Because session did not interact with FOA in either analysis, and because both analyses included Session 4D, there should be an effect of FOA on biomechanical variability in both analyses or in neither. The inconsistency is likely due to the greater noise in the data from the nondominant arm. The best conclusion one can draw from the data as a whole is that FOA affected movement variability of the dominant arm, and it is uncertain whether it had a similar effect on the nondominant arm. As mentioned above, we present the two analyses separately (rather than in one three-way analysis) because they highlight a qualitative difference in the relationship between performance and variability, as explained next.

Analysis of Inter-Joint Correlations

The foregoing analyses indicate a performance advantage for the dominant over the nondominant arm (Sessions 4D vs. 4N) and improvement with practice in the dominant arm (Sessions 1D vs. 4D), as well an advantage of more-external FOAs. However, the comparisons of effectors and of FOAs indicate differential roles for movement variability. The explanation proposed here for the functional variability observed with external FOAs in the dominant arm is that the increased variability in individual bodily dimensions results from selective control of a goal-defined dimension that is oblique in movement space to the individual bodily dimensions. To test this hypothesis, we analyzed the correlations among the biomechanical variables in all three sessions, in each of the five FOAs. As described in the Analysis section, the determinant of the correlation matrix, D, measures the proportion of the variance in the joint distribution of the biomechanical variables that is not explained by their intercorrelations. The smaller the value of D, the more the joint distribution is collapsed along one or more oblique dimensions. Because the knuckle coordinates are fully determined by the values of the other five variables (within each subject), we omitted these two variables and analyzed the 5-dimensional correlation matrix of shoulder X and Y, shoulder angle, elbow angle, and wrist angle. Omitting the knuckle coordinates leads D to measure only those correlations due to motor coordination, and not those due to structural constraints.

A 3 × 5 repeated-measures ANOVA was performed on D with within-subject factors of session (1D, 4D, and 4N) and focus. The ANOVA revealed a significant effect of focus, $F(4,196) = 2.47$, $p = .046$, and no main effect of session, $F(2,196) = 2.04$, $p = .133$. The interaction was nonsignificant ($F < 1$, $p > .5$). Mean values of D by focus and by session are shown in Figure 20a. The two more external foci (trajectory and board), as well as free focus, show lower values of *D* than the two more internal foci (arm and release), indicating greater coordination in the external conditions.

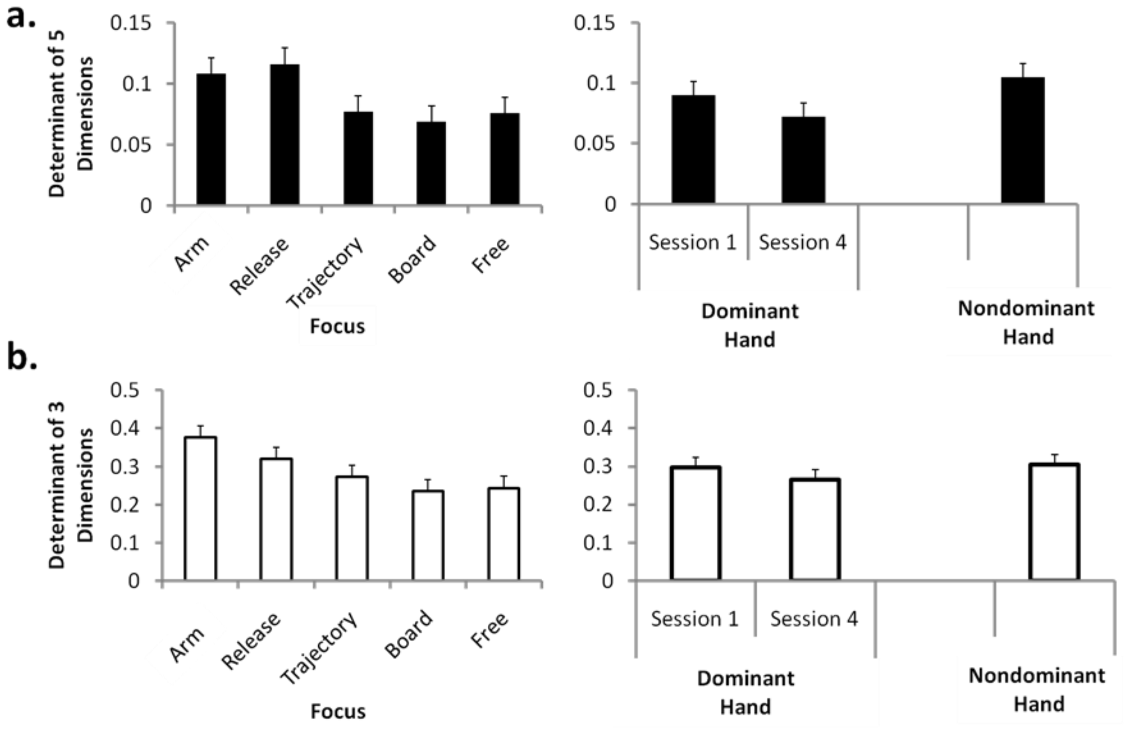


***Figure 20**. Determinants of the correlation matrices among biomechanical measures for five dimensions (a: shoulder X, shoulder Y, shoulder angle, elbow angle, & wrist angle) and three dimensions (b: shoulder angle, elbow angle, & wrist angle) as a function of FOA (left) and session (right). Error bars show within-subject standard error based on the mean squared error of the Subject X Focus and Subject X Session interactions, respectively (Loftus & Masson, 1994).*

A similar analysis was conducted restricted to shoulder angle, elbow angle, and wrist angle. This 3-dimensional subspace was chosen because these variables showed the highest correlations with each other in the 5 × 5 correlation matrices averaged across all sessions and FOAs. Because these variables appear to be highly coordinated in general, we expected their correlations might be especially sensitive to expertise (i.e., session) and FOA. The determinant, D_3, of the three-dimensional correlation matrix was computed as before, and the same repeated-measures ANOVA was performed on D_3 with within-subject factors of session and focus. The

ANOVA revealed a significant effect of focus, $F(4,196) = 3.21$, $p = .014$, but no effect of session and no significant interaction ($p = .53$; $p = .27$). Mean values of D_3 by focus and by session are shown in Figure 20b. The pattern of increasing coordination with increasingly external FOAs is even clearer than in the five-dimensional analysis.

Post-test Surveys and Analysis of the Free Focus Phase

Table 6 shows the self-report data from each subject. The Spearman rank-order correlation was computed between the FOA that subjects reported adopting during the free focus phase of each session and the FOA that subjects reported at the end of the experiment as the one in which they were most accurate (nominal categories were re-coded as arm = 0, release = 1, trajectory = 2, and board = 3). For the free focus phase of Session 1D this correlation was not significant, $r(13) = -.016$, $p = .56$. For Session 4D the correlation also was not significant, $r(13) = .393$, $p = .148$. However, the correlation was significant for the nondominant arm, $r(13) = .982$, $p < .001$.

Self-report data also suggest that a subject's preferred focus of attention changed as a function of which arm he or she was using. In Session 1D, subjects reported adopting a range of attentional foci during the free focus phase, but by Session 4D the vast majority of subjects reported using some type of external FOA (either the trajectory or the board focus). However, when switching to the nondominant hand (Session 4N), the majority of subjects reported adopting an arm focus during the free focus phase. The difference across sessions in distributions of free foci was significant by a chi-square test of independence, $\chi^2(6)= 17.89$, $p = .008$. Likewise, most subjects reported performing best in the trajectory or board condition with the dominant arm, but many subjects reported better performance in the arm condition with the nondominant arm, $\chi^2(3)= 7.34$, $p = .062$. Thus, there is evidence for a preference among subjects to shift attention more externally as a skill is learned, and then to shift attention internally again when an unskilled effector is used, guided by an explicit belief that more-external FOAs are relatively more effective with more-skilled effectors.

Table 6. *Summary of subjects' verbal reports.*

	Best Focus		Free Focus		
Subject	Dominant	Nondominant	Session 1D	Session 4D	Session ND
1	Traj	Traj	Traj	Traj	Traj
2	Board	Arm	Arm	Board	Arm
3	Board	Board	Board	Traj	Board
4	Traj	Arm	Board	Board	Arm
5	Board	Arm	Arm	Board	Arm
6	Arm	Arm	Release	Release	Arm
7	Traj	Traj	Board	Board	Traj
8	Traj	Traj	Board	Board	Arm
9	Board	None	Board	Board	Board
10	Traj	Arm	Board	Board	Arm
11	None	Board	Arm	Board	Board
12	Board	Board	Release	Board	Arm
13	Board	Arm	Board	Board	Arm
14	Board	Arm	Board	Board	Arm
15	Board	None	Board	Board	Board

Note. Best Focus indicates the focus each subject believed was most effective, as assessed at the end of the experiment for both the dominant and nondominant arms. Free Focus indicates the focus each subject reported using at the conclusion of each free focus phase.

General Discussion

The results of the current study support our proposal that the focus of attention plays a significant role in determining the control structure of human motor behavior. When attention was directed externally, subjects exhibited improved performance, greater trial-by-trial variability in individual bodily dimensions (i.e., joint positions and angles, at least for the dominant arm), and stronger correlations among those bodily dimensions. This pattern is consistent with the predictions of optimal control theory (Todorov & Jordan, 2002), assuming a control rule operating directly on the outcome of the task (i.e., the flight or landing point of the dart). Conversely, when attention was directed more internally, subjects exhibited worse accuracy and reduced variability of individual joints, consistent with a control rule operating on the arm's movement rather than on the movement outcome.

The accuracy results replicate numerous previous findings of external FOA improving motor performance (e.g., Bell & Hardy, 2009; Lohse et al., 2010; Marchant, Clough, & Crawshaw, 2007; Wulf, 2007a). However, the present study goes beyond previous research by elucidating the kinematic mechanisms that underlie the attention-performance relationship. Specifically, FOA appears to affect motor outcomes by a change in the pattern of trial-by-trial variability in the movement, reflecting a shift in how the movement is controlled. For three of the seven biomechanical variables measured in this study (horizontal position and angle of the shoulder, and angle of the elbow), more-external FOAs produced greater variability. Unlike the differential variability found between the nondominant and dominant arm, which was accompanied by poorer performance for the more variable arm, the increased variability with external FOAs was found to be functional, because it was accompanied by improved performance. This type of functional variability is also characteristic of the fluent and efficient performance of experts (Newell, 1985; Sparrow & Newell, 1998), suggesting that an external FOA changes the quality of movement to be more expert-like, whereas an internal FOA leads to rigid movements that are more novice-like in both quality and outcome.

The finding of increased functional variability with external FOA is explained by the additional finding that external FOAs strengthen the correlation structure among joints. We argue that this increase in coordination indicates a shift in control, whereby muscles and joints work together to minimize variability in the task outcome. In contrast, the reduced variability in individual joints and weaker correlation structure found with more-internal FOAs indicates a control strategy whereby variability in limb kinematics is minimized, at the expense of optimizing performance.

The connection between the correlation structure of bodily dimensions and selective control of the task outcome is based on the assumption that the abstract space of possible movements can be decomposed into two orthogonal subspaces, corresponding to the task goal and the redundant degrees of freedom in the movement (Scholz & Schöner, 1999). If the motor system's control strategy is to minimize variability along the goal-relevant dimension of the movement (as opposed to individual bodily dimensions), then trial-by-trial variance along the goal-relevant dimension should be reduced relative to variance along the redundant dimensions. Our novel mathematical approach to assessing anisotropic variance in the movement, via the determinant of the correlation matrix among bodily dimensions, allows this prediction to be tested without independent knowledge of how the goal dimension is oriented with respect to the bodily dimensions.

One limitation of this approach is that it cannot directly verify that the observed anisotropy is aligned with the goal-relevant dimension; it only indicates that the joint distribution is selectively compressed along some oblique dimension(s) in movement space. The inference that this dimension corresponds to the task goal is based on the fact that the increased anisotropy with external FOA was accompanied by improved performance. Selective reduction of variability on the goal-relevant dimension should, by definition, reduce variability in the task outcome, hence reducing absolute error. Logically it is possible that external FOA leads to selective reduction in variability of some other movement dimension unrelated to the goal, but it is unclear what that dimension would be or how it could explain the effects of FOA on performance. Therefore, we take the present findings, of improved performance and increased anisotropy, as support for the core proposal that external FOA improves performance through selective control of goal-relevant dimensions in movement space.

A further limitation of the correlation-based approach is that it assumes the task goal corresponds to a linear function of the bodily dimensions. More realistic is that this function is nonlinear, and hence the redundant “dimensions” constitute a curved manifold embedded in the movement space (cf. Scholz & Schöner, 1999). The present approach is based on the assumption that this manifold is locally linear around the average movement pattern for each subject, but even when nonlinearities become important, our core theory still applies. The variables that determine the task outcome (e.g., landing point of the dart) may not constitute a linear subspace of the movement space defined by the bodily dimensions, but selectively reducing their variability still entails increasing the statistical relationships among bodily dimensions while allowing their individual variances to increase. Even if those statistical relationships are somewhat nonlinear, Pearson correlation is still a useful approximation for assessing them. The finding of increased intercorrelations among joints with external FOA thus supports our core theory as well as the adequacy of the linearity approximation used to test it.

An important contribution of the present work is that it helps to tie cognitive variables such as attention to theories of motor control based on rational analysis and optimal control theory (Diedrichsen, Shadmehr, & Ivry, 2010; Latash et al., 2007; Todorov, 2004; Todorov & Jordan, 2002). These rational models provide a computational justification for the assumption above that movement variability should be greater along redundant than goal-relevant dimensions. In closed-loop control, where the brain can use feedback signals for online correction, deviations along the goal-relevant dimension will be corrected, but irrelevant deviations will be allowed to accumulate, to minimize signal-dependent motor noise (Todorov & Jordan, 2002). Thus, the pattern of movement variability found here with external FOAs is consistent with the predictions of optimal control theory: selectively reduced variability in the goal-relevant dimension, producing correlations among bodily dimensions but allowing their individual variances to be larger.

However, the present theory goes beyond purely rational models in positing that the appearance of this optimal pattern depends on the cognitive state of the subject. In particular, the control rule implemented by the motor system appears to depend on attention, which helps to determine which variables are controlled. When attention is focused internally, on the movement itself, the motor system no longer works to directly control the task outcome. Instead, a control policy is adopted that limits error in bodily dimensions, presumably based on a predetermined plan or expectation for what effector patterns will produce good performance. This control policy is (potentially) optimal with respect to the covert goal of minimizing deviation in the movement, but the shift in the effective goal of the motor system leads to a qualitatively different pattern of both control and behavior. This explanation of the interaction between attention and optimal control illustrates the power of combining mechanistic cognitive theories with computational-level rational analysis (Jones & Love, 2011).

Viewing the impact of attention in terms of kinematics and optimal control also offers a richer alternative to previous accounts of the effects of FOA on motor performance. For example, explicit monitoring theory (Beilock & Carr, 2001; Beilock et al., 2002; Masters, 1992) posits that explicitly attending to movement disrupts motion by unnecessarily engaging cognitive control. This hypothesis suggests that well-learned, or proceduralized, skills do not require cognitive control and largely operate outside of working memory (Allport, Antonis, & Reynolds, 1972; Fitts & Posner, 1967; Keele & Summer, 1976; Kimble & Perlmuter, 1970). Thus, when explicit monitoring is increased by attending to movement (as in an internal FOA), skilled performance is disintegrated into a sequence of smaller, independent units, similar to how the skill was represented early in learning (Koedijker, Oudejans, & Beek, 2007; Masters & Maxwell, 2008). In contrast, our theory posits that cognitive control is always involved in the execution of the motor skill, to specify either the target movement (internal FOA) or the target outcome (external FOA). Rather than impeding the motor system from carrying out goal-directed action, an internal FOA alters the effective goal, so that the motor system adopts a different control strategy that prioritizes the movement over the outcome. This view is closer to the constrained action hypothesis of Wulf (2007b), which states that internal FOA limits the degrees of freedom in a movement, preventing fluidity and coordination. However, the present theory goes beyond this idea to specify what those limitations are, from a kinematic standpoint, and the computational reasons that they arise.

Because most complex motor tasks involve far more bodily dimensions than goal dimensions, an internal FOA potentially induces an increased information-processing burden on working memory, because more variables are being controlled. Such an effect could explain why attentional capacity is limited with internal focus (Wulf, McNevin, & Shea, 2001), why reducing working-memory capacity through a secondary task appears to shift people to an external focus (Beilock, Carr, MacMahon, & Starkes, 2002), and why movement preparation time increases with an internal focus (Lohse, 2011).

The proposal that attention guides the control structure of complex movement, by helping to determine which variables are explicitly controlled, leads to the straightforward prediction that attended aspects of the movement will exhibit less variability. Thus, external FOA leads to less variability in the outcome, and internal FOA leads to less variability in individual effectors (joint angles and muscle activations). An encouraging aspect of this theory is that, at a mathematical level, it agrees closely with theories of attention in perception and learning (Maddox & Dodd, 2003; Nosofsky, 1986). In all three domains, attention can be viewed as increasing the precision or sensitivity of cognitive processing, which in turn fits well with formal theories of similarity that weight different dimensions according to their salience (Medin et al., 1993; Tversky, 1977). Although these abstract connections are promising, more work is needed to flesh out potential connections between notions of attention in these different domains at a more concrete psychological level.

One important question in research on attention and motor performance is the role of expertise. Previous research comparing expert and novice performance suggests that experts benefit from a more external FOA (Bell & Hardy, 2009) and tend to adopt this sort of focus spontaneously (Stoate & Wulf, 2011), whereas novices benefit from a more proximal focus of attention (Wulf et al., 2000, Experiment 2). Some evidence for these conclusions was also found in the present study, in that error increased sharply for the most external FOA (the dartboard) with the nondominant arm (Session 4N), but less so for the dominant arm before training (Session 1D) and almost not at all for the dominant arm after training (Session 4D; see Figure 3). In addition, subjects spontaneously adopted more-external FOAs in the free focus conditions with the dominant arm than with the nondominant arm.

Thus, although motor performance is generally better with more-external FOAs, there appears to be a limit beyond which performance decreases, and this limit appears to be more external for experts than for novices. The present theory relating attention to the structure of motor control can potentially explain these findings, through differences in the kinematic knowledge of novices and experts. The action concepts of experts are richer and more detailed than those of novices (Schack, 2004; Schack & Mechsner, 2006), making it possible for experts to direct their focus further down the chain of kinetic events in the task and potentially control more-distal effects of their actions. We postulate that novices have not fully learned the causal dynamics connecting movements to more distal outcome variables, making it difficult for them to identify and control the aspects of the movement that determine those variables. This proposal is consistent with findings regarding attention in perceptual tasks, which show that attention cannot operate on arbitrary dimensions in psychological space (Garner, 1974; Kruschke, 1993). However, once new perceptual dimensions are learned, they can be attended to (Goldstone & Steyvers, 2001). Thus, novices should benefit from a more proximal, but still external focus of attention (such as our trajectory focus condition compared to the board focus condition; see also Bell & Hardy, 2009; Wulf et al., 2000). Therefore, although the present theory does not address how causal dynamics and goal-relevant dimensions are learned, it ascribes an important role to this process in the transition to expertise.

This perspective on the role of learning goal-defined dimensions of a movement can potentially be generalized to explain the benefits of analogy use in motor performance (Poolton, Masters, & Maxwell, 2007). Previous research has shown that using analogies to teach novices a complex motor skill results in improved retention and performance, which is robust to distracting secondary tasks, increased stress, and thought suppression (Liao & Masters, 2001). Effective analogies thus potentially have the same effects as an external FOA, in that they help the learner to identify and focus on the task goal and the pattern of coordination needed to achieve it. In contrast to literal, body-focused instruction, which requires learners to progress through a stage of internal attention, learning through analogy may help learners identify the desired control rule more directly.

One goal for future research is to connect the present findings regarding attentional effects on movement variability to effects of FOA on other aspects of movement. Previous research by Lohse et al. (2011) has shown that an internal focus of attention can increase cocontraction during isometric force production, and numerous studies have shown increased muscle activation with an internal focus of attention during dynamic tasks (Lohse et al., 2010; Marchant et al., 2009; Vance et al., 2004; Wulf et al., 2010; Zachry et al., 2005). One potential explanation that integrates muscle recruitment and movement variability is limb stiffness. Increasing cocontraction between agonist-antagonist muscle pairs increases joint stiffness (Gribble, Mullin, Cothros, & Mattar, 2003; Osu et al., 2002). This increase in joint stiffness could lead to the reduction in variability of individual joint angles. Increased cocontraction can also explain previous findings that an internal FOA leads to lower-frequency and higher-amplitude deviations in a stabilometer balance task (McNevin, Shea, & Wulf, 2003; Wulf, Shea, & Park, 2001) because when a greater percentage of motor units are activated, there is greater signal-dependent noise in the motor system, creating unsteadiness.

In conclusion, this study illustrates the importance of studying cognitive effects on the details and quality of movement, beyond just behavioral outcomes, because the way in which the motor system coordinates complex movements helps to explain why behavioral effects occur. The biomechanical data show that an internal focus of attention leads to reduced variability in individual effectors at a cost of reduced coordination, similar to the locking of degrees of freedom that characterizes the behavior of novices. Attention thus appears to change the control structure that guides action, such that the motor system shifts between minimizing error in an abstract goal dimension versus bodily dimensions of the movement. We believe these findings contribute an important step toward integrating the effects of attention with broader theories of motor control, and they build on more descriptive theories of FOA effects by suggesting specific kinematic and control-theoretic principles by which attention constrains action. The theory offered here leads to the straightforward prediction that attention acts to increase the precision of attended movement parameters, consistent with theories of attention in other domains. We hope further research along these lines can open the door for more integrated theories of cognition and motor control, bringing together both mechanistic and rational principles.

Chapter 5: On the advantage of an external focus of attention: A benefit to learning or performance?

> *"In the case of archery, the hitter and the hit are no longer two opposing objects, but are one reality. The archer ceases to be conscious of himself as the one who is engaged in hitting the bull's-eye which confronts him."*
>
> -Eugene Herrigel, *Zen in the Art of Archery*, (1953, p. 10)

Coaches, athletes, physical therapists, and performers have known about the paradoxical effects of attention on performance for a long time; introspection, anecdotal evidence, and early experimental data suggest that when attention shifts to *how* a movement needs to be executed, rather than *what* needs to be done, performance suffers as a result (Baumeister & Showers, 1986; Carver & Scheier, 1978; Kimble & Perlmuter, 1970; Klatzky, 1984; Martens & Landers, 1972; Masters, 1992; Schneider & Fisk, 1983). One of the first experimental demonstrations of this phenomenon was a study conducted by Baumeister (1984) who showed, in an experiment using a complex visuo-motor task, that directing attention internally (to the motion of the hands) led to worse performance than focusing attention externally (to the motion of the apparatus being controlled). Three follow-up experiments showed that similar decrements in performance were produced by increasing the pressure to perform (e.g., through incentives, audience presence, and the presence of competitors; Baumeister, 1984).

Wulf and Weigelt (1997) studied skill acquisition in novice subjects learning how to use a ski-simulator in a similar experiment. One group of subjects was given explicit instructions about when to exert pressure during the movement in order to maximize the amplitude of side-to-side displacement of the simulator platform. (The goal in riding a ski-simulator is to make oscillatory movements as quickly as possible with the largest possible amplitude, simulating slalom skiing.) The second group of subjects was not given these explicit movement instructions and were instead supposed to discover proper movement form on their own. Both groups started out with similar levels of performance, but after three days of training the group that had been given explicit movement instructions was doing significantly worse than the self-discovery group. Another series of experiments (Wulf, Höβ, & Prinz, 1998) manipulated attention through the verbal instructions given to subjects in a ski simulator task and in a dynamic balance task. In both tasks, instructions directing attention externally (to the effect of the movement on the environment) led to superior performance compared to instructions directing attention internally (to the movement of the body itself) or to control conditions (in which attention was not explicitly manipulated).

This advantage of an external focus of attention (FOA) compared to an internal FOA has since been replicated across a wide range of tasks and subject populations (for reviews see Wulf, 2007a, 2007b). Athletic skills such as golf, darts, tennis, soccer and volleyball have all shown an advantage for an external FOA compared to an internal FOA and often an advantage over control conditions when no specific instructions are given (internal FOA and control groups perform comparably; Bell & Hardy, 2009; Maddox, Wulf, & Wright, 1999; Marchant, Clough, & Crawshaw, 2007; Wulf, Lauterbach, & Toole, 1999; Wulf, McConnel, Gärtner, & Schwarz, 2002; Wulf & Su, 2007). Many studies have also found an advantage for an external focus of attention in more rudimentary tasks such as balance (Vuillerme & Nafati, 2007; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001), leaping ability (Porter, Ostrowski, Nolan, & Wu, 2010; Wulf, Dufek, Lozano, & Pettigrew, 2010), and simple force production (Lohse, 2012; Lohse, Sherwood, & Healy, 2011; Marchant, Greig, & Scott, 2009). Furthermore, the advantages of an external FOA have also been demonstrated in clinical populations, such as patients recovering from stroke, Parkinson's disease, or musculoskeletal injury (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002; Landers, Wulf, Wallman, & Guadagnoli, 2005; Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007; Wulf, Landers, Lewthwaite, & Töllner, 2009).

A common finding in studies on FOA is that the advantages of an external FOA are not immediate, but often emerge only later in practice or on delayed retention and transfer tests (e.g., Lohse, 2012; McNevin et al., 2003; Wulf et al., 1998; Wulf & McNevin, 2003; Wulf et al., 2001). This result has led some researchers to speculate that an external focus of attention does not only improve performance, but could improve learning as well (Lohse, 2012; Wulf, 2007b; Wulf & Prinz, 2001). Thus, adopting an external focus of attention during training should expedite the learning process.

On the surface, this supposition is confirmed by experimental studies using retention and transfer tests. However, there is often a great deal of difficulty in discriminating an effect on performance from true effects on learning (a problem not unique to FOA research, see also Tolman & Honzik, 1930) because learning is generally inferred from changes in performance over time. Thus, to confirm an effect on learning, experimenters must be certain that factors other than learning have not influenced the performance being measured or be able to adequately control for these factors. For studies on the FOA, this problem arises because if subjects are adopting the same focus during testing as they are during training, then it is not clear whether subsequent improvement is attributable to the focus used previously or the focus during performance (a limitation acknowledged by Wulf, 2007b). A hypothetical example of this problem is shown in Figure 21.

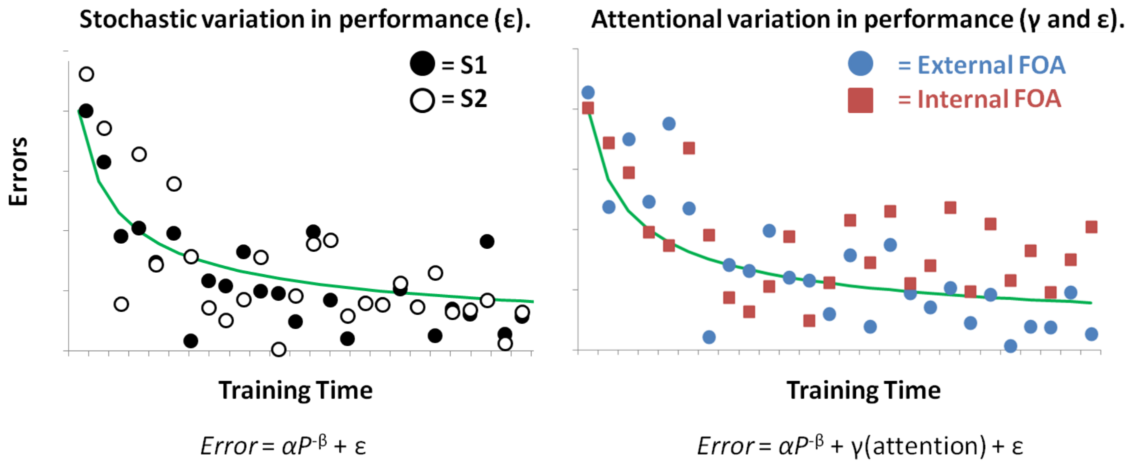


Figure 21. *Learning curves, as a function of time (on the left) and attention (on the right), for a hypothetical task showing a reduction in the number of errors over time (in arbitrary units). Stochastic variation (ε) is shown on the left. The green line represents a power law of improvement (*$\alpha P^{-\beta}$*) which is inferred from performance (individual data points for 2 subjects, S1 and S2). On the right, performance changes as a function of attention (an undefined parameter, γ) in addition to stochastic variation.*

Figure 21 shows hypothetical learning curves that underlie improvements in performance across time (shown as a reduction in errors). In standard experimental paradigms, learning (which is internal knowledge about the task represented by the green lines) is inferred from performance (which is subjects' measurable behavior, represented by the individual data points). On the left, individual variation in performance is simply treated as stochastic. On the right, attention creates non-random variation in performance. Internally focused attention tends to make performance worse, whereas externally focused attention tends to make performance better. The question then becomes should we estimate a single learning rate where attention biases performance (as is shown in the figure) or should we estimate two different learning rates (one internal and one external)? It is certainly possible that externally focused and internally focused subjects could be learning at the same rate (i.e., similar exploration of the problem-space), but an external FOA allows the subject to more effectively exploit their learning up to that point, which would create a significant difference in performance (for more on the difference between exploitation and exploration, see Sutton & Barto, 1998). Importantly, this difference in performance may not emerge until late in the learning processes because exploitation relies on robust internal representations of the skill. Thus, it is difficult to determine whether or not attentional affects performance, learning, or both.

Currently, there is a confounding in the FOA literature that prevents us from answering this question. As Lohse (2012) observed, subjects who train with an external focus of attention are more likely to reinvest an external focus during subsequent retention and transfer tests, even when these tests occur a week later. This reinvestment creates a confounding between training focus and testing focus. Thus, improved performance on a delayed retention or transfer test cannot be attributed to the FOA used during training unless the FOA used during testing is also experimentally controlled. Most previous studies of FOA on learning have not controlled the focus of attention at test and simply not given subjects specific FOA instructions during test.

Totsika and Wulf (2003) attempted to control for subjects' FOA during delayed retention and transfer testing by having subjects engage in a secondary verbal-cognitive task (counting backwards by threes) at test. The authors argued that this demanding secondary task would prevent subjects from adopting one focus or the other and thus any differences at testing be would attributable to the FOA adopted during training. Data showed that subjects who received external FOA instructions during training did better on this transfer test. However, other research suggests that an external focus of attention is less demanding of working memory than an internal focus (Koedijker, Oudejans, & Beek, 2007; Poolton, Maxwell, Masters, & Raab, 2006; Wulf et al., 2001), which means that the verbal-cognitive secondary task might have simply been more demanding for subjects who were reinvesting an internal focus of attention compared to subjects who were reinvesting an external focus of attention. This difference in the working memory load between internal and external FOA creates a problem for interpreting Totsika and Wulf’s (2003) results as evidence of improved learning.

Thus, we propose that the best way to delineate performance effects from true learning effects is to experimentally manipulate the FOA at testing the same way it is manipulated during training. In the current study, we used a dart-throwing task where subjects were biased to either an external focus or an internal focus during training. After a delay, subjects completed retention and transfer tests with either the same focus or the opposite focus. At both training and testing the FOA was manipulated through verbal instructions given by the experimenter. By counterbalancing these FOA conditions, four different FOA groups were created: subjects who trained and tested with external focus (EE), subjects who trained externally focused but tested internally focused (EI), subjects who trained and tested with an internal focus (II), and subjects who trained internally focused but tested externally focused (IE).

This experimental design allows us to test the effects of FOA on learning and performance directly and leads to two alternative hypotheses. If an external focus enhances *learning*, the focus during training should have a significant effect at test, regardless of the focus adopted during test [EI (and EE) do better than IE (and II)]. Conversely, if an external focus affects *performance* more than learning, the focus adopted during testing should have a significant effect at test, but the focus adopted during training should not [IE (and EE) do better than EI (and II)].

Furthermore, we were interested in how these learning rates might differ as a function of past experience. Previous research suggests that both novices and experts benefit from an external focus, but novices benefit more from a more proximal external focus than do experts (i.e., focusing on the motion of the club versus the flight of the ball in golf; Bell & Hardy, 2009; Castenada & Gray, 2007; Wulf & Su, 2007). Because all of our subjects were novices, we manipulated "experience" with the task by changing the inertial properties of the subjects' throwing arm (adding a 1.0 kg weight just below the wrist). Half of the subjects wore the additional weight during training and retention testsig, the remaining half of subjects without only wore the weight during the transfer test. Subjects who trained and tested with the weight are functionally more novice-like than the other subjects, because not only do they lack robust motor representations for accurate dart throwing, but they must also adapt their existing internal representations of their throwing arm to the new arm dynamics. In theory, if an external focus of attention relies on the exploitation of internal representations, then changing the inertial dynamics of the throwing arm (which requires updating of these representations) should diminish the benefit of an external focus.

Thus, assuming that an external FOA confers an advantage by exploiting existing, implicit motor representations, we hypothesized that, in the *unweighted* condition, an external focus of attention should show a large benefit to performance at testing because the brain already has robust representations for the arm dynamics. Conversely, in the *weighted* condition, we hypothesized that an external focus would have a minimal effect on performance, because the brain is adapting its representations of the throwing arm to accommodate the change in dynamics.

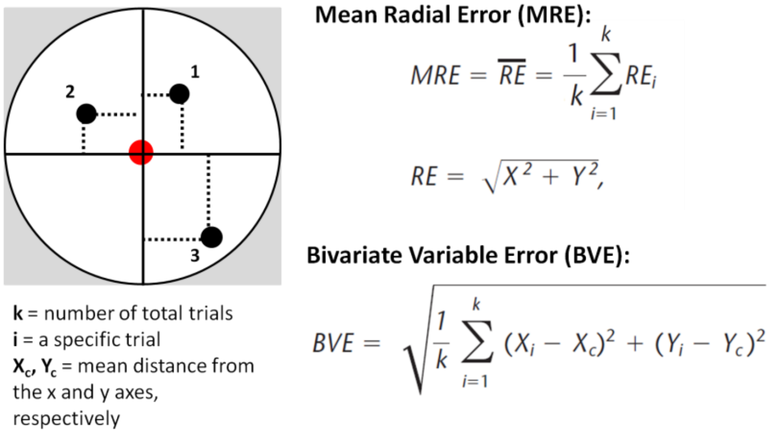
Method

Participants

Data were collected from 80 healthy and physically active subjects who had normal or corrected to normal vision (self-reported through a written survey prior to the experiment). Subjects also reported little to no prior experience with darts, with most subjects (*n* = 72) endorsing that they never play darts or rarely play darts (1-3 times per year). Subjects were recruited through introductory psychology classes in the Department of Psychology and Neuroscience at the University of Colorado, Boulder, and participated in the experiment to fulfill course credit requirements.

Apparati and Measurements

A commercially available competition bristle dart board was set to a regulation height (1.73 m off the ground) and distance (2.37 m from the throwing line). Subjects threw regulation steel tip darts that weighed 22 g. Through all phases of the experiment, subjects threw with their dominant hand (as identified through self-report in the written survey). Throughout the experiment, subjects threw three darts and then the experimenter measured the Cartesian coordinates of each dart using a hand-held metric tape-measure treating the bulls-eye as the origin (0,0; all measurements were made to the nearest mm). From these coordinates, a measure of accuracy (mean radial error; MRE) and a measure of precision (bivariate-variable error, BVE) were calculated. Equations for these calculations are shown in Figure 22 (based on two-dimensional accuracy and precision calculations in Hancock, Butler, & Fischman, 1995). Based on these calculations, MRE represents the average radial distance of all the throws in a block from the target (analogous to absolute error in 1-dimensional accuracy) and BVE represents the variation of throws around the centroid location (X_c,Y_c) for that block (analogous to the standard deviation in 1-dimensional precision).



Mean Radial Error (MRE):

$$MRE = \overline{RE} = \frac{1}{k}\sum_{i=1}^{k} RE_i$$

$$RE = \sqrt{X^2 + Y^2},$$

Bivariate Variable Error (BVE):

$$BVE = \sqrt{\frac{1}{k}\sum_{i=1}^{k} (X_i - X_c)^2 + (Y_i - Y_c)^2}$$

k = number of total trials
i = a specific trial
X_c, Y_c = mean distance from the x and y axes, respectively

Figure 22. *Description of the dependent variables of accuracy, measured as mean radial error (MRE), and precision, measured as bivariate variable error (BVE). Calculations based on Hancock, Butler, & Fischman (1995), using the Cartesian coordinates from three trials (dart throws) within a block.*

Design and Procedure

Upon arrival in the laboratory, subjects gave their informed consent for participation and filled out the written survey. Next, subjects completed six baseline throws with no instructions other than to aim for the bulls-eye in the center of the board and to try and be as accurate as possible. After these baseline throws, subjects entered the practice phase of the experiment. The practice phase consisted of 20 blocks of three throws each (60 throws total), with accuracy being measured after each block. Half of the subjects completed the practice phase with a 1.0 kg weight attached below the wrist of the throwing arm (the *weighted* group). The weight consisted of five 0.2 kg weights in a neoprene sleeve arranged radially around the wrist so that the weight was evenly distributed. The sleeve was secured with a Velcro fastener to prevent it from moving during the experiment. The sleeve was placed proximal to the wrist so that subjects would have full mobility in their wrist. Subjects were told that if the sleeve ever felt too loose or too tight, or if their arm ever felt tired, the weight could be adjusted by the experimenter. The remaining half of subjects completed the practice phase without any additional weights (the *unweighted* group). The variable of weighted or unweighted throwing arm is referred to as weight condition.

Half of the subjects in the weighted and unweighted groups were given external focus instructions at the beginning of the practice phase, "[…] aim for the bulls-eye trying to be as accurate as possible. We ask that you visually focus on the bulls-eye, but mentally try to focus on the *flight of the dart*. On each throw, concentrate on the flight of the dart. When you are off target, try to correct the flight of the dart." After each subsequent block of trials, subjects were reminded, "Try to aim for the bulls-eye, focusing on the flight of the dart."

The remaining half of the subjects received internal focus instructions at the beginning of the practice phase, "[…] aim for the bulls-eye trying to be as accurate as possible. We ask that you visually focus on the bulls-eye, but mentally try to focus on the *motion of your arm*. On each throw, concentrate on the motion of your arm. When you are off target, try to correct the motion of your arm." After each subsequent block of trials, subjects were reminded, "Try to aim for the bulls-eye, focusing on the motion of your arm." The variable of external or internal focus during the practice phase is referred to as "training focus".

After completing 60 throws in the practice phase, all subjects took a 15-min "rest" period that separated retention and transfer testing from the practice phase. During this rest period, subjects in the weight condition removed the weight from their wrist and were allowed no further practice. After 15 min of rest, subjects began the retention test (the retention test always preceded the transfer test). The retention test consisted of five blocks of throws (15 total throws). During the retention test, half of the subjects received instructions identical to their training focus and the remaining half of the subjects received the opposite instructions. The FOA during the retention test is referred to as “testing focus.” Thus, during the retention test half of the subjects had the same testing and training focus (EE & II subjects), and the remaining half of the subjects had different training and testing foci (EI & IE subjects). Weight condition was maintained during the retention test. Thus, subjects who trained weighted were also weighted during retention.

At the end of the retention test, subjects immediately began the transfer test. During the transfer test, testing focus was unchanged, but weight condition was reversed. Thus, during the transfer test, subjects who completed training and retention testing weighted had the weight removed from their wrist; subjects who completed training and retention testing unweighted had the weight added during the transfer test. The transfer test consisted of five blocks of throws (15 total throws). At the end of the transfer test, subjects were thanked for their participation and debriefed.

Analysis

The first analysis was to verify successful random assignment to groups. A 2X2X2 analysis of variance (ANOVA) with between-subjects factors of training focus, testing focus, and weight condition was run on the accuracy and precision data from the baseline phase. The analysis revealed no significant differences in accuracy or precision between groups. Thus, groups were successfully equated on their ability at the beginning of the experiment.

Next, an a priori test was conducted for the interaction between phase (first half of practice, second half of practice, retention test, transfer test), training focus, testing focus, and weight condition while controlling for baseline accuracy as a covariate. This interaction was significant, $F(3,213) = 2.99$, $p = .03$, $\eta_p^2 = .04$, which justified statistical analysis of the practice and testing phases separately.

The practice phase was analyzed using a 2X2X10 analysis of covariance (ANCOVA) with between-subjects factors of training focus and weight condition and a within-subject factor of block for the dependent measures of accuracy (MRE) and precision (BVE). Results of these ANCOVAs are presented in Tables 1 and 2. Testing was analyzed using a 2X2X2X2X5 ANCOVA with between-subjects factors of training focus, testing focus, and weight condition, and two within-subject factors of test type (retention versus transfer) and block for the dependent measures of accuracy and precision. Results of these ANCOVAs are also presented in Tables 1 and 2. Both ANCOVAs controlled for baseline performance as a covariate.

Results and Discussion

Table 7. Summary of ANCOVA results for Accuracy (MRE).

	Practice Phase			
Effect	***d.f.***	**MSE**	***F, p***	η_p^2
BaselineCOV	1	8,266.16	5.30, .02*	.512
Training Focus	1	17.89	0.17, .68	.002
Weight Condition	1	380.03	3.62, .06	.046
Error	*75*	*105.89*		
Block	9	46.64	2.45, < .01**	.032
Block X BaselineCOV	9	125.47	6.65, < .01**	.081
Block X Weight Condition	9	47.40	2.48, < .01**	.032
Error(Block)	*675*	*18.91*		

	Testing Phase			
Effect	***d.f.***	**MSE**	***F, p***	η_p^2
BaselineCOV	1	3,032.44	35.29, < .001***	.332
Training Focus	1	9.029	0.09, .75	.001
Testing Focus	1	1,095.34	12.75, < .001***	.152
Weight Condition	1	792.57	9.22, < .01**	.115
Testing Focus X Weight Condition	1	700.72	8.15, < .01**	.103
Error	*71*	*85.928*		
Test Type X Weight Condition	1	1,335.79	52.75, < .001***	.426
Error(Test Type)	*71*	*25.324*		
Block	4	16.54	0.77, .54	.010
Error(Block)	*300*	*21.37*		

Note: Significant effects are reported, or effects that are germane to the hypotheses of the experiment. All other effects were nonsignificant ($p > .05$).

* = denotes a significant effect below $p = .05$; ** = $p < .01$; *** = $p < .001$

Table 8. Summary of ANCOVA results for Precision (BVE).

	Practice Phase			
Effect	***d.f.***	**MSE**	***F, p***	η_p^2
BaselineCOV	1	2,291.86	47.58, < .001***	.388
Training Focus	1	1.08	0.02, .881	.000
Weight Condition	1	23.33	0.48, .49	.006
Error	*75*	*45.60*		
Block	9	19.79	1.41, .18	.020
Error(Block)	*675*	*14.02*		

	Testing Phase			
Effect	***d.f.***	**MSE**	***F, p***	η_p^2
BaselineCOV	1	1,086.35	34.77, < .001***	.329
Training Focus	1	5.69	0.18, .67	.003
Testing Focus	1	440.849	14.11, < .001***	.166
Weight Condition	1	71.52	2.29, .13	.031
Error	*71*			
Test Type X Weight Condition	1	345.06	18.41, < .001***	.206
Error(Test Type)	*71*	*18.75*		
Block	4	26.01	1.89, .11	.026
Error(Block)	*284*	*21.78*		

Note.

* = denotes a significant effect below p = .05; ** = p < .01; *** = p < .001

Accuracy (MRE)

During the practice phase, training focus had no significant effect on subjects' accuracy, nor was there a significant interaction between training focus and block. These null-results suggest that early in the learning process there was no strong advantage for one focus over the other, nor did the FOA change the rate of skill acquisition. The main effect of weight condition approached significance and is significant tested as a directional test (1/2 $p = .03$). This result shows that, on average, subjects who trained weighted had larger MREs than unweighted subjects during the practice phase. These effects are shown in Figure 23.

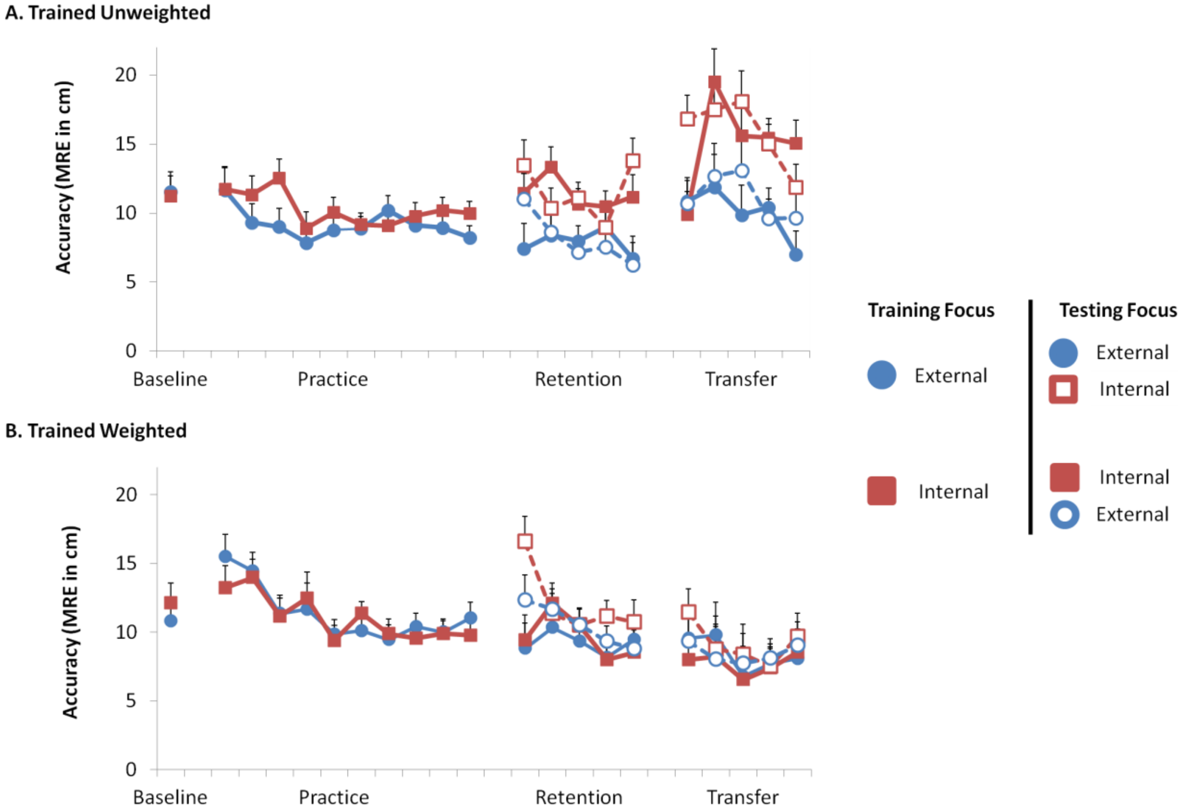


Figure 23. *Mean Radial Error across the different phases of the experiment as function of block, training focus, testing focus, and training condition. During the baseline and practice phase, data are averaged across testing foci. During the testing phase, the full Training Focus X Testing Focus interaction is shown. Panel A shows data for subjects who trained unweighted. Panel B shows data for subjects who trained weighted. Error bars show positive between-subjects standard errors.*

Furthermore, there was a significant main effect of block during practice, which shows that subjects did significantly improve over the course of the practice session. This interpretation of block must be tempered by two significant interactions, however. There was a significant Block X BaselineCOV interaction, such that subjects with lower MRE in the baseline phase tended to improve less across blocks compared to subjects with higher baseline MREs. Also, there was a significant Block X Weight Condition interaction, such that weighting the throwing arm had large initial effects on subjects' accuracy, but by the end of the practice phase, subjects had adapted to the weight and were performing more comparably to unweighted subjects.

In the analysis of the testing phase, there was no significant effect of training focus, but there was a significant effect of testing focus. Subjects who adopted an external focus of attention during testing did better than subjects who adopted an internal focus, regardless of the focus of attention used during training (EE and IE did better than II and EI at test). If an external focus of attention affected learning directly, we should not see this pattern of results and thus conclude that the FOA affects performance and not learning per se. These effects are shown in Figure 23.

Furthermore, there was a significant main effect of weight condition during the testing phase, showing that subjects who trained weighted (and were thus weighted during the retention test but not transfer test) had significantly smaller MREs, on average, compared to subjects who trained unweighted. However there was also a significant Weight Condition X Test Type interaction, shown in Figure 23. This interaction showed that subjects who trained unweighted tended to have much lower MREs on the retention test (9.79 cm) than on the transfer test (when weight was added (13.01 cm), whereas subjects who trained weighted had higher MREs on retention (10.39 cm) compared to transfer (8.44 cm; when the weight was removed). Thus, subjects performed worse with than without weights in both test types. The difference between retention and transfer test performance was also smaller for subjects who trained weighted.

Importantly, there was also a significant Testing Focus X Weight Condition interaction. This interaction showed that for subjects trained with no weights, the pattern of results is largely what one would expect from previous research on the FOA; that is, an external focus led to significantly better performance during testing (9.27 cm) compared to an internal focus (13.53 cm) [$t(35) = 3.56$, $p < .01$]. Conversely, for subjects trained with weights, an external focus (9.16 cm) during test was not significantly different from an internal focus (9.76 cm) [$t(35) = 1.02$, $p = .31$]. Interestingly, this lack of an effect of FOA does not appear to be because externally focused subjects were doing worse, but because internally focused subjects were doing better. This result suggests that when the inertial properties of the arm have changed and the motor system is adapting to these new dynamics, an internal focus is comparable to an external focus in its effects on performance.

Precision (BVE)

During the practice phase, there were no significant effects on precision. It is important to note that although weight condition had a significant effect on accuracy during practice (at least in the initial blocks), weight condition had no effect on precision. This finding suggests that adding weight to the throwing arm increased *bias* (systematic error), rather decreasing *precision* (variable error; Taylor, 1999), and that the motor system was then able to adjust for this bias during the practice phase (i.e., the significant Weight Condition X Block interaction for accuracy). Precision data for the practice phase are shown in Figure 24.

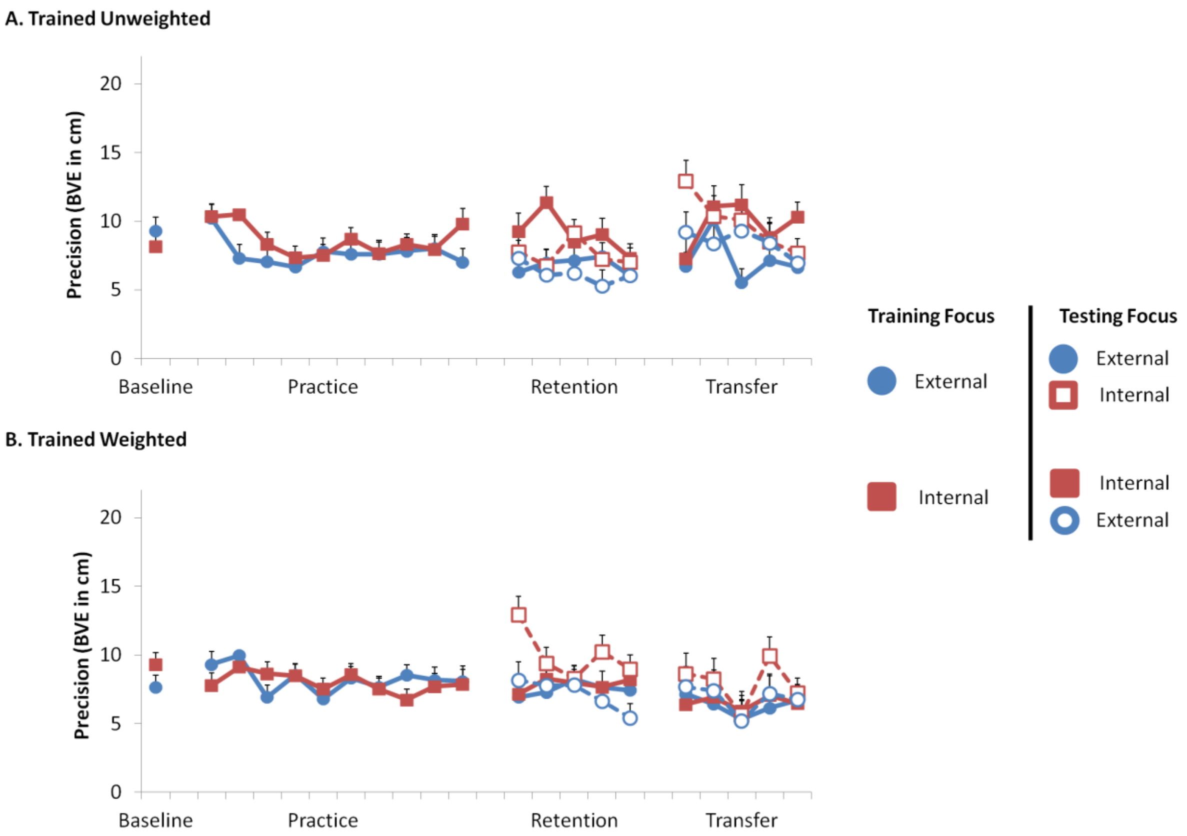


Figure 24. *Bivariate Variable Error across the different phases of the experiment as function of block, training focus, testing Focus, and weight condition. During the baseline and practice phase, data are averaged across testing foci. During the testing phase, the full Training Focus X Testing Focus interaction is shown. Panel A shows data for subjects who trained unweighted. Panel B shows data for subjects who trained weighted. Error bars show positive between-subjects standard errors.*

During testing, there was a significant effect of testing focus such that subjects who received external FOA instructions during testing showed lower BVE than subjects who received internal FOA instructions (shown in Figure 24). Similar to the effects for accuracy however, there was also a significant Weight Condition X Test Type interaction. This interaction showed that subjects who trained unweighted had lower BVE during the retention test than during the transfer test (when the weight was added), whereas subjects who trained weighted had higher BVE during retention than during transfer (when the weight was removed). Thus, as for accuracy, subjects performed worse in terms of in terms of precision with weights than without weights.

Conclusions

Previous research has shown that differences between internal and external FOA often do not emerge until late in practice or on delayed retention and transfer tests. This observation has led some researchers to conclude that an external focus of attention improves learning in addition to performance (e.g., Lohse, 2012; Totsika & Wulf, 2003). The findings of the current experiment, however, suggest this conclusion may have been premature; in the current experiment, there was no advantage of training with an external focus of attention when an internal focus of attention was instructed at test. Similarly, there was no disadvantage to training with an internal focus of attention when an external focus of attention was instructed at test. The lack of a significant effect of training focus with the presence of a significant effect of testing focus strongly suggests that an external FOA confers an advantage to *performance*, but not an advantage to *learning* (at least not directly).

An external FOA might indirectly enhance the rate of skill acquisition because it improves a learner's performance during practice (although it did not do so in the present study). Improved performance during practice can increase a learner's sense of self-efficacy, motivation, or engagement with the task at hand and these affective variables have been shown to facilitate learning (Bandura, 1982; Wulf & Lewthwaite, 2009; Salomon, 1983; Wulf, Chiviacowsky, & Lewthwaite, 2011). Thus, it is possible an external FOA indirectly facilitates learning, mediated by a learner's affective state. The results of the current experiment, however, suggest that accelerated improvement is not a function of a learner's FOA per se.

This findong raises an important question however, because if an external FOA improves performance, why are the advantages of an external FOA not visible immediately? We posit that an external FOA allows the motor system to exploit learned motor representations to optimize performance. This position is based on reinforcement learning research showing a trade-off between exploitation to improve short-term performance and exploration to improve long-term learning of the skill (Cohen, McClure, & Yu, 2007; March, 1991). Potentially, an external FOA could exploit learned motor representations to their fullest effect, because an external focus of attention relies less on explicit, working-memory dependent resources (Wulf et al., 2001) allowing implicitly learned, procedural information to govern the execution of the motor skill. The caveat to this method of control is that it would require robust motor representations in order to be successful. In this way, sufficient learning might need to take place before an external FOA has a demonstrable effect. Some research suggests that many hours of practice might be required to tune these implicit motor representations before an external focus can have an advantage (Beilock & Carr, 2001; Gray, 2004). On the contrary, the current experiment (and the work of many others including Hodges & Franks, 2000; Lohse, Sherwood, & Healy, 2010; Wulf et al., 1998; Wulf, Lauterbach, & Toole, 1999) suggest that novices benefit from an external FOA compared to an internal FOA. Because the difference is not visible immediately however, data suggest that a minimal, but sufficient, amount of practice must occur for an external FOA to be effective. As learning continues though, the advantage of an external focus of attention is exacerbated.

Conversely, an internal focus of attention hinders performance because it disrupts implicit, procedural representations in favor of explicit, working-memory dependent control (Wulf et al., 2001). Clearly an internal FOA is an ineffective mode of control for performance, but consciously directing attention internally in order to change the motor pattern might be an effective means of exploring the movement space when severe errors are encountered (for a related study see Dam & Kording, 2009).

Thus, the rate of acquisition for the “pure” motor skill (the representation of the skill somewhere in the learner’s mind which is inferred from performance) is similar regardless of the FOA adopted during training. However, the effective execution of the skill (observed in a subject’s behavior) is facilitated by an external FOA, but only when there are sufficiently robust motor representations to optimize the appropriate movement parameters, ultimately reducing error in the goal dimensions. It is important to note, this optimization is probably a local optimization and not a global optimization. As the learner develops a better representation of the dynamics of the task, an external FOA will continue to allow the motor system to implicitly find progressively better local maxima.

Interestingly, in the current experiment, subjects who trained without added weight and adopted an external FOA during testing performed better not only during retention, but also during transfer when the weight was added. This finding suggests that an external FOA is effective in optimizing motor control not only when task dynamics are known (retention), but also when task dynamics have been changed (transfer). It is unclear how far this statement can be generalized. If the dynamics of the task changed more significantly, would an external focus of attention still be as advantageous?

An important new finding from this experiment comes from those subjects who trained with the weight added to the wrist of their throwing arm. Subjects who trained unweighted showed results consistent with previous research: An external focus of attention led to significantly better performance on retention and transfer testing. For the weighted subjects, however, the data tell a dramatically different story. Subjects who trained with added weight showed no significant effect of focus for either retention or transfer testing. This result seems at odds with the significant effect of focus for unweighted subjects during the transfer test (when the weight had just been added to their throwing arm). This significant interaction of testing focus and weight condition suggests that changing the dynamics of the throwing arm has a hysteretic effect on performance. Training with one's normal arm dynamics and then shifting to novel dynamics is still facilitated by an external FOA. Conversely, training with novel arm dynamics significantly reduces or eliminates the advantage of an external FOA during subsequent testing, even when the arm dynamics are returned to normal. Note that for weighted subjects, the external FOA advantage was reduced not because externally focused subjects were doing worse, but because internally focused subjects were doing better.

We propose that this hysteretic effect is based on adaptation of the motor system's representation of the throwing arm. Training with the weight leads to updating the internal model of the arm. While this internal model is in flux, the advantage of an external focus is reduced because attention cannot effectively exploit a motor representation that is being adapted. If this updated model of the arm were to become stable (such as after a longer period of practice in the lab, or gaining/loosing muscle mass in daily life), an external FOA might again be an effective way to exploit existing representations to optimize performance. This hypothesis is scientifically grounded, but purely speculative. This hypothesis also raises important questions for rehabilitation science where representations of limb dynamics might change due to musculoskeletal injury, atrophy, or neurological insult.

Future research is needed to understand the effects of attention when internal models of limb dynamics are being learned, re-learned, or adapted. Related research in this area has shown that attention can significantly influence the rate of adaption in split-belt treadmill walking (Malone & Bastian, 2010). In that experiment, there was no direct comparison between external FOA and internal FOA, but subjects focused either on regulating their stride length or on a distracting secondary task. Focusing on stride length increased the rate of adaptation to walking on the split-belt treadmill (with a 3:1 difference in belt speed) and also led to a brief period of after-effects when the belts were re-coupled (normal treadmill walking). Conversely, subjects took a longer time to adapt to the split-belt under distracting secondary conditions, but also showed longer after-effects when normal walking was restored.

In summary, research on the FOA consistently demonstrates that an external focus is beneficial for novices, that subjects who train with an external FOA do better on subsequent testing following a delay (i.e., retention tests), and that an external FOA improves performance relative to an internal FOA on novel variations of the practiced skill (i.e., transfer tests). The results of the current experiment, in which training and testing FOAs were varied orthogonally, suggest that an external FOA does not proffer an advantage to learning, but does enhance performance. Optimizing performance may indirectly improve skill acquisition by increasing a learner's sense of self-efficacy and thus increasing effort and engagement during training (but again, this was not found in the present study). Interestingly, this study provides new data suggesting that when limb dynamics have been altered, internally focused subjects perform more comparably to externally focused subjects (further strengthening the argument that an external focus relies on the exploitation of implicit motor representations). Understanding the role of attention in adaptation and performance with novel limb dynamics has important applied and basic science implications.

Chapter 6: Conclusions and future directions for the focus of attention

> *"I suggest you try it again Luke. This time, let go your conscious self and act on instinct."*
>
> – Obi-Wan Kenobi to Luke Skywalker, *Star Wars: A New Hope* (1977)

A Brief Review of the Current Experiments

At the beginning of this dissertation, a review of experiments on the focus of attention showed that although the effects of attention were well established, they were not well understood theoretically (i.e., not being integrated with larger theories of motor control) and not well understood in terms of their physiological mechanisms (e.g., recent data on muscle recruitment, oxygen consumption, and kinematic variability were not predicted by the constrained action hypotheses). From the experiments in this dissertation, we now have a much better understanding of the physiological changes that mediate the attention-performance relationship, and these physiological data help to integrate attention into theories of motor learning and control.

Chapter 2 provided initial evidence of how attention could disrupt neuromuscular coordination at the most basic levels (intermuscular coordination and motor unit recruitment) in an isometric force production task. While trying to produce 30% of a maximum voluntary contraction (MVC), focusing attention internally on the agonist muscle increased cocontraction in the antagonist muscle and decreased accuracy in the force produced. Furthermore, within-subject regression models showed that the level of cocontraction was significantly and positively correlated with error on a given trial.

Chapter 3 replicated these data and studied the effects of attention in greater detail, using 30, 60, and 100 %MVC trials and having subjects produce force for 4-s (measuring accuracy in Experiment 3.1) or until failure (measuring fatigue in Experiment 3.2). In Experiment 3.1, an internal focus of attention led to increased cocontraction of the antagonist muscle. Furthermore, this increase in cocontraction was greater at higher levels of force produced. In Experiment 3.1, increased cocontraction was significantly correlated with error on a given trial for all %MVC targets.

In fatiguing trials (Experiment 3.2), the level of force produced was controlled so that neuromuscular changes would reflect efficiency, specifically. In these fatiguing trials, an internal focus of attention led to less efficient intermuscular coordination (i.e., increased cocontraction) and increased motor unit recruitment in the antagonist muscle. Similar to Experiment 3.1, increases in cocontraction were largest for 100 %MVC trials. Furthermore, the largest increases in cocontraction were seen early in the trial and as the trial progressed, cocontraction decreased for both internal focus and external focus conditions.

The task in Chapters 2 and 3 raises a few concerns about interpretation of the data. After all, in this relatively simple force production task, asking subjects to focus on the muscle seems quite different from asking subjects to focus on movement execution in more complex, full-body tasks. In both chapters, the instructions to subjects were designed so that attention was directed to the platform (in the external focus condition) or the agonist muscle (in the internal focus condition). Thus, in both internal focus and external focus conditions attention would be directed to task-relevant sources of information. Previous studies of the focus of attention have been criticized for internal focus conditions with low task relevance (see Hommel, 2007; Künzell, 2007), thus we tried to equate these foci on task relevance, making the only critical difference the external/internal distinction. Note also that the feedback and accuracy requirements were the same in all conditions and subjects were always instructed to be as accurate as possible. Thus, although some caution must be taken in generalizing results from this highly constrained task to internal focus instructions in the real-world, within the task there is a valid attentional focus manipulation that has clear effects on both movement efficiency and movement effectiveness.

A recent experimental study (Rudroff, Justice, Holmes, Matthews, & Enoka, 2010) shows a similar effect of attention on isometric force production in the arm musculature. In this experiment, attention was not specifically manipulated to be either internally or externally focused, but subjects were required to perform isometric elbow flexions while either maintaining a specific amount of force (arguably an external focus) or maintaining the angle of their elbow (arguably an internal focus). In the *force* condition, subjects performed isometric elbow flexions against a rigid restraint while trying to maintain target forces with the elbow fixed at a 90° angle. In the *position* condition subjects had to maintain a constant elbow angle of 90° while supporting an equivalent inertial load (load was equivalent to the force generated in the force condition for each subject). Thus, the same amount of force and the same elbow angle are required in each condition, but in the force condition the elbow was fixed and subjects needed to maintain the force produced, whereas in the position condition, the force was fixed and subjects needed to maintain a constant elbow angle. In each condition, the contraction was sustained for as long as possible. Force produced was identical for the force and position conditions, but the time to task failure was longer for the force condition than for the position condition. Shorter time to failure (i.e., faster fatigue) in the position condition was associated with increases in elbow flexor muscle activity, mean arterial pressure, heart rate, and subjects' rating of perceived exertion. Although the experimental manipulation is different and different muscle groups were measured, Rudroff et al.'s results are commensurate with those of Chapters 2 and 3; focusing on the body led to less efficient muscle recruitment compared to focusing on the force being produced, with greater energy being expended to maintain the same level of force.

Increases in cocontraction are an interesting result of an internal focus of attention, because increasing cocontraction increases joint stiffness, which is a characteristic of novice movement (Gribble, Mullin, Cothros, & Mattar, 2003; Osu, Franklin, Kato, Gomi, Domen, Yoshioka, & Kawato, 2002). Increased cocontraction might also explain the reduction in functional variability that occurs with an internal focus of attention, shown in Chapter 4, because cocontraction is an effective method for improving the accuracy and precision of a movement (Visser, de Looze, de Graaf, & van Dieën, 2004). The dart throwing study in Chapter 4 showed that an internal focus of attention led to worse accuracy, less joint variability from trial to trial, and a reduced correlation between kinematic variables (i.e., greater kinematic independence in the movement, which suggests less coordination) relative to an external focus of attention. These last two findings (decreased joint variability and decreased coordination) are the most important because they suggest an internal focus of attention changes what aspect of performance the motor system is attempting to control.

With an external focus of attention, subjects had greater accuracy, greater trial-by-trial variability in both the shoulder and elbow joint, and stronger correlations among kinematic variables. This pattern is consistent with the predictions of optimal control theory (Todorov & Jordan, 2002), assuming a control rule operating directly on the outcome of the task (i.e., the final landing point of the dart), which would allow greater variability in redundant dimensions of the movement. Conversely, with an internal focus of attention, subjects had worse accuracy and reduced trial-by-trial variability in the shoulder and the elbow, and less of a correlation between kinematic variables (i.e., less coordination). Thus, and internal focus of attention leads to greater explicit control of the movement itself, reducing functional variation in the kinematic dimensions, and ultimately impairing a subject's accuracy.

Elaborating on effects of attention in motor control in Chapters 2-4, Chapter 5 explored potential effects of attention on motor learning. Data from the dart throwing task in Chapter 5 did not include any physiological measurements; however, the accuracy and precision data from Chapter 5 suggest that attention's principal effect is on motor performance and not on motor learning. In Chapter 5, the focus of attention that subjects used during a training phase and a testing phase was manipulated orthogonally. The focus of attention had no effect during the training phase. Furthermore, the focus of attention subjects trained with had no significant effects during the testing phase. However, the focus of attention at test had a significant effect on subjects' performance during the testing phase. When subjects were instructed to adopt an external focus during testing they were both more accurate and more precise than when subjects were instructed to adopt an internal focus, regardless of training focus. Furthermore, an external focus of attention during testing improved performance relative to an internal focus on a transfer test when weights were added to the wrist of the throwing arm. These data strongly suggest that an external focus of attention confers an advantage to performance, but little or no advantage to learning, at least not directly. An external focus of attention may indirectly improve learning because better performance during practice might increase a learner's sense of self-efficacy or motivation, and thus effort expended on the task (these variables have been shown to improve learning; Bandura, 1982; Lewthwaite & Wulf, 2009; Salomon, 1983; Wulf et al., 2011).

Interestingly, for the experiment reported in Chapter 5, although an external focus of attention improved performance significantly and learning only very little, if at all, the effects of attention were not visible immediately (i.e., no effect of training focus during the training phase). This result suggests that a certain amount of practice is required, albeit a small amount of practice, before an external focus of attention is advantageous. A plausible explanation for this effect is that an external focus of attention allows implicit representations of the motor skill to control the movement. In order for these implicit representations to be effective, they must be tuned through physical practice before they are a more effective means of control than explicit, working-memory dependent control that is invoked by an internal focus of attention (Koedijker et al., 2007; Poolton et al., 2006; Wulf et al., 2001).

Also in Chapter 5, a second group of subjects trained with weights attached to their throwing arm, took the retention test with these weights attached, and then removed these weights during the transfer test. Curiously, for these subjects there was no significant effect of focus of attention at either training or testing (i.e., performance was comparable for internally focused and externally focused subjects). Also, comparable performance between the internal and external focus groups did not appear to be the result of the externally focused group doing worse, but rather the internally focused group doing better after training with the weight attached. This is a surprising new finding that opens the door for future research on the effects of attention when limb dynamics are novel.

Across these five chapters, there is substantial new data to suggest a new role for attention in motor and control and modification of the constrained action hypothesis (Wulf, 2007a, 2007b). In the next section, I present a framework that explains these new data on attentional focus effects by comparing research on attentional focus with more general research on motor learning. This framework is a modification of the constrained action hypothesis that draws on neurophysiological and behavioral evidence to explain precisely how an internal focus of attention constrains the motor system. Furthermore, this framework is applicable not only to research on the focus of attention, but also to other effects in human motor performance such as implicit learning and choking under pressure. The full framework is presented in detail below, but in short this framework posits that shifting attention from internal to external changes both the efficiency and effectiveness of movement in a manner physiologically similar to changing from a novice to an expert. An external focus of attention appears to be a short-cut to more "expert-like" control, whereas an internal focus of attention constitutes a reversion to a more "novice-like" mode of motor control at a physiological level.

Changes during Learning as a Model for the Focus of Attention

The proposition that shifting the focus of attention leads to motor control strategies that are more novice-like (for an internal focus) or more expert-like (for an external focus) is based on three peripheral physiological changes that parallel observed physiological changes during skill acquisition. *First*, increased cocontraction around a joint is characteristic of motor control early in the learning process (Gribble et al., 2003; Osu et al., 2002). Cocontraction is defined as the simultaneous activation of muscles around a joint. Changing the magnitude of cocontraction is a method for the motor system to control mechanical impedance in the limb. Increased impedance provides mechanical stability in the presence of both environmental perturbations (Biryukova, Roschin, Frolov, Ioffe, Massion, & Dufosse, 1998; Lacquaniti & Maioli, 1989; Osu et al., 2002; Thoroughman & Shadmehr, 1999) and forces arising from within the body, such as the interaction torques between joints (Gribble & Ostry, 1999; Koshland, Galloway, & Nevoret-Bell, 2000).

Early in training, human subjects show significantly higher levels of cocontraction between agonist and antagonist muscles compared to when a skill is well practiced (Gribble et al., 2003; Osu et al., 2002; Thoroughman & Shadmehr, 1999). This result may in part be a conscious attempt on the part of the learner to exercise greater control over the movement pattern in the face of uncertainty. This can either be uncertainty due to outside perturbations (e.g., perturbing environmental forces) or uncertainty about the body's own dynamics (e.g. poorly coordinated muscle forces). Note that cocontraction of muscles around a joint to stabilize the movement does not necessarily decrease with practice; this effect is dependent upon movement speed. When movement speed is controlled (e.g., Gribble et al., 2003; Osu et al., 2002), there is a consistent reduction in cocontraction, which suggests improved predictive control of the movement. However, if subjects' movement speeds increase with learning, increased cocontraction may emerge to stabilize the joints against higher inertial forces (Spencer & Thelen, 1999).

Secondly, both longitudinal studies and cross-sectional studies comparing experts to novices show that novices functionally reduce the number of degrees of freedom in a movement (Schorer et al., 2007; Vereijken et al., 1992; Wilson et al., 2008). Congruent with Bernstein’s (1967) proposal that motor learning leads to “unlocking” degrees of freedom in the motor plant, there are numerous studies that have reported the freezing of joint segments in the early stages of learning a motor skill.

According to Bernstein (1967), motor learning can generally be categorized by three stages, although these stages are not necessarily discrete. Initially, the learner attempts to “freeze” degrees of freedom in order to simplify the motor control problem. With continued practice, novices learn to release degrees of freedom, increasing the fluidity of the movement. In the final stage, experts have not only unlocked degrees of freedom that were once rigid, but experts are also able to exploit passive forces during movement, improving the efficiency of the movement (e.g., exploiting gravitational or Coriolis forces, relying less on internally generated forces from the musculature). Currently, there is debate about the linearity of these motor learning stages and debate about the correct frame of reference for describing degrees of freedom (e.g., joints, muscles, or resultant forces like torques and kinematics; see Newell & Vaillancourt, 2001); however, there is considerable experimental data to show freezing degrees of freedom early in the learning process. These studies include tasks as varied as learning to hand-write one’s signature with the nondominant hand (Newell & van Emmerik, 1989), dart throwing (McDonald, van Emmerik, & Newell, 1989), throwing shots in team-handball (Schorer et al., 2007), using a ski-simulator (Vereijken et al., 1992), performing the triple-jump (Wilson et al., 2008), and engaging in prehension tasks (Steenbergen, Martenuik, & Kalbfleisch, 1995).

Thirdly, unlocking degrees of freedom allows experts to exploit redundant degrees of freedom in the movement pattern, controlling variability in only the most goal-relevant dimensions (Haggard et al., 1995; Lee et al., 1982; Müller & Loosch, 1999; Scholz et al., 2000). Earlier studies of skilled pistol shooting (Arutyunyan, Gurfinkel, & Mirksii, 1968, 1969) showed an increase in the motion of distal arm joints as a result of learning. A similar study by Southard and Higgins (1987) demonstrated a progressive release of the distal arm joints in a racquetball forehand shot. Note that unlocking degrees of freedom does not necessarily proceed from the proximal to distal joints and can even be bidirectional (e.g., Broderick & Newell, 1987; unlocking the elbow joint in learning to dribble a basketball). Unlocking these redundant degrees of freedom in the motor system allows for increased variation in movement dimensions irrelevant to the task goal, referred to as the *uncontrolled manifold* (see Kang, Shinohara, Zatsiorsky, & Latash, 2004; Scholz & Schöner, 1999). For instance, Scholz et al. (2000) showed that skilled marksmen allowed greater variation in the uncontrolled manifold of the action space in a pistol shooting task (such as roll of the pistol, which does not affect the final placement of the shot) compared to goal relevant dimensions (such as pitch and yaw of the pistol, small deviations in which can significantly affect accuracy).

These three physiological changes (reducing cocontraction, unlocking degrees of freedom, and exploiting redundant dimensions) have already been well documented in motor learning. Data from the experiments in this dissertation show congruent physiological changes as a result of shifting the focus of attention. A summary of these effects is shown in Table 9.

Table 9. Parallels between physiological changes as a result of learning and as a result of changing the focus of attention.

	Learning		**Attention**	
Physiological Effect	**Novice**	**Skilled**	**Internal**	**External**
1. Cocontraction.	Increased	Decreased	Increased	Decreased
2. Mechanical degrees of freedom.	Locked	Unlocked	--	--
3. Redundant dimensions in the movement space.	Independent	Coordinated	Independent	Coordinated

Note. Changes in the mechanical degrees of freedom have not been directly measured in studies of attention. However, cursory evidence on kinematic variability (Chapter 4; Lohse et al., 2010) suggests functional unlocking of degrees of freedom with an external compared to an internal focus.

Based on these observations, changes in motor control as a result learning suggest a model for the effects of attention on motor control. Specifically, an internal focus of attention constitutes a regression to a more novice-like form of motor control, a conscious attempt to increase joint stiffness in order to decrease variability in the movement pattern. From behavioral and kinematic data, focusing internally is functionally similar to novice-like performance (i.e., decreased functional variability, increased cocontraction, and decreased levels of performance), and focusing externally is similar to expert-like performance (i.e., increased functional variability, decreased cocontraction, and improved performance). Consequently, I propose that at a neurophysiological level, focusing internally invokes neural structures that were involved in the control of movement prior to the development of expertise. This proposition provides a fruitful re-formulation of the constrained action hypothesis as an explanation for the focus of attention. This proposed neurophysiological framework has advantages over the original formulation of the constrained action hypothesis not only because it can explain the most recent physiological data, but also because it provides specific and testable mechanisms by which attention can constrain the motor system.

A Neurophysiological Framework for Attention in Motor Control

Voluntary human movements are unique in that they are both volitional and controlled through the desire to effect a change in the environment. That is, human beings do not generally attempt to control movement based on the actions of individual muscles or even joints, but instead through the desired sensory consequences of the movement (e.g., I don’t need to consciously coordinate a sequence of muscle activations to grab my coffee; consciously, I decide to grab the cup). This notion of effect-based control in voluntary movements has been explored at the psychological level (e.g., ideomotor theory; James, 1890; Stock & Stock, 2004) and at the mechanistic level (e.g., control systems using forward and inverse internal models; Wolpert & Kawato, 1998).

Current data on the focus of attention align with the notion of effect-based control. Importantly, findings on inter-muscular coordination and movement variability suggest not only that attention is important for setting the nominal goal of the task (e.g., “generate 350 N of force”) but also that attention shapes the control structure of the motor system (e.g., “how to generate 350 N of force”). The finding that attention affects the control structure of the motor system is not a new finding in itself (see Wulf, McNevin, & Shea, 2001, for differential effects of attention on error correction in a balance task), but what is new about the current studies is an understanding of how attention affects motor control at the most basic neuromechanical levels. These new data offer a new empirical grounding from which we postulate about the central nervous system (CNS) mechanisms that mediate thought and action. As Hollerbach (1982) suggested, the problem of motor control can be framed as the problem of which processes intervene between the thought of the goal and the muscle activations that result in movement; these new data address that gap.

Based on the similarities between learning (novice to skilled performer) and attention (internal to external) in both behavioral and physiological effects, I suggest that changes in the motor control as a result of learning are a fruitful model for understanding the effects of attention on motor control. Thus, having established the similarities between learning and attention in behavioral measures of movement outcomes and in peripheral physiological measures (limb kinematics, sEMG), I will invoke motor learning as a model to generate predictions about changes in the CNS that might underlie the focus of attention.

This framework builds on past research in the area of attention and motor control (see Koedijker, Oudejans, & Beek, 2007; Masters & Maxwell, 2008; Willingham, 1998; Wulf 2007a; 2007b). This framework posits that an internal focus of attention leads to a motor control strategy that is more novice-like not only in terms of its effectiveness, but also in terms of it physiological substrates. Limited research has been done to study the effects of attention on the CNS directly (see Jueptner, Stephan, Frith, Brooks, Frackowiak, & Passingham, 1997; Zentgraf, Lorey, Bischoff, Zimmermann, Stark, & Munzert, 2009), but the effects of motor learning on the CNS have been studied in considerable detail in both humans and animals. Data from neuroimaging studies of human motor learning will be discussed next, highlighting changes in activity of cortical and subcortical brain areas. These learning induced changes in the CNS will be compared to the limited data available from studies of attention. Congruent changes in the CNS as a result of learning are found for an external focus of attention. Finally, the framework will be discussed in detail, demonstrating how the framework explains current data on the focus of attention and making unique predictions for future research.

In general, this framework posits that an external focus of attention leads to an efficient mode of control in which movement goals are created using working-memory dependent, explicit cognition (as evidenced by prefrontal cortex, PFC, activity). These movement goals are then transformed, through a series of intervening processes, from a high-level representation of the task goal into a specific sequence of muscles activations that actuates the movement. The proposed framework is agnostic as to what these intervening transformations actually are; however, integrating perceptual information, translating from an allocentric representation to an egocentric representation, and the sequencing of movement subcomponents are all transformations that are likely to occur. Furthermore, these implicit transformations are tuned/improved by physical practice (Hikosaka, Nakamura, Sakai, Nakahara, 2002; Willingham, 1998); however, explicitly learning strategic information can also improve performance (e.g., deliberately aiming away from the target in a prism adaptation task, Willingham, 1998).

The framework posits that an internal focus of attention leads to a less efficient mode of control, in which not only are movement goals explicit, but greater explicit control is allocated to the intervening motor transformations. Thus, an internal focus of attention should lead to an increased processing burden at the psychological level, but also increased activity in brain areas associated with working memory (such as PFC) and reduced activity in brain areas associated with implicit motor control (such as the supplementary motor area, SMA, and the primary motor cortex, M1). In this way, an internal focus of attention should show a characteristic pattern of neural activity that is similar to early stages of motor learning and an external focus of attention should show a characteristic pattern that is similar to later stages, when subjects have achieved a higher level of proficiency with the task.

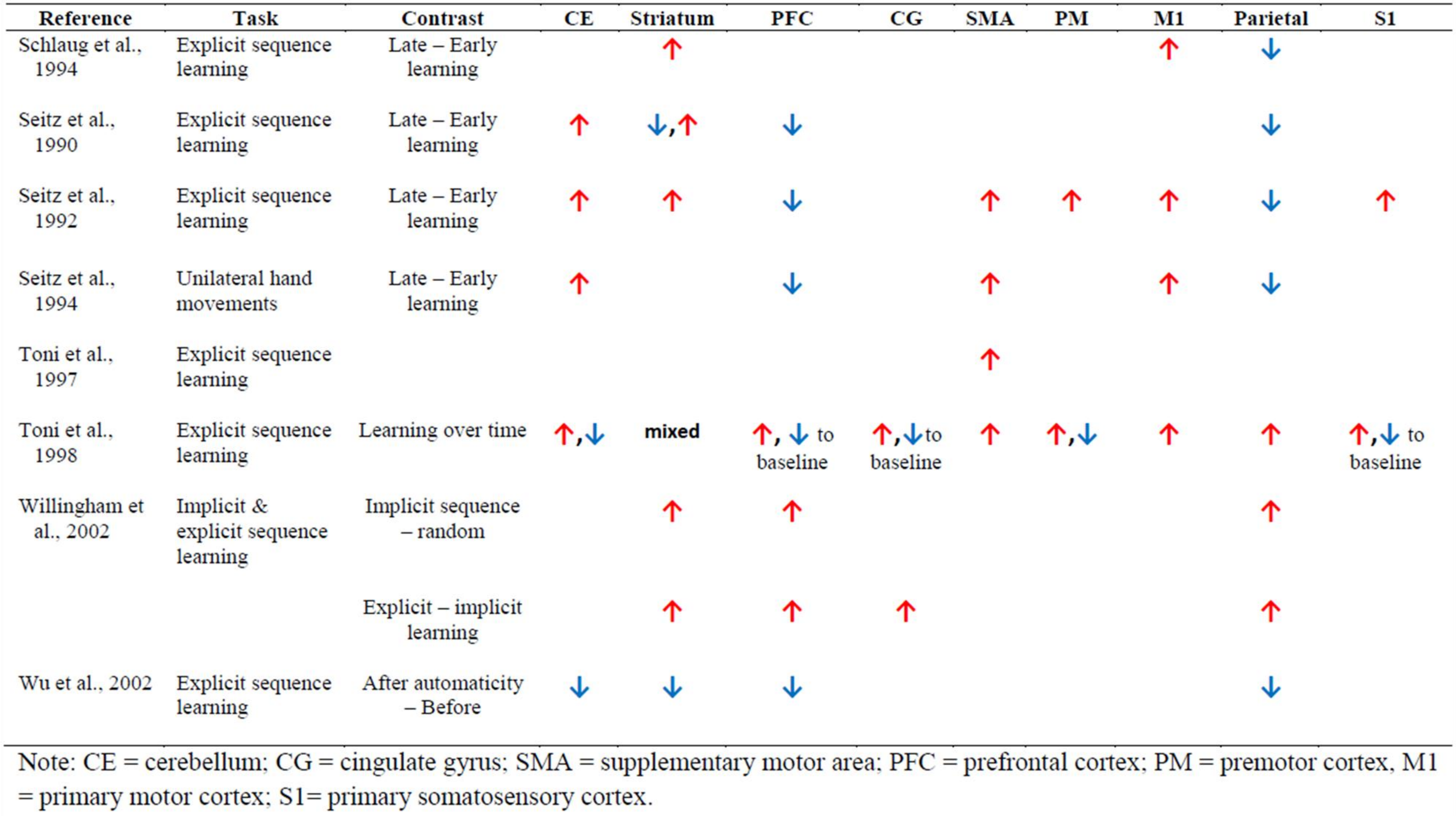
Changes in the CNS as a Result of Motor Skill Learning

Table 10 provides a summary of human imaging studies that have explored changes in activity in the CNS as a function of motor skill learning. Certainly there is much more detail in these individual studies than is present in the table, but the table reports significant contrasts, in either PET or fMRI analysis, that relate directly to learning (although specific contrasts differ between studies). Furthermore, the table provides a grosser level of anatomical description than do the individual studies. For instance, distinct effects of learning on the caudate nucleus and the putamen are referred to collectively here as the striatum. Similarly, differences between dorsolateral, ventrolateral prefrontal, and orbitofrontal cortex are ignored to form the more general anatomical distinction of the PFC. This simplification helps to establish general trends in CNS activity as a function of motor learning across many types of tasks, but it does not provide a mechanistic explanation of the computations performed by these brain areas, which are also more likely to be task-dependent.

Table 10. Summary of changes observed in the CNS as a result of motor learning.

Reference	Task	Contrast	CE	Striatum	PFC	CG	SMA	PM	M1	Parietal	S1
Doyon et al., 1996	Serial response time	Learned - random sequence	↑	↑	↓	↑				↑	
	Serial response time	Explicit – Implicit learned seq.	↓		↑						
Doyon et al., 2002	Serial response time	Session 2 -1	↑			↑		↑		**mixed**	
		Session 3 – 2	↓	↑	↑	↓	↑	↓		↑	
Friston et al., 1992	Explicit sequence learning	(Trial 3 – Rest 3) – (Trial 1 – Rest 1)	↓								
Grafton et al., 1992	Pursuit rotor task	Late – Early learning		↑			↑		↑		
Grafton et al., 1994	Pursuit rotor task	End – Beginning training (Day 1)	↑			↑	↑		↑	↑	
		End – Beginning training (Day 2)		↑	↓			↑		↑	
Grafton et al., 1995	Implicit sequence learning	Late – Early learning		↑			↑		↑		
	Explicit sequence revealed	Explicit – Implicit learning		↑	↑					↑	
Honda et al., 1998	Serial response time	Implicit sequence learning					↑				↑

Reference	Task	Contrast	CE	Striatum	PFC	CG	SMA	PM	M1	Parietal	S1
Honda et al., 1998	Serial response time	Explicit sequence learning			↑		↑	↑		↑	
Jenkins et al., 1994	Trial and error sequence learning	Prelearned sequence – New sequence	↓	↓	↓		↑	↓		↓	
Jueptner et al., 1997a,b	Explicit sequence learning	Prelearned sequence – New sequence	↓	↓	↓	↓	↑	↓		↓	
Karni et al., 1995	Explicit sequence learning	Prelearned sequence – New sequence							↓, ↑		
Karni et al., 1998	Explicit sequence learning	Prelearned sequence – New sequence							↑		
Pasqual-Leone et al., 1994	Serial response time	Implicitly trained group – Control group							↑		
		Explicit awareness – Control group							↓ to baseline		
Penhune & Doyon, 2002	Explicit timing sequence	Day 1: Learned – control sequence	↑								
		Day 5: Learned – control sequence		↑			↑				
		4 Weeks: Learned – control sequence						↑	↑	↑	
Peterson et al., 1998	Mirror tracing	Late – Early learning					↑	↓		↓	
Poldrack et al., 2005	Serial response task	Dual task: After automaticity – Before	↓	↓	↓			↓		↓	



Reference	Task	Contrast	CE	Striatum	PFC	CG	SMA	PM	M1	Parietal	S1
Schlaug et al., 1994	Explicit sequence learning	Late – Early learning		↑					↑	↓	
Seitz et al., 1990	Explicit sequence learning	Late – Early learning	↑	↓,↑	↓					↓	
Seitz et al., 1992	Explicit sequence learning	Late – Early learning	↑	↑	↓		↑	↑	↑	↓	↑
Seitz et al., 1994	Unilateral hand movements	Late – Early learning	↑		↓		↑		↑	↓	
Toni et al., 1997	Explicit sequence learning						↑				
Toni et al., 1998	Explicit sequence learning	Learning over time	↑,↓	**mixed**	↑, ↓ to baseline	↑,↓to baseline	↑	↑,↓	↑	↑	↑,↓ to baseline
Willingham et al., 2002	Implicit & explicit sequence learning	Implicit sequence – random		↑	↑					↑	
		Explicit – implicit learning		↑	↑	↑				↑	
Wu et al., 2002	Explicit sequence learning	After automaticity – Before	↓	↓	↓					↓	

Note: CE = cerebellum; CG = cingulate gyrus; SMA = supplementary motor area; PFC = prefrontal cortex; PM = premotor cortex, M1 = primary motor cortex; S1= primary somatosensory cortex.

Qualitative comparison of these imaging studies reveals a few notable trends in the data. Although many brain areas do not show a consistent direction in the pattern of activation, there is evidence for a general decrease in PFC activity with practice and a corresponding increase in the SMA and M1. In studies exploring PFC activity at multiple time points (Day 1 for Grafton et al., 1994; early trials for Toni et al., 1998), there is an interesting nonlinearity in the pattern of activation. Early in learning process, activity in the PFC increases and then, later in the learning process, there is a significant decrease in the amount of PFC activity. Thus, early in the learning process, frontal areas play a larger role in motor control, which diminishes with continued practice. These neurophysiological data align well with psychological theories of motor learning, which suggest that early in the learning process, subjects rely on more verbal-cognitive strategies of motor control before implicit motor control mechanisms have been sufficiently tuned to accurately guide movement (Anderson, 1983; Fitts, 1964; Fitt & Posner. 1967).

As a motor task is practiced, activity increases in the SMA and M1. This increased activity is challenging to interpret, but it does suggest an increase in the influence of purely motoric structures in motor control; conversely, early in the learning process there is greater involvement of the PFC, which is more verbal-cognitive in nature. Increases in SMA activity potentially reflect a shift from explicit movement sequencing, dependent on PFC mechanisms, to more implicit movement sequencing. There is considerable evidence to suggest that SMA is involved in the sequencing and organization of voluntary movements (Dick, Benecke, Rothwell, Day, & Marsden, 1986; Gaymard, Pierrot-Deseilligny, & Rivaud, 1990; Halsband, Ito, Tanji, & Fruend, 1993;

Rao et al., 1993; Roland, Larsen, Lassen, & Skinhoj, 1980). Furthermore, combined neuroimaging and electrophysiologyical data suggest that regions of SMA have inhibitory effects on M1, selecting the next action out from among potential actions (Ball, Schreiber, Feige, Wagner, Lücking, & Kristeva-Feige, 1999). Additionally, damage to SMA is associated with anarchic or "alien" limbs in neuropsychological studies (Goldberg, Mayer, & Toglia, 1981), which strengthens the argument for an inhibitory role of the SMA in regulating movement.

The function of the SMA is fairly well established, but the exact function of M1 is uncertain. It is unclear what information is represented in M1, but it appears that M1 represents movement at an egocentric, spatial level rather than at the level of muscle activations (Georgopoulos, Kalaska, Caminiti, & Massey, 1982; Georgopoulos, Kettner, & Schwartz, 1988; Georgopoulos, Schwartz, & Kettner, 1986). There is also considerable evidence of experience dependent plasticity in M1 neurons (Barayani & Feher, 1978), specifically in the horizontal connections between pyramidal cells (Aronaidou & Keller, 1995; Hess & Donoghue, 1994). Furthermore, the functional somatotopic area of an effector in M1 increases with repetition practice (Pascual-Leone et al., 1994). This finding suggests that with increased practice, the active neural substrates in M1 not only expand, but also develop greater interconnectivity (at least within a somatotopic region). Thus, although M1 may not be involved in motor learning per se, effector representations in M1 change as a function of learning. As Sanes and Donoghue (2000) conclude in their review of experience dependent plasticity in M1, the primary motor cortex is not a static, neural "keyboard" that is played upon by up-stream motor areas. Instead, M1 is a roughly somatotopically organized and dynamic set of modules and, within a module, lateral interconnectivity between neurons increases as a function of practice.

Looking at changes in sub-cortical structures in Table 10 does not reveal a consistent, qualitative pattern of results. This lack of a clear pattern is problematic because many motor control structures are sub-cortical and thus, understanding experience dependent changes in these sub-cortical regions is tremendously important. Previous research, however, suggests two distinct sub-cortical neural circuits in motor control: a cortical-striatal loop (which is principally involved in new sequences of movement) and a cortical-cerebellar loop (which is principally involved in motor adaptation) (Doyon, Penhune, & Ungerleider, 2003). Anatomically, these are distinct neural circuits (Cavada & Goldman-Rakic, 1989; Fang, Stephaniewska, & Kass, 2005; Middleton & Strick, 1997; Picard & Strick, 1996; Tanji, 1996)). The "sequence learning" loop originates in the SMA, which projects to the caudate nucleus of the striatum, the caudate projects to the globus pallidus, which projects to the ventral lateral thalamus (VL), which connects back to cortical motor areas. The "adaptation" loop originates in the M1, which projects to the pons, to the cerebellum, up to VL, and returns to cortical motor areas.

The cerebellum is a critical structure for motor adaptation and regulating neuromuscular coordination. Damage to the cerebellum has been shown to disrupt the coordination between agonist and antagonist muscles in multi-joint movements (Bastian, Zackowski, & Thach, 2000; Hallett; Berardelli, Matheson, Rothwell, & Marsden, 1991; Hallett, Shahani, & Young, 1975) leading to "decomposition of movement," in which patients with cerebellar damage lock degrees of freedom and move individual joints in serial to simplify the movement (Bastian, Martin, Keating, Thach, 1996). Locking degrees of freedom is a successful strategy for cerebellar patients because the cerebellum calculates the interaction torques between joints (Bastian, 2002; Bastian et al., 2000). Consequently, without a robust representation of these interaction torques (i.e., how movement at one joint will affect the dynamics at subsequent joints), compensatory variation between joints becomes very difficult, if not impossible. Although some studies implicate the cerebellum in learning new motor sequences, more recent evidence suggests that the cerebellum adapts movement parameters based on sensory prediction errors (rather than on-line, feedback-based control of the movement; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007) and that the cerebellum is more involved in expressing learned representations than in learning itself (Seidler, Purushotham, Kim, Uğurbil, Willingham, & Ashe, 2002).

With respect to these motor areas as a whole, with practice there is some evidence of an increase in the *connectivity* of cerebellum, cingulate motor area, supplementary motor area, and putamen as movements become proficient and a corresponding decrease in the connectivity of the precuneus (Wu, Chan, & Hallett, 2008). (The precuneus serves a variety of functions depending on the sub-areas in question, but is generally implicated in tasks requiring attention and self-reflection; Kjaer, Nowak, & Lou, 2002; Lou, Luber, Crupain, et al., 2004.) Seidler, Noll, and Theirs (2004) conducted a complex neuroimaging study using a parametric manipulation of difficulty in a speeded aiming task (based on the reciprocal tapping task by Fitts, 1954). Parametric manipulation of the target size allowed the researchers to manipulate the amount of feedforward and feedback control in the movement. For larger target sizes, when less feedback control is needed, there was increased activity in left M1, left dorsal PM, and PFC regions (such as the frontal operculum and dorsolateral prefrontal cortex). For smaller target sizes, when greater levels of feedback control are needed, there was increased activation in right M1, left ventral PMC, left cingulate motor area, and also in subcortical structures of the right basal ganglia and bilateral cerebellum. Thus, the cortico-striatal network contributed more during easier movements (when targets were largers), whereas the cortico-cerebellar network was more active during more difficult movements (when targets were smaller).

Implicit versus Explicit Learning: A Bridge from Learning to Attention

Some of the studies summarized in Table 10 made direct comparisons between implicit and explicit learning. Doyon et al. (1996) conducted a PET study of subjects implicitly learning a serial response time task, comparing a well practiced, implicitly learned sequence to a new, random sequence. In this comparison, there was an increase in activity in both the dentate nucleus of the cerebellum and the right ventral striatum for the implicitly learned sequence. Interestingly, when subjects acquired explicit knowledge of the learned sequence there was a significant increase in the activity of the right ventromedial PFC compared to the implicit condition. Similarly, Grafton et al. (1995) found that when subjects were implicitly learning sequences of finger movements, there was increased activity in the SMA and the striatum in late trials compared to early trials. After the sequence was explicitly revealed to subjects however, there were significant increases in the PFC, the precuneus of the parietal cortex, and a further increase in the activation of the striatum. Pasqual-Leone et al. (1994) used a similar manipulation comparing an implicitly learned sequence in a serial response task with a random sequence as a baseline condition. Next, the explicit sequence was revealed to subjects and this explicit activation was compared with a random sequence baseline. Previously, implicit learning led to significantly greater activity in M1, but after the explicit sequence was revealed, M1 activity returned to baseline levels. Analysis in this case was restricted to M1, so it is not clear how activity in the PFC might have been related to activity in M1. From other studies that have recorded PFC and M1 activity simultaneously (Seitz et al., 1992; Toni et al., 1998), PFC activity appears to decrease as M1 activity increases during learning.

Similar to studies on implicit/explicit awareness of movement sequences, a few neuroimaging studies have addressed attention directly. These studies of attention in motor control also implicate changes in PFC and M1. Jueptner and colleagues (1997) demonstrated that during learning there is a decrease in PFC activity, but consciously attending to the execution of a highly-practiced movement reactivated brain areas that were active early in the learning process. Specifically, dorsolateral PFC and the right anterior cingulate were both active early in the learning process and then reactivated when subjects paid attention to a well-learned sequence of finger movements. In a similar manipulation, Zengraf et al. (2009) used fMRI to explore the neurological effects of focusing externally (on keys to be pressed) versus internally (on the movements of the fingers themselves) while learning a sequence of key presses. An external focus of attention led to increased activation in S1 and M1, which the authors interpreted as enhancing feedback from environmental stimuli (in this case tactile feedback from the keys) in the external focus condition, which facilitated performance.

The Neurophysiology of Attention: Explaining Current Findings

Although the physiological details of attention in motor control are far from clear, there does seem to be evidence to support a shift from explicit and capacity-limited processing in the frontal cortex to more posterior and sub-cortical networks as learning progresses. The current framework posits that shifts in attention parallel shifts in learning; when an external focus of attention is adopted explicit processes are restricted to setting the movement goal and then passing this high-level information to more implicit mechanisms that transform the abstract goal representation into motoric representations and finally actuating these movements through complex patterns of muscle activity. With an internal focus of attention however, the explicit system steps beyond this role and attempts to actively specify movement during execution, taking some of these representational transformations out of implicit processing and into explicit processing (e.g., increased PFC activity; Jueptner et al., 1997). Not only is this an ineffective method of control, but it also places a processing burden on working memory, which could explain why dual-task performance is impaired by an internal focus of attention (Wulf, McNevin, & Shea, 2001). Furthermore, because the explicit system lacks the robust sensori-motor representations of the implicit system, it is worse at controlling movement in all but the simplest circumstances when on-line, working-memory based processing can meet processing demands.

This framework is a powerful method for conceptualizing the effects of attention in motor control and can explain a number of extant empirical findings. (a) An internal focus of attention places a greater processing burden on working memory (Wulf, McNevin, & Shea, 2001), which the framework predicts because an internal focus of attention means that a greater number of movement parameters are being explicitly controlled. (b) Although an external focus in generally beneficial, experts benefit from a more distal focus, whereas novices benefit from a more proximal focus (Bell & Hardy, 2009; Wulf & Su, 2007). The framework predicts that experts will benefit from a more distal external focus because experts have more robust representations at an implicit level, allowing them to set more abstract goals at the explicit level (e.g., “lofting a shot with backspin” is computationally meaningless to a golf novice, but might be an appropriate level of focus for a skilled golfer). (c) Subjects tend to lock degrees of freedom with an internal focus of attention, reducing functional variability in the movement pattern (Chapter 4; Lohse et al., 2010). Similar effects arise from increased anxiety, which also shifts attention internally (Beilock & Gray, in press). The framework would predict increased rigidity in the movement with an internal focus of attention because the capacity-limited explicit system is attempting to deliberately sequence and control the movement. In contrast, when an external focus of attention is adopted, the explicit system sets the high-level goal of the movement and allows implicit transformations to calculate the specific details of the movement pattern. (d) An internal focus of attention leads to slower movement corrections in dynamic balance tasks (McNevin et al., 2003; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001), whereas an external focus of attention leads to more efficient and faster corrections. The framework predicts slower movement correction with an internal focus because explicit, cortical mechanisms are being exploited to maintain balance in the internal focus condition creating a top-down signal in postural control that competes with implicit postural control mechanisms (see also Woollacott & Shumway-Cook, 2002). (e) There is evidence that an internal focus disrupts coordination at the most basic levels of intermuscular coordination and muscle activation (Chapters 2 & 3). Similar to the reasons the framework predicts that an internal focus leads to locking degrees of freedom, the framework predicts these increases in cocontraction because an internal focus of attention changes the control policy of the motor system. With an external focus, the goal is to minimize error in the attended dimensions (which are the nominal goal of the task). Conversely, with an internal focus of attention, the goal is to minimize error in the attended dimensions, which now include aspects of the movement itself. To reduce error in these movement dimensions, the motor system increases limb impedance through cocontraction in order to generate more regular movement patterns.

With respect to the isometric force production studies on cocontraction, it should also be noted that an internal focus might also be disruptive because humans lack experience controlling movement at this low level. Human beings do not typically attempt motor control at the level of muscle activations, but there is laboratory evidence that human subjects can learn to control specific muscle groups and agonist/antagonist relationships (Cohen, Brasil-Neto, Pascual-Leone, & Hallett, 1993; Osu & Gomi, 1998). If subjects were given general training in how to reduce cocontraction during force production, for instance via biofeedback, then the effects of attention could be more purely separated from the effects of experience in these force production tasks.

Unique Predictions for Attention and Explicit Processing

Perhaps most importantly, this framework generates a number of testable hypotheses about changes in the CNS that might underlie the effects of an external focus of attention (Wulf, 2007a). These predictions do not apply only to research on the focus of attention, as this framework readily applies to other domains of human performance, such as implicit skill-learning (Masters & Maxwell, 2008) and choking under pressure (Baumeister, 1984; Beilock & Carr, 2001). Indeed, this framework could be more generally conceptualized as adding an attentional gradient to motor control. Within the framework, attention has a gradient within motor control from attending to the most abstract levels of task representation (i.e., very little explicit monitoring of the movement itself) to attending to the low-level neuromechanical properties of the movement (i.e., very high levels of explicit monitoring of the movement itself). Directing attention internally is similar to early stages of motor learning, where explicit control is exerted over goal selection, the integration of perceptual information, and the sequencing of the movement itself. Conversely, when attention is directed externally, goal selection is the only explicit process and implicit, procedural representations of the motor skill regulate movement.

With respect to electrophysiogical changes, there should be demonstrable changes in electroencephalography (EEG) as a function of attention that parallel known changes as a function of learning. Experts tend to show less coherence between verbal-analytical areas of the left temporal lobe and motor planning regions of the frontal lobes during skilled performance (i.e., less coherence between electrodes at recording sites T3 and Fz; Deeney, Hillman, Janelle, & Hatfield, 2003; Hatfield et al., 2004; Janelle & Hatfield, 2008). Coherence is a measure of the correlated changes in different frequency bands between brain regions. If an internal focus of attention invokes a novice-like mode of motor control, more coherence should be seen during an internal than an external focus of attention, because internally focused subjects would be using more explicit, verbal-cognitive means of motor control. Although their study did not address the question of attentional focus directly, Hung and colleagues (2005) used EEG to show that poor dart throwing performance under stress was concurrent with increased coherence between verbal-analytical (left-temporal) and motor planning (midline-frontal) areas in skilled dart throwers. This finding supports the related theory that reinvestment of declarative knowledge under pressure hurts performance (Masters, 1992; Masters & Maxwell, 2008), but also suggests that similar effects might underlie an internal focus of attention.

Furthermore, the power spectrum of EEG recordings could change as a function of attention. Cross-sectional studies comparing experts and novices suggest that alpha-band power (8-12Hz) in left temporal areas is increased in experts, suggesting less involvement of left temporal areas (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick, Douglass, & Hatfield, 2004; Landers, Han, Salazar, Petruzzello, Kubitz, & Gannon, 1994). This shift in the spectral density is consistent with the theory that experts rely less on verbal-cognitive control strategies than novices (Anderson, 1983; Fitts, 1964; Fitts & Posner, 1967) because increased alpha-band power suggests a decrease in conscious control or attention (Kerick et al., 2004). Thus, externally focused attention might have a similar effect of increasing alpha-band power, because an external focus of attention leads to less conscious control of the movement.

Similarly, attention might also significantly affect theta-band power (4-8 Hz) especially in frontal midline areas. Some researchers have suggested that frontal midline theta-band activity reflects the involvement of the anterior cingulate cortex, which is often implicated in tasks requiring attention (Gevins, Smith, McEvoy, & Yu, 1997; Pardo, Fox, & Raichle, 1991). Neuroimaging studies have also suggested focusing internally increases right anterior cingulate activity (Jueptner et al., 1997). Relatedly, Baumeister, Reinecke, Leisen, & Wiess (2008) found that expert golfers had lower theta-band power in frontal electrodes than novice golfers prior to the initiation of a golf putt. Thus, similar to predictions about coherence between frontal and temporal regions, our framework would predict that an internal focus of attention would increase theta-band power in frontal midline areas while reducing alpha-band power in temporal areas because, at a psychological level, adopting an internal focus of attention is essentially regressing to novice-like motor control that relies more heavily on explicit, verbal-cognitive mechanisms.

Application: Attention in Rehabilitation and Athletics

From an applied perspective, neuromuscular changes as a result of an internal focus of attention are problematic because coaches and therapists frequently give internally focused instructions to their athletes and patients (Durham, van Vliet, Badger, & Sackley, 2009; Porter, Wu, & Partridge, 2010). This is not necessarily to say that professional coaches and therapists are wrong to give their patients these instructions, but data on the focus of attention continues to show that directing attention internally leads to less efficient neuromuscular coordination, less efficient movement patterns, and less effective movement outcomes. Thus, although it might be beneficial to have attention directed internally during the training/rehabilitation process, at the moment of performance, there is strong evidence to suggest that an external focus is beneficial across many skills and skill levels (Wulf, 2007b). These data are qualified by the results of Chapter 5, however, which found no effect of attentional focus when training with novel limb dynamics.

These changes in efficiency could be particularly important at both ends of the motor behavior spectrum (elite athletes on the one end and persons rehabilitating motor impairments on the other). Consider elite runners who start thinking about their form during a 5 km race. Assuming a 2 m stride length, even a tiny difference in the efficiency of a single stride could be amplified 2,500 times over the course of the race. Although an internal focus of attention might lead to only small increases in cocontraction in our isometric tasks, if this difference in neuromuscular efficiency is multiplied across joints or across time, it is reasonable to predict that internally focused attention would lead to greater fatigue. (An analogous situation exists in sports engineering, where bicycle-frames, swim suits, and running shoes are constantly being re-engineered to save fractions of weight or resistance for the cumulative effect of these savings.) But that is assuming the differences between foci are small and, to the contrary, one experimental study of elite swimmers (Stoate & Wulf, 2011) suggests that simple, attentional manipulations can have large practical significance for swimming speed.

On the other side of the motor behavior spectrum, therapists giving internally focused instructions might be creating a more difficult movement for their patients, because the internal focus instructions are unnecessarily reducing the efficiency of movement. Obviously, for a patient who is already working from a motor deficit there are a lot of practical reasons to encourage efficiency. This observation raises a problem for therapists because following neurological or musculoskeletal insult, there are good intuitive reasons to suggest a more novice-like mode of control through an internal focus. If patients are re-learning control of an impaired/affected limb they are, effectively, returned to a novice state. However, using internally focused instructions disrupts neuromuscular muscular efficiency. Theoretically then, there may be a trade-off in the relative merits of internal and external attention.

Empirically, however, research on patients with different motor disorders suggests a general advantage for an external focus of attention compared to internally focused attention or control conditions (Fasoli et al., 2002; Landers et al., 2005; Laufer et al., 2007; Wulf et al., 2009). From a neurophysiological perspective, I would suggest that an external focus of attention is still beneficial for patients with motor disorders when the neural representation of the motor skill is not damaged (because implicit transformations from the task goal into muscle activity are still intact). For instance, in patients with Parkinson's disease or patients with severe musculoskeletal injury, forward and inverse models that control action in the motor system are still intact and thus the motor system should be able to reap the benefits of effect-based control that accompanies an external focus of attention. Conversely, in patients with damage to the parietal cortex (involved in state estimation; Desmurget, Epstein, Turner, Prablanc, Alexander, & Grafton, 1999; Gréa et al., 2002; Rushworth, Nixon, & Passingham, 1997) or patients with cerebellar damage (involved in building forward models; Nowak, Timmann, & Hermsdörfer, 2007; Wolpert, Miall, & Kawato, 1998) more attention might have to be paid to the movement itself, because these patients would need to rely on more explicit, verbal-cognitive control of the movement than on implicit, effect-based internal models.

Empirical work continues to show that an external focus of attention is beneficial for motor performance across a range of motor impairments, and part of this advantage may be attributable to improved neuromuscular efficiency. When neural structures involved in implicit control of the movement are damaged, however, more conscious control of the movement may be required. This is an open question that can be resolved concretely through experimentation and the field of human movement science would benefit from more translational work on the role of attention in the rehabilitation of movement disorders. The experimental results from Chapter 5 are relevant to this point, because those results suggest that when limb dynamics have changed, an internal focus of attention is less detrimental to performance compared to when limb dynamics are normal.

Conclusions

The problem of motor control is complex. It is amazing to consider how the brain learns to control a body with as many degrees of freedom as we have, and even more impressive that we can learn to have so much reliability and accuracy in our movements given the complexity of control. Research on the focus of attention continues to demonstrate that beyond these mechanical complexities of the motor system, motor behavior is not a result of the motor system acting in isolation. Cognitive variables, such as attention, have clear and demonstrable effects on the overt results of behavior, but also on the physiology and efficiency of movement itself. If we consider motor control as a problem of the intervening processes between thought and action (see Hollerbach, 1982; Willingham, 1998), it is clear that attention affects these intervening transformations. When attention is directed internally, these transformations are more explicit; when attention is directed externally, these transformations are more implicit. Thus, there is growing evidence that cognitive variables need to be integrated into existing models of motor control. Indeed, there is a current trend in human movement science to study social, affective, and cognitive effects in motor behavior (Lewthwaite & Wulf, 2010). As this research moves forward, it becomes increasingly important to move beyond descriptive explanations of how these variables affect behavior and into mechanistic theories of motor control that have social, affective, and cognitive components. The experiments presented in this dissertation build on previous, descriptive explanations of attentional focus effects (the constrained action hypothesis, Wulf, 2007a; 2007b) to provide a testable framework that predicts the physiological changes mediating the effects of attention on performance.

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