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It is well established that focusing on the external effect of one's movement (an external focus of attention) results in enhanced motor learning and produces superior motor performance compared to focusing inward on the body's own physical execution of the motor movement (an internal focus). While the benefits of an external focus in motor learning, and the detriments of an inward or 'internal' focus have been highly replicated, there is still little mechanistic understanding pertaining to the brain-related changes that may result from these two different foci of attention during motor training. Since the brain is highly malleable and has been shown to adapt in response to motor training (i.e., neuroplasticity), it is postulated that attentional focus may change the brain's structure and function. However, no direct examination exploring the influence of attentional focus on neuroplasticity (structural or functional) exists. The primary objective of this study was to determine the effects of balance training with different attentional foci on brain-related neuroplasticity in a young healthy population. Participants (*n* = 33) were randomly assigned to a control, internal focus, or external focus condition. Functional and structural brain connectivity analyses was conducted using neuroimaging data collected through functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI) prior to (baseline) and following a seven-day balance training intervention (retention). Between baseline and retention data collection, participants in the internal and external focus training groups practiced a dynamic balance task for one hour per day, each day for seven consecutive days (acquisition). For the

internal focus trials, participants were asked to, 'focus on keeping their feet level;' whereas, for the external focus trials participants were asked to, 'focus on keeping the board level.' The control group did not complete any balance training, but completed baseline and retention balance measurements. An inertial measurement unit was attached to the center of the balance board to assess the performance and learning of the balance task. Resting-state brain connectivity analyses were performed on the fMRI data to contrast connectivity differences for each group at retention relative to baseline, and, for the diffusion data (DTI), fractional anisotropy analyses (a metric to quantify water diffusion within a voxel of white-matter) was performed to quantify the relationship between changes in balance and water diffusivity within white-matter tracts. Classical attentional focus effects were observed for acquisition, with those in the external focus condition producing significantly less mean and standard deviation velocity compared to the internal focus group (both $p < .05$). Likewise, at retention, those in the external focus group produced significantly less mean and standard deviation velocity compared to the control group (both $p < .05$). We also observed a significant within-day effect in which both training groups adopted a more patterned and rigid movement behavior from early to late trial blocks (as measured by SampEn; $p < .05$). Our resting-state connectivity data revealed that those in the external focus group displayed less correlated brain activity amongst motor and sensory regions at the retention test compared to baseline ($p < .05$). While a few similar brain connectivity results were exhibited for the internal focus group such as in the cerebellum, this group also showed increased correlated resting-state brain activity at the retention test relative to their baseline test between motor and sensory

regions ($p < .05$). To assess the relationship between balance and fractional anisotropy changes within white-matter we calculated percent change scores for mean velocity and fractional anisotropy within the frontal pole, precentral gyrus, and lingual gyrus. No significant relationships were revealed for these comparisons (all $p > .05$). These results suggest that a seven-day balance training program with attentional focus in a young healthy population influences brain function (specifically correlated activity at rest), but longer training programs or more rest may be needed to influence brain structure (as measured by fractional anisotropy). These findings have important implications for a variety of clinical populations who show altered resting-sate connectivity and deteriorations in balance control (e.g., Alzheimer's disease, stroke survivors). Seven days of balance training with an external focus may be useful in improving balance control and may influence correlated brain activity at rest, but longer training programs or more rest may be needed to influence brain structure. We discuss these findings in the context of the constrained-action hypothesis and OPTIMAL theory.

THE INFLUENCE OF ATTENTIONAL FOCUS ON NEUROPLASTICITY

FOLLOWING A SEVEN-DAY BALANCE

TRAINING INTERVENTION

by

Jed Allen Diekfuss

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To Teri:

Thank you for your continued love and support. Your consistent help, feedback, and editing never went unnoticed. This would not have been possible without you.

APPROVAL PAGE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Statement of Problem

The goal of practitioners, coaches, and instructors is to enhance their performer's ability to perform motor skills with the goal of retaining these changes over time. A variety of factors, such as dyad training (Shea, Wulf, & Whltacre, 1999), verbal feedback (Mizner, Kawaguchi, & Chmielewski, 2008), video feedback (Oñate et al., 2005), and verbal instruction (Milner, Fairbrother, Srivatsan, & Zhang, 2012) are all influential on motor performance outcomes and subsequent retention of motor skills. Further, it has been revealed that providing instruction that directs a performer's attention towards the effects of one's movement (an external focus) is superior to providing instruction that directs a performer's attention towards movement execution (an internal focus) (Wulf, 2013). While researchers have often advocated for the implementation for an external focus into rehabilitation settings (Gokeler et al., 2013), using an external focus in applied environments has not been widely adopted. For example, division 1 NCAA collegiate coaches provide more internal focus instruction than external focus instruction during practice (Diekfuss & Raisbeck, 2016) and practitioners give more internal focus feedback than external focus feedback during gait rehabilitation (Johnson, Burridge, & Demain, 2013). It is anticipated that the use of internal focus instructions is so ingrained that it is difficult for practitioners, irrespective of domain, to modify instructions to become more externally focused. It is reasonable to suggest that the lack of application to the field stems from the minimal mechanistic understanding we have that supports the use of an external focus. The literature is concise and affirmative in that an external focus produces more effective (Wulf, McNevin, & Shea, 2001) and efficent (Stoate & Wulf, 2011; Zachry, Wulf, Mercer, & Bezodis, 2005) movement, however, there is limited information explaining the neural relationship which could potentially explain *why* an external focus is so beneficial.

The constrained-action hypothesis is a widely accepted theoretical understanding (McNevin, Shea, & Wulf, 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, & Park, 2001), suggesting that an internal focus constrains the motor system, whereas an external focus allows the motor system to behave more reflexively and automatically. This theory has been substantiated by the reduction in electromyography (EMG) activity when performers adhere to an external focus in dart-throwing tasks (Lohse, Sherwood, & Healy, 2010) and bicep curls (Vance, Wulf, Töllner, McNevin, & Mercer, 2004), yet corresponding brain changes have been marginally explored. Minimal evidence does exist, however, pertaining to the role of attentional focus on brain activation (Zentgraf et al., 2009; Zimmermann et al., 2012). Zentgraf et al. (2009) asked participants to complete a key-pressing task while either focusing on their fingers (an internal focus) or the keys (an external focus). Using functional magnetic resonance imaging (fMRI), the authors revealed augmented blood oxygenation level dependent (BOLD) activation in the primary motor cortex, somatosensory cortex, and insular region of the left hemisphere when participants used an external focus. The authors suggested that an external focus facilitated movement execution by promoting task-adequate brain signals. Further, Zimmermann et al. (2012) demonstrated than when participants switched from a trained internal focus to an external focus, it increased activation in the premotor cortex, an area highly involved in action-planning (Nakayama, Yamagata, Tanji, & Hoshi, 2008). However, findings from these studies only provide partial evidence pertaining to the areas of the brain associated with attentional focus and movement execution. The aforementioned studies only examined fine motor skills, such as key-pressing, whereas the majority of attentional focus literature has explored tasks that require gross motor movement such as sprinting (Winkelman, Clark, & Ryan, 2017), jumping (Ducharme, Wu, Lim, Porter, & Geraldo, 2016; J. Porter, Wu, & Partridge, 2010), or balance control (Chiviacowsky, Wulf, & Wally, 2010; McNevin et al., 2003). Further investigation exploring how extended training using an external focus changes the resting-state connectivity and structure of the brain would be crucial in understanding the benefits for an external focus. This would be important from a both a theoretical perspective to understand *why* an external focus is beneficial for skilled learning, and from a practical perspective to provide neural evidence to practitioners pertaining to the benefits of an external focus.

Resting-state connectivity can be defined as spatially distinct brain regions that share temporal linkages at rest (Biswal, Zerrin Yetkin, Haughton, & Hyde, 1995). It is believed that a history of regions ‘co-activating’ during task execution increases the consistency of spontaneous activation while at rest (Corbetta, 2012). In other words, if two distinct brain regions regularly activate during a task, it is more probable for these regions to exhibit low level fluctuations in the BOLD signal when at rest. Wulf and Lewthwaite (2016) have suggested that an external focus may contribute to changes in resting-state connectivity and may also play a role in structural changes within the brain. While it has been established that gray and white matter pathways become more developed and localized through practice (Dayan & Cohen, 2011; Draganski et al., 2008), there is no evidence specifically exploring brain changes as a result of external focus training. These conclusions are based on the distinct neural differences (e.g. resting-state connectivity) when comparing highly-skilled performers to low-skilled performers (Kim et al., 2014; Milton, Solodkin, Hluštík, & Small, 2007), yet no direct investigation into the effects of attentional focus training on neuroplasticity exists.

Objective and Hypotheses

The primary objective of this study was to determine the effects of balance training with attentional focus on neuroplasticity in a young healthy population.

Aim 1: Determine the extent to which attentional focus influenced participants' performance and learning of a dynamic balance task over the course of a seven-day training program.

***Hypothesis 1a**:* Those who practiced the dynamic balance task with an external focus would display significantly more favorable postural control characteristics (lower mean velocity, lower standard deviation [SD] velocity, and higher Sample Entropy [SampEn] velocity) throughout acquisition compared to those who practiced with an internal focus of attention.

Hypothesis 1b: Those who practiced the dynamic balance task with an external focus would demonstrate significantly more favorable postural control characteristics (lower mean velocity, lower SD velocity, and higher SampEn velocity) at day 9 retention compared to those who practiced with an internal focus or did not practice the dynamic balance task (control).

Hypothesis 1C*:* All participants who practiced the dynamic balance task would elicit significant improvements in balance control (lower mean velocity, lower SD velocity, and higher SampEn velocity) from the early to late trial blocks and from the early to late days of training, regardless of condition due to practice effects.

Aim 2: Determine the extent to which attentional focus influenced participants' resting-state connectivity over the course of a seven-day training program.

Hypothesis 2a*:* Those who practiced the dynamic balance task with an external focus of attention would demonstrate significantly less correlated brain activity amongst various motor and sensory regions when contrasting their brain activity at rest during retention with their brain activity at rest during baseline.

Hypothesis 2b*:* Those who practiced the dynamic balance task with an internal focus would demonstrate significantly more correlated brain activity amongst various motor and sensory regions when contrasting their brain activity at rest during retention with their brain activity at rest during baseline.

Aim 3: Determine the extent to which attentional focus influenced the relationship between participants' changes in balance performance and changes in fractional anisotropy within the frontal pole, precentral gyrus, and lingual gyrus over the course of a seven-day balance training program.

Hypothesis 3a: Those who practiced with an external focus would elicit a significant negative relationship between percent change in fractional anisotropy in the prefrontal cortex and percent change in balance performance (decrease in fractional anisotropy and increase in balance performance; congruent with Taubert et al., 2010).

Hypothesis 3B: Those who practiced the balance task with an internal focus would elicit no significant relationship between percent change fractional anisotropy in the prefrontal cortex and percent change in balance performance.

Hypothesis 3C: Those who did not practice (control) would elicit no significant relationship between percent change in fractional anisotropy in the prefrontal cortex and percent change in balance performance.

Limitations and Assumptions

1. All participants adhered to their respective focus of attention instruction during acquisition.

2. Participants did not practice the dynamic balance task outside of the scheduled training times.
3. Random assignment was satisfactory to account for individual differences in day to day activities.
4. The sampling frequency of 100 Hz for the inertial measurement unit (Xsens Technology, MA, USA) was adequate to accurately track and calculate the movements of the balance board.
5. fMRI is an indirect measure of blood flow, but is a widely-accepted technique to assess changes in neural activity resulting from motor or cognitive tasks.
6. Participants remained mostly motionless while inside the MRI scanner.

Delimitations

1. Participant recruitment was limited to healthy college-aged males and females between the ages of 18 and 35.
2. Participants were considered healthy, as defined by no lower extremity injury in the last 6 months.
3. Participants were excluded if they had 1) previous history of injury to the capsule; ligament, or menisci of either knee; 2) any vestibular or balance disorder; 3) any metal or implanted medical device in the body that would be a contraindication to MRI assessment; 4) undergone a previous balance training program.

Operational Definitions

External Focus of Attention: Attention directed towards the effect of one's movements (Wulf, Höß, & Prinz, 1998) (e.g., Focus on keeping the balance board level.')

Internal Focus of Attention: Attention directed towards the performers own body movements (Wulf et al., 1998) (e.g., 'Focus on keeping your feet level.')

No Focus of Attention Instruction: Providing instruction that does not direct attentional focus (e.g., 'Do your best.').

Acquisition: The period in which a performer practices a skill. During this time feedback or instruction is provided. This term is used interchangeably with practice.

Retention: An assessment of performance following a rest period typically ranging from 10 minutes to one week. During this time, no feedback or instruction is provided. This term is used interchangeably with learning.

Motor Learning: The process of an individual's ability to acquire motor skills with a relatively permanent change as a function of experience (or) practice (Schmidt & Wrisberg, 2005).

Neuroplasticity: The brain's ability to change its structure and (or) function (Chang, 2015).

Resting-State Connectivity: Temporal correlations of spontaneous low frequency fluctuations of the blood oxygen dependent level (BOLD) signal between different brain regions at rest (Biswal et al., 1995; Greicius, Krasnow, Reiss, & Menon, 2003).

Voxel: A 3-deminsonal image representing a cube of the brain.

Seed: A cluster or region of voxels.

Region of Interest (ROI): A region of the brain that is of interest to the research questions. ROI's are often used to explore one's data, control for Type I error by lessening the number of regional comparisons, and are used when a separate scan or condition identifies a region that is 'of interest' (Poldrack, 2007).

Diffusion Tensor Imaging (DTI): A technique for characterizing microstructural changes in magnitude, anisotropy (i.e., directional dependency), and orientation of water molecules.

Variables

Independent Variable

Condition: Participants were randomly assigned to one of three conditions: 1) control, 2) internal focus of attention, 3) external focus of attention.

Dependent Variables

Medial-Lateral Mean Velocity. The mean of the medial-lateral velocity time-series (m/s). This data was collected using an inertial measurement unit and described in more detail in chapter 3.

Medial-Lateral Standard Deviation Velocity. The standard deviation of the medial-lateral velocity times series (m/s). This data was collected using an inertial measurement unit and described in more detail in chapter 3.

Medial-Lateral Sample Entropy Velocity The sample entropy of the medial-lateral velocity times series (no units). This data was collected using an inertial measurement unit and described in more detail in chapter 3.

Resting-State Connectivity: Temporal correlations of spontaneous low frequency fluctuations of the blood oxygen dependent level (BOLD) signal between different brain regions at rest (Biswal et al., 1995; Greicius et al., 2003).

Fractional Anisotropy: The direction of water diffusion within a voxel (0 – 1; isotropic [identical properties in all directions] – anisotropic [properties depend on the direction]) (Mori & Zhang, 2006).

CHAPTER II

REVIEW OF THE LITERATURE

Attentional Focus

There is an irrefutable connection between attention and motor behavior. Prinz (1990) claimed that successful movement execution occurs when there is congruency between perception and action. This lead to the development of his common-coding theory (Prinz, 1997) showing that when individuals optimally attend to and perceive the environment, successful movement ensues. This theoretical framework laid the groundwork for a series of studies in motor behavior that systematically directed attention either towards movement execution (an internal focus) or towards the effects of one's movement (an external focus). The first published study (Wulf et al., 1998; experiment 1) examined whether an external focus facilitated greater performance and learning of a novel ski-simulator task relative to an internal focus. Participants were randomly assigned to an internal or external focus condition and balance performance was assessed throughout acquisition and after a rest period (retention). In the internal focus condition participants were told to focus on their 'feet,' whereas in the external focus condition participants were told to focus on the 'wheels'. The results revealed greater performance and improved learning for those in the external focus condition. These results were further replicated by the same set of researchers using a stabilometer instead of a ski-simulator (Wulf et al., 1998; experiment 2). These findings lead to a proliferation of studies examining whether an external focus improved movement effectiveness in other motor tasks, often measured through performance outcomes. For example, an external focus has resulted in improved performance and learning in other balance tasks (McNevin et al., 2003; Wulf, Weigelt, Poulter, & McNevin, 2003), golf pitch shots (Wulf & Su, 2007), and volleyball serves (Wulf, McConnel, Gärtner, & Schwarz, 2002). The high replicability of these findings lead to the development of the constrained-action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001). The constrained-action hypothesis suggests that an external focus facilitates automaticity as it reduces interference in control processes, whereas an internal focus disrupts a performer's previously learned movement (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001). Simply, the constrained-action hypothesis suggests that an internal focus constrains the motor system, while an external focus allows the motor system to self-organize and produce more reflexive behavior. Further, it was revealed that an external focus enhances performance as opposed to an internal focus which degrades performance. When no attentional focus instruction is provided, performance is similar to those given internal focus instruction (Landers, Wulf, Wallmann, & Guadagnoli, 2005; Wulf & Su, 2007), indicating that an external focus is superior to an internal focus or no focus of attention instruction.

The constrained-action hypothesis was later revisited as researchers explained why single-word manipulations could have such a dramatic effect on movement (Wulf & Lewthwaite, 2010). It was proposed that an internal focus acts as a 'self-invoking trigger'

(McKay, Wulf, Lewthwaite, & Nordin, 2015) that engages self-regulatory processes, neural access to the self, and self-evaluation which ultimately leads to micro-choking episodes and poor motor performance (Wulf, 2013). A few studies have provided preliminary evidence in support of this hypothesis (McKay et al., 2015; Perreault & French, 2016). For example, McKay et al. (2015) had performers reflect on a previous task experience which resulted in degraded future performance relative to a control group. In sum, attention directed towards movement execution (internal focus) and reflecting or thinking about oneself (self-invoking trigger) seem to constrain and inhibit the motor system from optimal performance. Currently, the beneficial effects of an external focus on motor behavior is still grounded in the constrained-action with recent preliminary evidence supporting the self-invoking trigger hypothesis.

Movement Effectiveness

There are numerous studies highlighting the beneficial effects of an external focus of attention on motor outcomes (see Wulf, 2007, 2013 for reviews). Using a variety of tasks, researchers have compared the performance and learning differences when participants use an internal and external focus of attention. To do this, researchers measure task performance throughout the practice phases while focus of attention instruction is provided. Then, after a short (e.g., 10 minutes) or delayed (e.g., 24 hours) rest period (i.e., retention), researchers again measure task performance. Importantly, there is no focus of attention instruction provided during the retention period which allows researchers to understand what the participant learned. The most widely replicated task thus far has been balance performance or measures of postural sway. Following the initial study by Wulf et al. (1998), subsequent studies have used a ski-simulator or stabilometer to determine the effectiveness of an external focus of attention (Chiviacowsky et al., 2010; McNevin et al., 2003; Wulf et al., 2003). Other studies examining balance performance and attentional focus have used inflated rubber disks (Wulf, Landers, Lewthwaite, & Töllner, 2009; Wulf, Mercer, McNevin, & Guadagnoli, 2004; Wulf, Töllner, & Shea, 2007), or movable balance platforms such as the Biodex (Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007; Rotem-Lehrer & Laufer, 2007). These studies all revealed superior balance performance throughout acquistion and enhanced learning at retention when participants utilized an external focus of attention.

To further pursue this line of research, we used a force plate to capture changes in young and older adults' balance control resulting from an external focus. To do this, we had participants stand directly on a force plate (AMTI, Watertown, MA) and on a foam pad placed over the force plate (Raisbeck, Diekfuss, Fairbrother, Karper, & Rhea, in preparation). We then asked participants to focus on aspects of movement (an internal focus) and the effects of their movement (an external focus). For example, in some of the trials we asked participants to 'focus on their feet', whereas in other trials we asked participants to 'focus on the surface' beneath them. Results revealed that the structure of participants' center of pressure signal changed because of our attentional focus manipulation. By using metrics derived from entropy (Rhea, Kiefer, Haran, Glass, & Warren, 2014; Rhea, Kiefer, Wright, Raisbeck, & Haran, 2015), specifically sample entropy, our results revealed greater sample entropy values when participants stood on the force plate and focused externally compared to baseline (see Figure 2.1; Raisbeck et al., in preparation). Greater sample entropy values indicate less repeatability in the center of pressure signal which is suggestive of more adaptive behavior (Manor et al., 2010). In the context of motor behavior literature, these findings suggest that using an external focus while balancing may allow the body to better self-organize This supports the recent findings that an external focus improves stability following a perturbation (Ducharme & Wu, 2015) and complements earlier work (Wulf, McNevin, et al., 2001) suggesting that an external focus allows the body to move more freely.

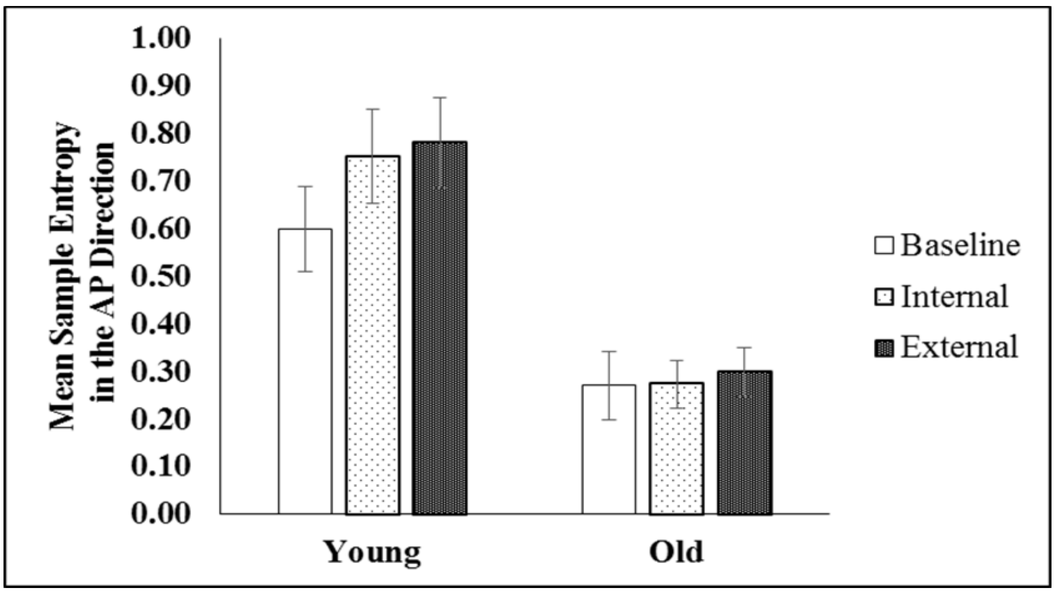

Figure 2.1. Attentional Focus and Balance Data. Significantly greater sample entropy values when participants focused externally compared to baseline ($p < .05$)

In addition to balance, the benefits of an external focus on movement effectiveness have been replicated in other skills and activities such as golf (Wulf & Su, 2007), basketball (Al-Abood, Bennett, Hernandez, Ashford, & Davids, 2002), and volleyball (Wulf et al., 2002). For example, Wulf, Lauterbach, and Toole (1999) found that an external focus (swing of the club) resulted in more accurate golf pitch shots than an internal focus (movement of their arms). Likewise, putting accuracy was increased when participants use an external rather than an internal focus (Poolton, Maxwell, Masters, & Raab, 2006). Further, basketball free-throw shooting accuracy is enhanced when performers focus on the basket or ball-trajectory instead of their arm movement (Zachry et al. 2005) and the accuracy of volleyball serves (Wulf et al., 2002; experiment 1) and soccer kicks (Wulf et al., 2002; experiment 2) are improved with an external focus. Another accuracy task shown to improve with an external focus is dart-throwing (Lohse et al., 2010; Marchant, Clough, Crawshaw, & Levy, 2009; McKay & Wulf, 2012; McKay et al., 2015). In these tasks, participants are asked to focus on the flight of the dart or the target (an external focus) and performance is compared with those focusing on their arm or wrist movement (an internal focus). Following the theme of the aforementioned studies, an external focus consistently improves dart throwing accuracy both during acquisition and after a rest period.

One of the most intriguing aspects of these studies is the subtlety of the manipulations. The only differences across or between conditions is the changing of one or two words. Simply directing attention using concise verbal phrases that direct attention externally enhances performance and learning. Interestingly, however, this has not always garnered application. Instructors in skilled domains often provide instruction that conflicts with the effectiveness of an external focus (Diekfuss & Raisbeck, 2016; Johnson et al., 2013; J. Porter, Wu, et al., 2010). For example, firearms instructors at the Police Training Institute at the University of Illinois teach new recruits to focus on a variety of cues, such as the sights, trigger squeeze, and firing arm. Since providing multiple verbal cues can disrupt the fluidity of movement (Wiese-Bjornstal & Weiss, 1992), we sought to investigate whether the number of verbal cues influences motor performance and learning differently if those cues are designed to manipulate attention internally or externally. Using a simulated target-shooting task, we demonstrated that a single verbal cue compared to multiple verbal cues enhanced shooting performance at immediate retention, while an external focus of attention compared to an internal focus improved shooting performance at delayed retention (Raisbeck & Diekfuss, 2016; see Figure 2.2). Results from this study further support the positive influence an external focus has on learning while highlighting the importance of providing short and concise instruction. Taken together, our work, as well as the previous research described, demonstrate the beneficial effects of an external focus on movement effectiveness.

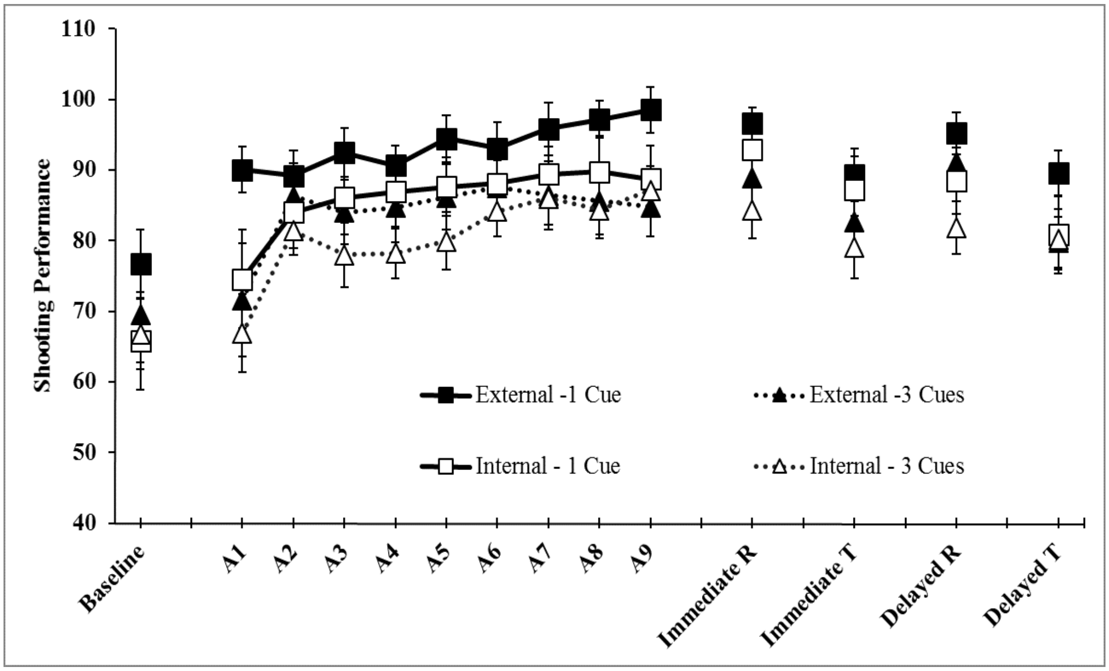

Figure 2.2. Attentional Focus and Target-Shooting Data. Shooting performance at baseline, across 9 trials of acquisition, after a short (10 minute) break and after a prolonged rest period (3 days). Those receiving one cue performed significantly greater than those receiving three cues at immediate retention ($p < .05$). Those receiving external focus of attention instruction performed significantly greater than those receiving internal focus of attention instruction at delayed retention ($p < .05$).

Movement Efficiency

According to the constrained-action hypothesis, an external focus promotes reflexive and natural movement, which is in contrast to the constraining influence an internal focus has on the motor system. Thus, it is important to establish the influence of attentional focus on movement patterns and movement fluidity. To do this, a series of studies were published that examined movement efficiency. Per Wulf (2013), a movement pattern is more efficient if the same movement can be achieved again with less energy expended (p. 84). Thus, studies manipulating attentional focus began integrating measures of muscular activity (via EMG, e.g., Zachry et al., 2005), maximum force production (Wulf, Zachry, Granados, & Dufek, 2007), speed (e.g., swim speed; Stoate & Wulf, 2011) and endurance (Marchant, Greig, Bullough, & Hitchen, 2011). These studies have conclusively shown that an external focus facilitates more efficient movement relative to an internal focus. For example, Lohse et al. (2010) used a dart-throwing task and asked participants to focus on either the flight of the dart (an external focus) or the movement of their arm (internal focus) while measuring muscular activity with EMG. The authors revealed that in addition to accuracy improvements, an external focus reduced EMG activity and preparation time in the upper arm relative to an internal focus and baseline. The authors suggested that external focus was more efficent and neuromuscularly economical.

EMG has also been used in conjunction with attentional focus in other motor tasks (Vance et al., 2004). For example, Vance et al. had participants complete a biceps curl while their focus was directed towards the movement of the bar (an external focus) or their arms (an internal focus). The authors revealed that an external focus resulted in faster movements than an internal focus (experiment 1) and reduced integrated EMG activity during the external focus compared to the internal focus (experiment 2). These results potentially suggest that the central nervous system sends less efferent signals to the effectors if an external focus is adopted. Likewise, Zachry et al. (2005) revealed that focusing on a basketball hoop (an external focus) resulted in lessened EMG activity in the biceps and triceps brachii than focusing on wrist flexion (an internal focus). An interesting finding from this study was that the reduction in EMG activity occurred in muscle areas that participants were not specifically asked to focus on, suggesting that the detrimental effects of an internal focus can spread throughout the body.

An external focus also seems to aid in optimal coordination among muscles resulting in enhanced maximal force production. For example, Porter, Ostrowski, Nolan, and Wu (2010) examined the influence of attentional focus on standing long-jump performance. Using a between-subjects design, participants were either told 'when you are attempting to jump as far as possible, I want you to focus your attention on extending your knees as rapidly as possible' (an internal focus) or 'when you are attempting to jump as far as possible, I want you to focus your attention on jumping as far past the start line as possible'' (external focus). Again, this change in instruction is subtle, yet the authors revealed significantly greater jump distances for the group receiving external focus of attention instruction. Several subsequent studies replicated these findings using the standing long-jump (Ducharme et al., 2016; Wu, Porter, & Brown, 2012), and have also been found in other maximum force production tasks such as discus throwing (Zarghami, Saemi, & Fathi, 2012).

Other tasks that require full body coordination, such as running, or completing agility courses have been investigated to determine if an external focus can enhance speed. For example, Porter, Nolan, Ostrowski, and Wulf (2010) had participants complete an agility 'L' course following instruction that induced either an internal, external, or no focus of attention instruction. Using a within-subjects design, results revealed that participants' time to complete the course was faster when they were asked to 'focus on pushing off the ground as forcefully as possible' (external focus) compared to when they asked to, ‘focus on moving their legs as rapidly as possible’ (internal focus) or when no specific focus of attention instruction was provided. Similarly, Porter, Wu, Crossley, Knopp, and Campbell (2015) demonstrated that an external focus resulted in significantly faster 20 meter sprint times relative to an internal focus or no focus of attention instruction.

Some tasks, however, do not have a quantifiable performance outcome (e.g., gymnastics routine), and researchers have questioned whether an external focus is effective when movement form is the primary outcome (Peh, Chow, & Davids, 2011). While this area of research is still in its infancy, there is evidence supporting an external focus for enhancing movement form (Abdollahipour, Wulf, Psotta, & Palomo Nieto, 2015). Specifically, Abdollahipour et al. asked 12-year old gymnasts to perform a maximum vertical jump while performing a 180 degree turn in the air. When performers were asked to focus on a piece of tape attached to their chest (external focus) as opposed to their hands (an internal focus) it resulted in enhanced movement form while also increasing jump height.

Movement Kinematics

One way to quantify the effects of attentional focus is through the integration of kinematic analyses. An, Wulf, and Kim (2013) used three-dimensional motion capture to determine whether an external focus influenced the ‘X-factor stretch’ (rotation of the shoulders relative to the pelvis) in novice golfers. To do this, one group of participants were asked to focus on shifting their weight to their left foot (internal focus) during a golf swing, whereas another group of participants were asked to focus on pushing off the ground (external focus). Following a three-day retention period, the results revealed that those who were asked to focus externally produced a greater X-factor stretch, and higher maximum angular velocities of the wrist, shoulder, and pelvis compared to those who were asked to focus internally. Further, in a study of novice rowers, participants who were given external focus instructions produced more efficent movement patterns as evidenced by a shorter time and distance to lock the row blade compared to those given internal focus of attention instruction (Parr, Button, MacMahon, & Farrow, 2009).

Findings from these studies have lead researchers to suggest that an external focus allows for more functional variability (Wulf, 2013). Wulf and Dufek (2009) suggested that an external focus ‘frees degrees of freedom’ as evidenced by the correlated joint moments amongst the ankle, knee, and hip when participants were asked to focus on their finger (internal focus) during a jump-and-reach task. Similar moment correlations were revealed during soccer kicks when performers were asked to focus internally (Ford, Hodges, & Williams, 2005). These findings support the notion that an external focus allows the body to automatically adjust to reach the desired effect (Wulf & Prinz, 2001) and further research has begun exploring the impact of attentional focus on movement variability across skill levels (Raisbeck, Suss, Diekfuss, Petushek, & Ward, 2015).

The benefits of an external focus on movement kinematics have also received considerable attention from the orthopedic literature (Benjaminse et al., 2015). For example, Gokeler et al. (2015) recruited 16 participants who had recently undergone an anterior cruciate ligament (ACL) reconstruction and asked them to perform a series of single-leg hops for distance. Using a between-subjects design, one group of participants were asked to ‘focus on extending their knee as rapidly as possible’ (internal focus), whereas the other group was asked to ‘think about pushing themselves as hard as possible from the floor’ (external focus). Sagittal plane knee kinematics were obtained and results revealed that those who were asked to focus externally had significantly larger knee flexion angles at initial contact, larger peak knee flexion, greater total range of motion, and increased time to peak knee flexion for the injured leg. Increased flexion range of motion has been associated with decreased load on the ACL (Blackburn & Padua, 2008) making an external focus a safe and feasible technique to reduce the likelihood of subsequent injuries (see Gokeler et al., 2013).

Neural Activity and fMRI Basics

Another approach to understanding the influence of attentional focus on movement is by assessing changes in neural activity using fMRI. As briefly described in Chapter 1, there are only two published studies that have directly examined brain activity following an attentional focus manipulation (Zentgraf et al., 2009; Zimmermann et al., 2012). Before providing a critical review of these studies, however, a basic understanding of fMRI and the BOLD signal is warranted. fMRI is a widely-used technique to measure brain activity. fMRI is based on the understanding that when neurons in the brain become active, blood flow to these regions increase via the hemodynamic response function. Interestingly, the amount of blood sent to these regions is more than what is needed to replenish the depleted oxygen and leads to a relative surplus in blood oxygenation – this change in blood oxygenation is referred to as the BOLD signal. There are two basic features that must be understood to analyze an interpret the bold signal. First, the hemodynamic response is very slow relative to neuronal processing. It takes approximately 5 seconds for blood to reach its maximum and approximately 15 to 20 seconds to return to baseline (Poldrack, Mumford, & Nichols, 2011). Second, the BOLD signal is linear. In other words, if neural activity is doubled, the BOLD response would also be doubled. This allows for separate events occurring within a single time frame to be summed together. This linearity allows for the integration of the general linear model (GLM; Friston et al., 1995; Worsley et al., 2002) to quantify changes in the BOLD signal. A pre-determined number of 3-dimensional cubic spaces (i.e., voxel) will produce individual time series that can be analyzed and interpreted using a variety of software packages (e.g., FSL, Oxford) and easily accessible Matlab based platforms (e.g., CONN toolbox, MA).

While fMRI does provide unique insights in the human brain, limitations with this methodology must also be considered. First, fMRI is an indirect measure of blood flow. However, since blood has magnetic properties, we can infer changes in the ratio of oxygenated and deoxygenated blood using the BOLD response. Secondly, researchers often define the size of the voxels *a priori* and we only have minimal understanding of the exact location of each brain region. We can make educated assumptions based on a variety of histological atlases (e.g., Julich histological atlas), but these atlases are limited in their generalizations. In other words, we must be careful when making claims that a certain region was or was not active. Further, since the HDRF is very slow (5-20 seconds) relative to neural activity (which occurs in milliseconds), it results in poor temporal resolution for fMRI. Thus, we must be careful when interpreting the ‘timing’ of brain function with respect to tasks and stimuli. In other words, it is very difficult to determine when a brain region becomes active relative to a stimulus. Fortunately, researchers can integrate other modalities, such as EEG which have high temporal resolution (Dale & Halgren, 2001) to better understand the relative timing of brain activation relative to a stimulus. Another limitation of fMRI is the noise emitted from the scanner itself which can confound studies of attention (Gaab, Gabrieli, & Glover, 2007) and resting-state networks (Gaab, Gabrieli, & Glover, 2008). This limitation can be addressed, however, with hearing protection and creative designs that interleave stimuli presentation. Additionally, one of the biggest limitations of fMRI is head motion (Poldrack et al., 2011), which needs to be considered when analyzing and interpreting the data with respect to brain function. Since fMRI takes a series of images during a scan sequence, any head motion (from the participant moving) can cause a mismatch from image to image; voxels can appear in some images while disappearing in others. Head motion can also disrupt proton excitation when a voxel is interfered with by a neighboring voxel (spin history effect; Friston, Williams, Howard, Frackowiak, & Turner, 1996). If the head motion is correlated with the task, it can result in any activation being regressed out of the final analyses. Take for example a task that requires participants to 'speak.' If the head moves every time the participant speaks, there will be little activation data if all 'movement' (i.e., speaking time) data is removed. In this case, however, the slow process of the HRF allows researchers to construct jittered event-related designs (e.g., Xue, Aron, & Poldrack, 2008) to reduce the correlation between head motion and the BOLD response.

The spatial resolution of fMRI, though, is superior to other related forms of instrumentation (e.g., Positron Emission Tomography [PET], Functional Near Infrared Spectroscopy, and Electroencephalography [EEG]), which makes it a sought-after tool for researchers interested in neuroimaging. Further, fMRI is extremely safe; there are no 'dyes' that need to be injected (like in PET) and performers can lie comfortably within a scanner for relatively long periods of time. Early research into understating brain function used behavioral outcomes, but with the advent of fMRI we can complement this work with high resolution brain images previously unavailable. Albeit cautionary, we can use this tool to help us better understand which brain regions are active during different cognitive and motor states

Using fMRI, the purpose of Zentgraf et al.'s study was to combine research stemming from the attentional focus literature and the attention-to-action neurophysiology literature. At the time, the neural correlates of internal and external focus were unknown. Further, there was only preliminary evidence describing how attentional modulation influences motor execution (Johansen-Berg, Christensen, Woolrich, & Matthews, 2000; Johansen-Berg & Lloyd, 2000; Rowe, Friston, Frackowiak, & Passingham, 2002). These studies revealed that consciously controlling finger movements (relative to rest) increased activation in premotor, prefrontal, superior parietal areas, and the cerebellum, suggesting that attentional modulation enhances cortical activation and acts as a mechanism affecting the motor system (Rowe et al., 2002). Similarly, it was demonstrated that the primary motor cortex (M1) is sensitive to cognitive modulation which suggests that the M1 is not an executive system acting in isolation (Binkofski et al., 2002).

For Zentgraf et al.'s study, the authors asked participants to learn a novel key-pressing task (moving three fingers in a patterned order) while adhering to an internal or external focus of attention. Specifically, performers completed a pre-training one day prior to scanning and performed the task using no focus of attention instruction until it could be completed without error. In the final pre-training trials, participants received specific attentional focus instruction. For the external focus group, participants were told 'from now on, please concentrate on the keys that need to be pressed in the sequence.' For the internal focus group, participants were told 'from now on, please concentrate on your moving fingers when you press the sequence.' Participants in both conditions were then asked to close their eyes and complete 50 correct trials using their respective focus.

On the following day, participants recalled the finger sequence and were familiarized with the experimental design. Participants were to told complete the finger sequence under three conditions while inside the MRI scanner. Specifically, participants completed the key-pressing task while adhering to an internal or external focus, while just moving (no attentional focus instruction provided), and while a secondary task was played (dual-task). fMRI was used to capture changes in blood flow and simple contrasts were conducted to compare brain activation between the conditions. The authors found increased activation in the primary motor cortex, somatosensory cortex, and insular region of the left hemisphere when participants used an external focus. Zentgraf et al. showed that an external focus enhanced the processing of tactile information which mediated the performers' actions with the environment. In contrast, their results showed that an internal focus may disrupt the flow of neural signals between sensory and motor areas, which supports the constrained-action hypothesis.

In a follow up study using the same data set and participants from Zentgraf et al., Zimmerman et al. explored how switching from an internal focus to an external focus influenced brain activity. The rationale for this study was that sport experts often switch their focus of attention in skilled domains (Bernier, Codron, Thienot, & Fournier, 2011; Diekfuss & Raisbeck, 2017). For example, expert golfers often switch between a series of foci while going through the preparation and execution of a golf shot (Bernier et al., 2011). Thus, Zimmerman et al. were interested in whether switching attentional focus changes neural processing and activates attentional brain networks. To accomplish this, participants who were trained in the key pressing task (see Zentgraf et al. above) were informed that they now needed to switch to a different focus of attention. For example, those who were trained to use an internal focus, were now asked to use an external focus and vice versa. Again, fMRI was used to capture changes in blood flow and contrasts were used to differentiate areas of activation amongst the conditions. The authors' results revealed that switching from either focus (internal to external or external to internal) increased activation in frontal and parietal networks. These regions are consistent with other studies in which participants were asked to switch their attention to other locations (Wager, Jonides, & Reading, 2004) and are believed to be part of supramodal frontoparietal attentional network (Driver & Spence, 1998). In addition, the authors found unique increased activation in the inferior parietal lobule extending to the supplementary motor area for the participants who switched from an external to internal focus. Further, the authors found increased activation in the left lateral premotor cortex (PMC) for the participants who switched from an external to internal focus. The participants used their right hand during the tasks, which explains the left lateralization of activity, and the PMC is highly involved in the mapping between sensory stimuli and motor responses (Amiez, Hadj-Bouziane, & Petrides, 2012) and the selection of motor commands (Rushworth, Johansen-Berg, Göbel, & Devlin, 2003; Schumacher, Elston, & D'esposito, 2003). These findings contribute to the previously described constrained-action hypothesis as switching from an internal to external focus seems to facilitate adequate motor processing. In sum, this study highlights the sensory modalities involved when participants switch their focus of attention.

While the aforementioned studies (Zentgraf et al., 2009; Zimmermann et al., 2012) do provide invaluable information regarding the brain activation succeeding a skilled acquisition phase, limitations of these studies minimize the generalizability of the findings. First, participants practiced to succession before receiving attentional focus instruction. Participants inevitably use their own attentional strategies from time to time (Marchant, Clough, & Crawshaw, 2007) and without directed instruction it is unknown what focus participants used throughout acquisition. Thus, we still did not know which areas of the brain were activated when performers were in the skill-acquisition phase of learning. Secondly, these studies examined fine motor skills only. We have recently suggested that fine motor skills are more cognitively demanding than gross motor skills (Raisbeck & Diekfuss, 2015). Since many motor tasks require gross motor action (e.g., running, jumping, catching, throwing, etc.), it is essential to understand the influence of attentional focus on neural activation during the execution of a gross motor skill.

While head motion can be problematic in fMRI, researchers have keenly developed new methods that permit the assessment of brain activity during gross motor tasks such as leg movement (Grooms, Page, & Onate, 2015; Kapreli et al., 2007). Thus, we implemented this methodology while manipulating participants' attentional focus. Specifically, we had ten participants lay supine on an MRI scanner, flex and extend their leg in conjunction with a metronome, and used fMRI to measure changes in the BOLD signal. To determine how attentional focus altered brain activity, we used a within-subjects design in which participants were given internal focus of attention instruction and external focus of attention instruction. Specifically, during the external focus condition, we asked participants to focus on a target positioned a few inches above their tibia, whereas in the internal focus condition we removed the target and asked participants to focus on squeezing their quadriceps (see Figure 2.3).

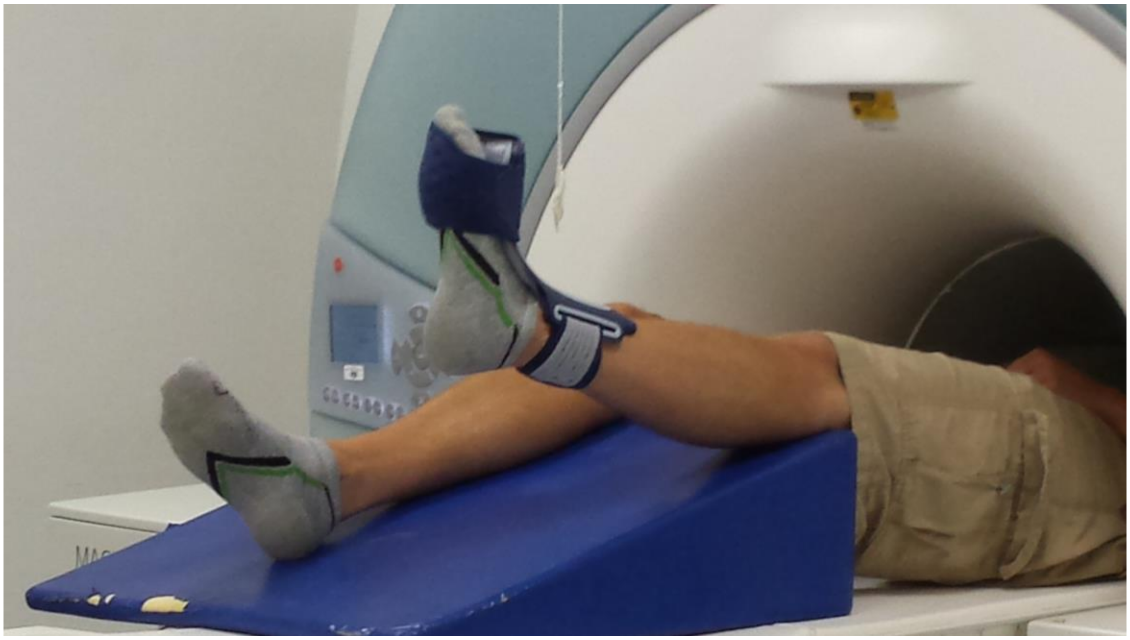

Figure 2.3. Leg Movement Task Using MRI. Participant moving their leg in the external focus condition while inside an MRI scanner. The hanging target was removed during the control and internal focus conditions.

Participants completed 5 blocks of 30 seconds rest and 30 seconds move equating to 4 minute and 30 second runs. This allowed us to contrast activation during the move states versus the rest states for each condition and enter the resulting data into second-level analyses for group comparisons. Results from the group analyses are presented in Tables 1.1 and 1.2.

Table 2.1. External Focus > Internal Focus Contrast.

Cluster Index	Brain Regions	Side	Voxels #	p-value	MNI Coordinate of Peak Voxel			*z*-max
					x	***y***	***z***	
1	Occipital pole Cuneal cortex Lateral occipital cortex Intracalcarine cortex	Right	1048	2.98E-07	12	-94	18	6.22
2	Lingual gyrus (anterior) Temporal occipital fusiform cortex Parahippocampal gyrus (posterior)	Right	674	4.63E-05	32	-46	-4	4.46
3	Lateral occipital cortex	Right	337	0.0113	46	-80	6	3.95

Table 2.2. Internal Focus > External Focus Contrast.

Cluster Index	Brain Regions	Side	Voxels #	p-value	MNI Coordinate of Peak Voxel			*z*-max
					x	***y***	***z***	
1	Lingual gyrus Occipital pole Occipital fusiform gyrus	Left	725	2.21E-05	2	-80	-6	4.28
2	Lateral occipital cortex	Left	473	0.00106	-54	-72	6	4.01
3	Postcentral gyrus Heschl's gyrus Precentral gyrus	Left	301	0.0223	-58	-14	20	3.54
4	Cerebellum: IX, VIIb	Left	265	0.005	-30	-65	-54	3.35

Results from this study make multiple contributions to our understanding of attentional focus on neural activity during a gross motor task. In the external focus condition, our data revealed increased cortical activation in regions of the brain associated with vision (occipital pole, cuneal cortex, anterior portion of the lingual gyrus and intracalcarine cortex). This highlights the participants' ability to effectively process the visual target and provides a partial understanding for motor performance enhancements exhibited using similar manipulations (Porter, Anton, & Wu, 2012). It is also possible that the external instruction (not necessarily the visual stimuli) influenced these regions' activation as it has been speculated that external focus instruction aids visual processing (Abdollahipour, Psotta, & Land, 2016). Further, we found increased activation in the occipital fusiform gyrus during the external focus manipulation. This region is often activated when participants are asked to identify objects (Tyler et al., 2013), thus, we posited that visual targets used during external focus manipulations aid in the encoding of relevant environmental information (Raisbeck, Diekfuss, Grooms, Kraft, & Schmitz, under review).

Additionally, our data revealed increased activation in motor regions (precentral gyrus, postcentral gyrus, and cerebellum) for the internal focus condition relative to the external focus. The precentral gyrus is the primary brain region responsible for motor function (Rao et al., 1993), the postcentral gyurs is responsible for planning and coordination of complex movements (Porro et al., 1996), and the cerebellum is highly associated with balance control (Morton & Bastian, 2004). This increased activity in motor regions may reflect the demanding cognitive control processes associated with an internal focus (Wulf, McNevin, et al., 2001) and supplements the constrained-action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001), by providing empirical data demonstrating that an internal focus elicits conscious control over movement.

Taken together, these findings highlight the role of an external focus for visual recognition and object identification, while also demonstrating that an internal focus increases cognitive awareness of motor movement during the execution of a gross motor movement. Our research is the first to empirically describe the role of attentional focus on brain execution during the execution of a gross motor task. Since increased cortical activation, specifically in the striatum and premotor cortex, are believed to contribute to motor learning (Gabitov, Manor, & Karni, 2015), it is imperative to understand how brain activity resulting from attentional focus influences the motor learning process. Particularly, it would be useful to understand how an external focus modulates sensory information and its association with motor output.

Mechanisms

Wulf and Lewthwaite (2016) theorized that an external focus plays a dual role that promotes goal-action coupling (OPTIMAL Theory; see Figure 2.4). Specifically, an external focus not only directs attention to the task and goal, but reduces the focus on one's self. The former allows the performer to elicit a movement pattern similar to a highly-skilled performer by 'freeing' degrees of freedom (Wulf & Dufek, 2009) and minimizing the number of co-contractions of agonist and antagonists muscles (Lohse & Sherwood, 2012). This evidence is in line with the previously described constrained-action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001) which suggests that an external focus promotes automaticity. The latter (reducing focus on the one's self), on the other hand, minimizes access to the self which can disrupt movement automaticity by eliciting a conscious control over behavior, sometimes referred to as 'micro-choking' (Wulf & Lewthwaite, 2010). There are numerous examples of performers 'choking' in athletic domains (Beilock, 2010), resulting in a plethora of studies exploring the influence of attention on choking behavior (Beilock, Bertenthal, McCoy, & Carr, 2004; Beilock et al., 2004; Beilock & Carr, 2001). Results from these studies are in line with the previously described self-invoking trigger hypothesis (McKay & Wulf, 2012; McKay et al., 2015) which advocates for an external focus to direct attention away from the self.

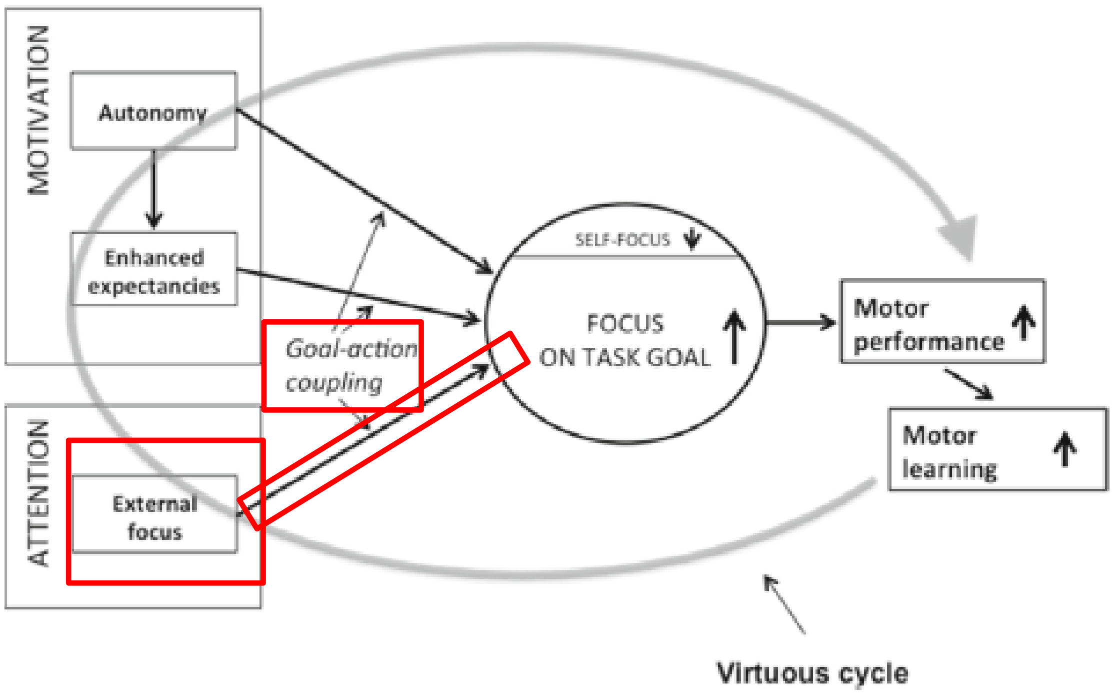

Figure 2.4. OPTIMAL Theory (Wulf & Lewthwaite, 2016). This dissertation will explore the influence of an external focus on goal-action coupling (in red).

It is postulated that directing attention externally permits the brain to develop more effective neural connections (Wulf & Lewthwaite, 2016). This concept was partially developed from the accumulating data comparing brain activity and networks of novice and expert performers (Di et al., 2012; Kim, Han, Kim, & Han, 2015; Kim et al., 2014; Milton et al., 2007). For example, Kim et al. (2014) had elite, expert, and novice archers mentally rehearse the execution of firing an arrow while brain activity was measured using fMRI. Their results revealed more localized areas of brain activity in the expert and elite archers, particularly in the dorsal pathways, whereas novices demonstrated broad activity across frontal and motor areas. The authors concluded that elite and expert archers were more neurally efficent at integrating sensory motor information. In a similar study, Kim et al. (2015) explored the functional connectivity (in the resting state) between the cerebellum, temporal, parietal and frontal lobes in expert and novice golfers. New to previous research, the authors also explored the correlations between resting-state brain activity and swing patterns. Consistent with their predictions, the authors found that expert golfers showed greater functional connectivity between the cerebellum and the temporal, parietal, and frontal lobes compared to the controls. Further, the results revealed a significant correlation between impact angle and functional connectivity for the cerebellum, thalamus, frontal and parietal lobes for the experts only. There are clear distinctions in functional connectivity for those varying in skill level which supports those who have linked motor skill learning with functional connectivity (Albert, Robertson, & Miall, 2009).

Neuroplasticity

Before making specific predictions pertaining to the effects of attentional focus on neuroplasticity, it is necessary to establish the influence of motor learning, in general, on neuroplasticity – regardless of the focus of attention used. This sets the framework for determining the intervention time that would be optimal to see changes resulting from my manipulations.

Structural Changes

It is well established that the brain is able to change its structure and function throughout the life span (Jäncke, 2009; Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Zilles, 1992). The brain is also highly responsive to motor practice and experience (Bangert & Altenmüller, 2003). For example, Draganski et al. (2004) had novices practice a juggling task for three consecutive months. Compared to a control group that did not practice, those who juggled showed increased grey matter density in the intraparietal sulcus and the midtemporal area of the visual cortex – these areas are associated with visually controlling movement. Interestingly, after 3 months of no juggling practice, the changes diminished, suggesting that the brain can revert to its previous state when practice no longer occurs. Similarly, increased gray matter density has occurred in the precentral gyrus following 15 months of musical instrument training (Hyde et al., 2009) and 40 hours of golf training is associated with gray matter increases in sensorimotor regions of the dorsal stream (Bezzola, Mérillat, Gaser, & Jäncke, 2011).

In additional to longitudinal studies, there are a myriad of cross-sectional studies that have examined structural brain differences amongst experienced musicians and non-musicians (Bangert & Schlaug, 2006; Gaser & Schlaug, 2003) and experienced athletes compared to novices (Hänggi, Koeneke, Bezzola, & Jäncke, 2010; Jacini et al., 2009; Jäncke, Koeneke, Hoppe, Rominger, & Hänggi, 2009; Park et al., 2009). In general, these studies reveal distinct structural differences amongst highly-skilled and lesser-skilled individuals. While it was initially believed that structural changes took extended time-frames to change, recent evidence has revealed that seven days of juggling alters grey matter volume in the occipto-temporal cortex (Driemeyer, Boyke, Gaser, Büchel, & May, (2008) and researchers have demonstrated rapid changes in the motor cortex following motor training (Sagi et al., 2012; Xu et al., 2009).

In a three-experiment study, Taubert, Mehnert, Pleger, and Villringer (2016) examined gray matter changes in the M1 following a complex balance training task. In experiment 1, participants were assigned to a training group consisting of a challenging balance activity, a motor imagery group that imagined balancing, or a crossword puzzle only group (control). MRI was used to collect imaging data before and after the intervention. Of interest to my current dissertation is the comparison between the training group and control group. The training group stood on a movable platform and the goal of the task was to keep the board level. Importantly, this study did not clarify the specific instructions used, but if the goal of the task was to 'keep the board level' it is possible that participants adopted an external focus of attention. Using regions of interest (ROI) specific to the M1 that are responsible for maintaining balance (e.g., lower extremities and trunk; Taubert et al., 2010) , the authors revealed increased cortical gray matter thickness from the pre to the post test in the M1 region associated with controlling foot and trunk movement. No differences, however, were observed from the pre to the post test for control ROIs (M1 regions for hand and tongue movements). Further, the authors provided evidence that the change in cortical thickness was not related to changes in resting cerebral blood flow (experiment 2) and not due to the repetitive use of specific body parts (experiment 3). These findings are influential as they distinguish between use-dependent plasticity (i.e., consistently reproducing a movement pattern) and motor learning. Specifically, the results from this study revealed that motor learning induces quick and specific alterations in cortical structure.

In conclusion, it appears that motor training does influence rapid changes in cortical gray matter thickness and more stable changes in grey matter density with extended training. These changes are believed to occur as a result of the mismatch between repeated task-evoked demand and the resulting influx of neural resources (Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010). While practicing a motor task does result in localized brain representations (e.g., perceptions, thoughts), it is the secondary compensatory responses (e.g., improved performance, structural changes) that reflect the brains neuroplasticity (Bengtsson et al., 2005; Draganski et al., 2004; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; May et al., 2007).

Resting-State Connectivity Changes

In addition to the accumulating evidence that the brain structurally adapts to practice or experience, there is also a rich literature describing the functional brain changes associated with motor training (Albert et al., 2009). Resting-state connectivity refers to temporal correlations of spontaneous low frequency fluctuations of the BOLD signal between brain areas during rest (Biswal et al., 1995; Greicius et al., 2003). Brain regions are believed to correlate at rest following a history of coactivation during active states (Corbetta, 2012), which in turn allows for the assessment of training-related changes in brain function (Biswal et al., 1995; Fox & Raichle, 2007; Lowe, 2012; Snyder & Raichle, 2012).

There are a variety of studies that have implemented resting-state fMRI to explore the effects of motor training on brain function (Ma, Narayana, Robin, Fox, & Xiong, 2011; Vahdat, Darainy, Milner, & Ostry, 2011). A variety of different motor tasks have been used ranging from discrete fine motor tasks such as finger pressing (e.g. Floyer-Lea, Wylezinska, Kincses, & Matthews, 2006) and chopstick handling (Yoo, Sohn, & Jeong, 2013), to more complex tasks such as dynamic balance board training (Taubert, Lohmann, Margulies, Villringer, & Ragert, 2011) and aerobic fitness training (Voss et al., 2010). For example, Demirakca, Cardinale, Dehn, Ruf, and Ende (2015) had 21 participants partake in ‘life kinetik’ training sessions for one hour per week over a course of 13 weeks. ‘Life kinetik’ training combines motor and cognitive exercises into single training session which allowed the researchers to explore the influence of a multimodal training regime on changes in brain function. Using resting-state connectivity analyses, the authors reported seed-to-voxel regions that increased for the training group, but did not increase for a control group who did not complete the training. The authors found increased connectivity for the training group between the visual cortex and parts of the superior parietal area as well as between the premotor area and cingulate gyrus. Demirakca et al. concluded that challenging coordination tasks that manipulate visual perception and working memory induced specific changes in brain function.

In another recent study, Amad et al. (2016) was interested in the effects of an extended drumming intervention on brain function in novices. Drumming is a task that requires body coordination, cardiovascular exercise, bilateral arm and leg movements, and sensory integration (De La Rue, Draper, Potter, & Smith, 2013) which can provide unique insight into a the developing brain function during the acquisition of a novel motor skill. Amad et al. assigned 16 participants to a training group and 15 participants to a control group. In the training group, participants practiced drumming for 30 minutes a day, three times a week, for eight weeks. The control group was asked to not participate in any musical activities during the eight weeks. Using a strictly data-driven approach (multivariate pattern analyses), the results revealed significantly increased resting-state connectivity between the posterior part of the bilateral superior temporal gyri and the rest of the brain. Then, using seed-to-voxel analyses, the authors found that the posterior part of the bilateral superior temporal gyri (the identified seed) showed significantly increased resting-state connectivity with motor regions and the right parietal lobe. The authors concluded that their drum-training intervention provided partial understanding of the neural mechanistic changes involved in novice motor learning, but would be enhanced using other neuroimaging techniques such as DTI tractography.

Microstructural Changes Assessed via DTI

Using a diffusion MRI framework, DTI tractography is a technique that can show tissue density and organization (Assaf & Pasternak, 2008), and is often used to study white matter anatomy of the human brain. DTI is useful as it measures water diffusion in different spatial directions in the brain. One commonly used parameter is fractional anisotropy, which provides a simple and robust way to assess anisotropic diffusion with a brain region (Pfefferbaum et al., 2000) by quantifying the directionally of water diffusion within a voxel (0 – 1; isotropic [identical properties in all directions] – anisotropic [properties depend on the direction]) (Mori & Zhang, 2006). Since axonal fibers within white matter of the brain are linear, and diffusion is constrained perpendicular to the orientation of these fiber bundles, fiber tracking algorithms can be used to determine length and orientation. Simply, fractional anisotropy is high in brain regions with high organization, such as the corpus callosum, and fractional anisotropy is low in areas that are not specifically oriented or consist of free fluid (e.g., cerebral spinal fluid). Further, fractional anisotropy increases in white matter maturation in the developing brain

(Beaulieu, 2002; Eluvathingal, Hasan, Kramer, Fletcher, & Ewing-Cobbs, 2007), but decreases during normal aging (Moseley, 2002) and in those suffering from neurodegenerative diseases (Sundgren et al., 2004). Thus, high fractional anisotropy is broadly interpreted as an indicator of white matter integrity (Alexander, Lee, Lazar, & Field, 2007), as it has also been positively correlated with reading ability (Niogi & McCandliss, 2006) and executive function (O'Sullivan et al., 2004a).

While training-induced plastic changes in the brain are still little understood (Alexander et al., 2007; Beaulieu, 2002), fractional anisotropy has been useful in comparing microstructural differences in nerve fiber tracts between controls and experts through cross sectional designs (Bengtsson et al., 2005; Imfeld, Oechslin, Meyer, Loenneker, & Jancke, 2009). For example, Bengtsson et al. explored the relationship between fractional anisotropy and estimated childhood practice time in musicians and non-musicians. The authors found higher fractional anisotropy values in the posterior limb of the right internal capsule in the musicians, suggesting a physiological mechanism for motor learning. Imfeld et al. (2013), however, found decreased fractional anisotropy values in both the left and right corticospinal tract for musicians compared to non-musicians suggesting that training-induced changes increase plastic changes in the axonal membrane, thus increasing radial diffusivity and lowering fractional anisotropy values.

Other studies, however, have used experimental designs to determine the casual influence of practice or training on white matter connectivity (Scholz, Klein, Behrens, & Johansen-Berg, 2009; Takeuchi et al., 2010). For example, Scholz et el. demonstrated that a six-week juggling intervention resulted in alterations in white matter microstructure and Takechui et al. demonstrated a significant relationship between fractional anisotropy in the intraparietal sulcus and corpus callosum following a two-month working memory training intervention. Both studies indicate that the brain's microstructure is malleable to both motor and cognitive training. Similar effects, however, have even occurred on much shorter time-scales (Sagi et al., 2012). For example, Hofstetter, Tavor, Moryosef, & Assaf, (2013) had participants practice car-racing game for two hours and demonstrated changes in diffusion indices between the fornix and hippocampus. These changes were also significantly correlated with performance changes suggesting that short-term motor training can induce rapid changes in white matter.

Resting-State Connectivity Pilot Data

Before developing this dissertation, we conducted a pilot study to ascertain whether attentional focus training influences resting-state connectivity. The purpose of this pilot study was to demonstrate that and attentional focus manipulation would be effective in eliciting both performance and neuroplasticity (resting-state connectivity, only) changes.

First, participants (*n* = 10) underwent baseline structural and functional imaging (resting-state fMRI). Next, participants completed three baseline trials on the dynamic balance board (described in detail in chapter 3) and were randomly assigned to an internal (*n* = 5) and external focus condition (*n* = 5). Each participant completed 25 separate 30 second trials of balance. In the internal focus condition, participants were asked to 'focus on keeping their feet level,' whereas in the external focus condition, participants were asked to ‘focus on keeping the board level.’ Immediately after, participants completed a resting-state fMRI scan.

For the performance data, we calculated the number of seconds the board was within +/- 5 degrees from horizontal in the AP direction and averaged this time across the three baseline trials and across the 25 practice trials. After controlling for baseline scores, our performance results indicated that participants’ time in balance was significantly greater during the external focus condition compared to the internal focus, F (1, 7) = 4.33, p = .04, partial η^2 = .38 (see Figure 2.5).

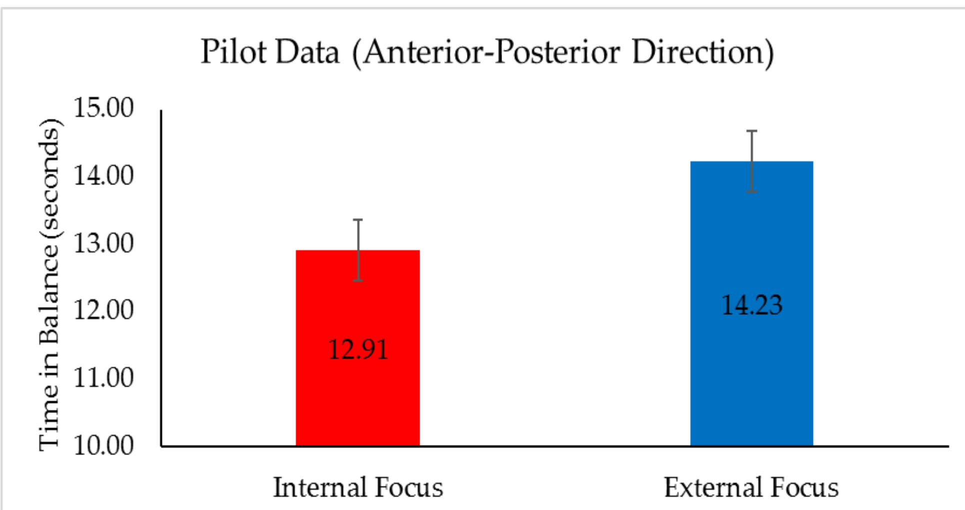

Figure 2.5. Time in Balance Pilot Data. Greater time in balance for the external focus condition compared to the internal focus condition (p = .04, partial η^2 = .38).

Using an exploratory ROI to ROI approach, we investigated the influence of the vermis, an area of the brain that is known to receive input from the motor cortex (Coffman, Dum, & Strick, 2011), and its relationship to other ROIs throughout the brain. Separate t tests and a false discovery rate correction for multiple comparisons were used to determine significance with an alpha level set *a priori* at $p < .05$. Our data revealed significantly greater temporal correlations between the third lobule of the vermis and left *t* (8), false discovery rate error corrected *p (p-FDR)* = .037 and right cerebellum_6 *t* (8), *p-FDR* = .037 for the internal focus compared to the external focus condition following the balance training (see Figure 2.6). Importantly, no differences were observed before the balance training or when comparing the external focus to the internal focus condition for these ROI comparisons.

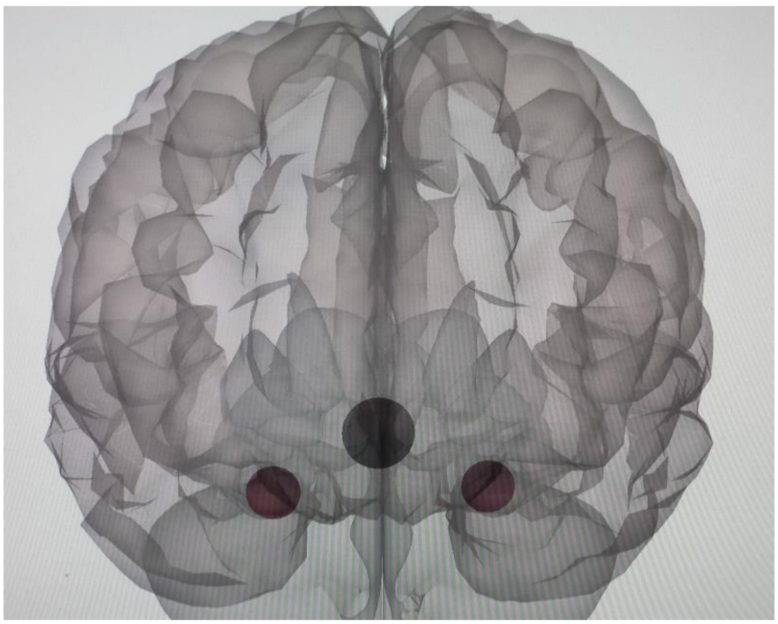

Figure 2.6. ROI to ROI Pilot Data. Significantly greater correlated activity between the third lobule of the vermis (center circle) and the left *(p-FDR* = .037; left circle) and right cerebeullum_6 *(p-FDR* = .037; right circle) for the internal focus compared to the external focus condition post balance training

The vermis connects the two lateral hemispheres of the cerebellum and share similar functions. For example, the vermis is believed to be involved with cognitive operations such as working memory (Küper et al., 2016) through shared anatomical connections with the prefrontal cortex (Desmond & Fiez, 1998). Likewise, the left and right cerebellum are associated with cognitive operations (Chen, He, Rosa-Neto, Germann, & Evans, 2008; Schmahmann & Caplan, 2006) and have been suggested to play a role in personality and mood (Cutting, 1977; Wolf, Rapoport, & Schweizer, 2009). Importantly, however, both the vermis and cerebellum are highly involved in postural stability (Morton & Bastian, 2004) which we challenged during the dynamic balance task. Thus, this data suggests that an internal focus may result in participants continued self-awareness towards motor control, specifically balance control, following a dynamic balance task. This complements our previous findings using task-based fMRI analyses discussed earlier (Raisbeck et al., under review) in which we suggested that an internal focus increases cognitive awareness during the execution of gross motor skill. Importantly, this provides some understanding for the detrimental effects associated with an internal focus following an acquisition period in which no attentional focus instruction is provided (Wulf, 2013) and provides data to support hypotheses 2a (i.e., less correlated activity between motor and sensory regions at rest following external focus training) and 2b (i.e., more correlated activity between motor and sensory regions at rest following internal focus training) of this dissertation.

Summary

Taken together, the literature exploring motor learning and neuroplasticity reveals that the brain is highly adaptable and is capable of remodeling because of practice or experience. Our pilot data also revealed that attentional focus may influence changes in resting-state connectivity. A critical review of this literature, however, reveals substantial gaps that warrant investigation. First, the published studies outlined in the previous section do not specifically manipulate attentional focus. With our preliminary data revealing that internal and external focus instruction differentially affects brain activation (Raisbeck et al., under review), it is plausible to suspect that previous studies are confounded by the attentional instruction provided or the unknown attentional focus strategies used by participants. For example, in the classical study by Draganski et al. (2004), participants practiced the juggling task, specifically the three-ball cascade at home for three months without daily directed attentional focus instruction. We know, however, that attentional focus instruction influences the performance and movement kinematics of the three ball-cascade (Zentgraf et al., 2009), indicating that neural changes may be occurring as a result of the focus of attention strategy performers adopt.

Further, in the studies investigating neuroplasticity resulting from dynamic balance training (Taubert et al., 2010, 2011, 2016), a discovery learning approach was used (Orrell, Eves, & Masters, 2006; Wulf et al., 2003) in which no information pertaining to the performance strategy was provided. In other words, performers had to discover their own strategy for optimal balance and no attentional focus was utilized. Since participants often perform in a manner similar to an internal focus when no instruction is provided (Landers et al., 2005; McNevin & Wulf, 2002; Wulf & Su, 2007; Wulf, Zachry, et al., 2007), it is reasonable that participants behaved in a manner consistent with an internal focus. Thus, participants may have been actively engaging brain regions that elicit conscious awareness over movement (e.g., occipital fusiform gyrus; Raisbeck et al., under review) which may have influenced the outcome of previous findings. This is particularly relevant as the dynamic balance board used in the neuroimaging literature is a stabilometer (Taubert et al., 2010, 2011, 2016) which is a common apparatus used in the attentional focus literature (Chiviacowsky et al., 2010; Jackson & Holmes, 2011). Specifically, it has been widely demonstrated that an external focus has been shown to positively impact performance and learning of this balance task (McNevin et al., 2003; Wulf et al., 1998, 2003; Wulf, Shea, et al., 2001). Therefore, to bridge these gaps, I propose a seven-day dynamic balance training intervention study that explores the influence of attentional focus on both the performance and learning of a dynamic balance task and the associated changes in neuroplasticity. We elected to use a seven day-training program to provide a natural progression of the attentional focus literature. Most attentional focus literature exploring the effects of attentional focus on balance have participants practice 20 – 100 trials over the course of one session (Chiviacowsky et al., 2010; Wulf et al., 1998, 2003), three sessions (Laufer et al., 2007), or five sessions (Porter, Makaruk, & Starzak, 2016) and assess learning via a retention test 24 hours later. Albeit there is one attentional focus balance training study with an extended training paradigm of four weeks (Landers, Hatlevig, Davis, Richards, & Rosenlof, 2015), this study examined those with Parkinson's disease. Thus, a natural extension of attentional focus literature in young healthy adults would be to examine the influence of attentional focus balance training over the course of seven days of training.

CHAPTER III

METHODS

Participants

Thirty-three right-handed and left-footed young adults between the ages of 18 and 35 years of age were recruited (16 males, age = 23.0 ± 3.7 yrs, height = 175.9 ± 5.8 cm, mass = 74.0 ± 12.7 kg; 17 females, age = 22.6 ± 3.9 yrs, height = 164.8 ± 6.0 cm, mass = 62.0 ± 10.6 kg). Participants were excluded if they had: 1) a previous history of injury to the capsule, ligament, or menisci of either knee; 2) any vestibular or balance disorder, 3) any metal or implanted medical device in the body that would be a contradiction to MRI assessment; 4) undergone a previous balance training program. Prior to the study, all participants read and signed an informed consent form approved by the University of North Carolina at Greensboro's Institutional Review Board for the Protection of Human Subjects (Appendix A). No compensation was offered for participation.

Procedures

This was a nine-day study; each day required one hour of the participants' time. On day one, participants met the researcher (Diekfuss) outside of the Joint School of Nanoscience and Nanoengineering. Participants signed into the facility and were seated at a table located within the MRI suite. Participants read and signed an informed consent form (Appendix A), completed a general intake questionnaire pertaining to health history, exercise behavior, and demographic information (Appendix B), completed the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix C) to assess handedness, and the Waterloo Footedness Questionnaire-Revised (Elias, Bryden, & Bulman-Fleming, 1998; Appendix D) to assess footedness. Next, participants completed the University of North Carolina at Greensboro's (UNCG) MRI screening form that screens for contradictions to MRI (Appendix E). Mr. Diekfuss was trained in screening participants and verbally verified that there were no contradictions.

Once it was determined that the participant wasMRI compatible, the participant underwent baseline testing for balance performance. Participants were asked to stand on a dynamic balance board and look forward for 30 seconds. All participants were only told to 'do their best' – no specific attentional focus instruction or other instruction was provided. Participants completed five separate 30 second trials with 30 seconds rest between each trial. An inertial measurement unit was attached to the center of the balance board to measure balance performance and is described in more detail below (Data Processing section). Following the baseline trials, participants were also asked to complete a workload questionnaire (Appendix F; National Aeronautics and Space Administration – Task Load Index; NASA-TLX; Hart & Staveland, 1988) to assess perceived cognitive demands which we have used previously (Diekfuss, Ward, & Raisbeck, 2016; Raisbeck, Diekfuss, Wyatt, & Shea, 2015).

Next, participants completed pre-intervention functional and structural imaging on a 3.0 T MRI scanner using a 12-channel head coil (Siemens Trim Tri; Erlangen, Germany). The participants were instructed to lay supine on the MRI table and the head coil was positioned. Participants were given a safety ball and were provided with instruction on how to call for assistance. The researcher then moved the table so the participant's upper torso and head was within the bore of the scanner. Participants were asked to keep their eyes open and remain as motionless as possible. A mirror was positioned so that the participant could see the researcher throughout the entire experiment.

The entire MRI session took approximately 35 minutes. Following a series of localizer scans (approximately five total minutes) a 6.5 minute T1-weighted MPRAGE structural image was obtained (TR = 2000 ms; TE = 4.58ms, FOV = 256mm; flip angle = 7°, voxel size = 1 × 1 × 1mm). Following the structural image, a fMRI resting-state scan was acquired (TR = 3000ms, TE = 28ms, FOV = 212mm, flip angle = 73°, bandwidth = 2520 Hz, acquisition matrix = 64 × 64, slice thickness=3.3 mm, voxel dimensions = 3.3 × 3.3 × 3.3 mm), 48 slices, interleaved slice ordering. Participants were asked to look at a cross (a black 'x' drawn on a piece of paper and taped in full view of the participant), remain motionless, and let their mind wander; the total time of the resting-state fMRI session was approximately 5.5 minutes. Finally, DTI data was acquired with the following parameters: TR = 9000ms, TE = 94ms, matrix field of view = 350mm, bandwidth = 1346 Hz, acquisition matrix = 64 × 64, slice thickness = 2.7 mm, voxel dimensions = 2.7 × 2.7 × 2.7 mm, 59 slices, diffusion mode = MDDW, noise level = 30, diffusion directions = 64, b value 1 = 0 s/mm^2, b value 2 = 1300 s/mm^2, interleaved slice ordering. The total time for the DTI scan was 10 minutes and 14 seconds. Participants were then removed from the scanner, thanked for their time, and escorted out of the facility.

Participants were then randomly assigned to a control, an internal focus, or an external focus condition. On days two through eight, those assigned to the internal and external focus condition (training groups) met the researcher on the UNCG campus and completed a series of balance tasks for approximately one hour on each day (training intervention [acquisition]). Those in the control group did not meet the research during acquisition. Specifically, participants in the training groups completed six blocks of five separate 30 second balance trials on the balance board. A 30 second rest was given between each trial and a two-minute rest was given between trial blocks. In sum, participants completed 30 balance trials per day. Prior to the first trial, and congruent with baseline testing, all participants were told ‘to do their best.’ However, to manipulate attentional focus, prior to every testing block, participants in the internal and external focus conditions received additional instruction. Specifically, those in the internal focus condition were asked to ‘focus on keeping their feet level,’ whereas those in the external focus condition were asked to ‘focus on keeping the board level.’ Participants were also asked to complete the workload questionnaire and asked to provide an open-ended response pertaining to their focus of attention after each day’s intervention (Appendix G). These two questionnaires served as manipulation checks. Each training session lasted approximately one hour and the researcher made considerable effort to test participants at approximately the same time on each day.

On day nine, all participants (including the control group) completed a retention balance test. They also completed post-intervention structural and functional imaging. This portion was identical to baseline testing (same number of balance trials and same imaging sequences) Importantly, at this time, no attentional focus or other instruction was provided during the balance testing to assess learning. Figure 3.1 depicts a flow chart of the experimental design.

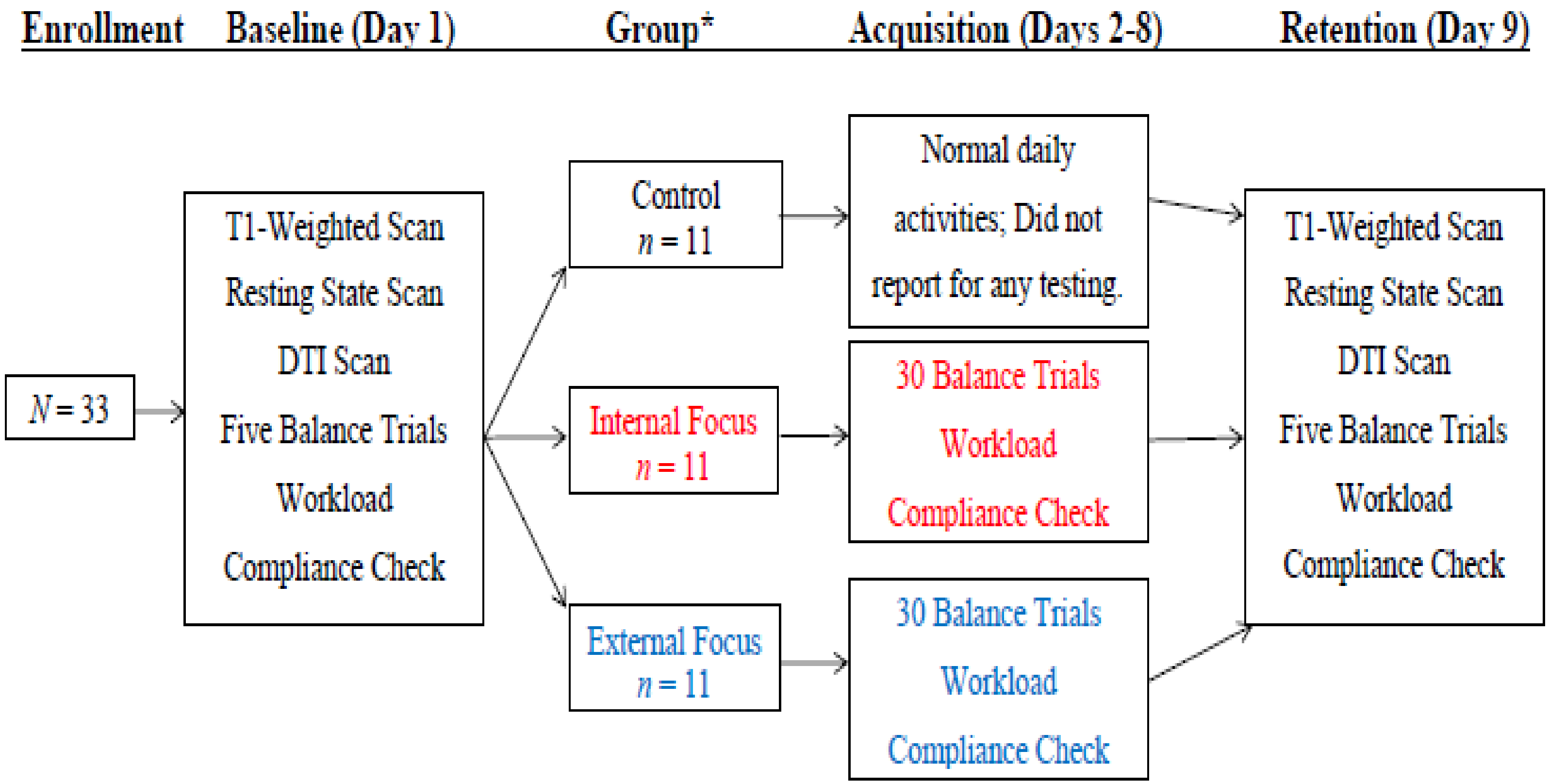

Figure 3.1. Experimental Design Flow Chart. * Participants were randomly assigned to the control, internal focus, or external focus condition.

Data Processing

Balance Performance

Acceleration and velocity data was collected from an inertial measurement unit (IMU; Xsens Technology, MA, USA) attached to the center of movable balance board which collected time series data in 3-dimensions (Figure 3.2). All data was collected at 100hz.

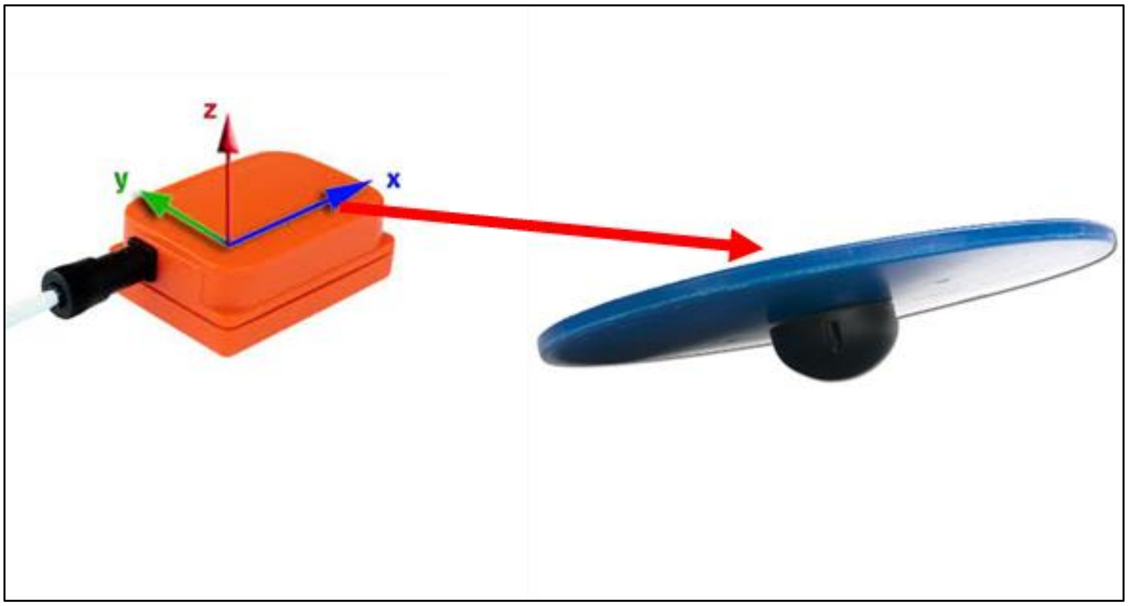

Figure 3.2. Balance Board and Inertial Measurement Unit. Xsens technology was attached to the center of the balance board.

The raw velocity time series (m/s) in the medial-lateral direction was extracted from the IMU and filtered with a 5th-order low-pass Butterworth filter using a 5 hz cut-off. This data was then entered customized scripts in MATLAB (MathWorks, Inc., Natick, MA) to calculate the mean, SD, and SampEn of the velocity time series for each individual trial. For SampEn, a customized optimization script was used to extract optimal length (*m*) and tolerance (*r*) values (see Lake, Richman, Griffin, & Moorman, 2002). An $m = 2$ and $r = .15$ were used for this study.

Resting-State Connectivity

Resting-state data analyses were implemented in MATLAB using the CONN toolbox (http://www.nitrc.org/projects/conn; Whitfield-Gabrieli & Nieto-Castanon, 2012). Preprocessing was performed on the data within the CONN toolbox with the CompCor method (Behzadi, Restom, Liau, & Liu, 2007) to identify principal components associated with segmented cerebrospinal fluid (CSF) and white matter (WM). CSF, WM, and realignment parameters were entered as confounds in a first-level analysis (Behzadi et al., 2007) and the data was band-pass filtered to .008 Hz - .09 Hz. The global signal was not regressed as CompCor addresses the confounding effects of subject movement without affecting intrinsic connectivity (Chai, Castañón, Öngür, & Whitfield-Gabrieli, 2012).

Fractional Anisotropy Changes

DTI data was analyzed using FSL's (FMRIB [The Oxford Centre for Functional Magnetic Resonance Imaging of the Brain] Software Library) FDT toolbox (http://www.fmrib.ox.ac.uk/fsl/fdt/index.html). Images were first eddy current corrected to remove non-linear artifacts and distortions from the data sets (Jenkinson & Smith, 2001). Tensors were then fit using the *b*-factor and diffusion direction matrix with the DTIfit toolbox and brain extracted using FSL's brain extraction tool (BET) (Smith, 2002). Eigenvalues, the resulting eigenvectors, and the FA indices were calculated for each voxel resulting in diffusion weighted brain maps. Tract-based spatial statistics

(TBSS; Smith et al., 2006) were then carried out using FSL. Using the nonlinear registration tool FNIRT (Andersson, Jenkinson, & Smith, 2007a, 2007b), all subjects' fractional anisotropy data was aligned to common 1x1x1mm MNI152 space and the subsequent mean FA image was created and thinned to produce a mean FA skeleton at a threshold value of 0.2.

Statistical Approach

Balance Data

Hypothesis 1a*: Those who practiced the dynamic balance task with an external focus would display significantly more favorable postural control characteristics (lower mean velocity, lower standard deviation [SD] velocity, and higher Sample Entropy [SampEn] velocity) throughout acquisition compared to those who practiced with an internal focus of attention..*

To answer Hypothesis 1A, each block of five trials was averaged for each of the dependent variables (mean velocity, mean SD velocity, and mean SampEn). Then, three separate 2 (condition) × 6 (block) × 7 (day) mixed ANOVAs with repeated measures on the last two factors were conducted for the dependent variables mean, SD, and SampEN velocity. We specifically examined between subjects' differences for this hypothesis.

Hypothesis 1b: *Those who practiced the dynamic balance task with an external focus would demonstrate significantly more favorable postural control characteristics (lower mean velocity, lower SD velocity, and higher SampEn velocity) at day 9 retention compared to those who practiced with an internal focus or did not practice the dynamic balance task (control).*

To answer hypothesis 1B, the five trials for baseline and retention were averaged and entered into separate between-subjects' (three factors; control, internal, external) ANOVAs for each of the dependent variables mean, SD, and SampEN velocity. Tukey's post hoc procedure was used to identify significant between-group differences. Analyzing the retention data separately from the practice data is consistent with how others have examined acquisition and retention data in motor learning research (Raisbeck & Diekfuss, 2016; Wulf, Chiviacowsky, Schiller, & Ávila, 2010).

Hypothesis 1C*: All participants who practiced the dynamic balance task would elicit significant improvements in balance control (lower mean velocity, lower SD velocity, and higher SampEn velocity) from the early to late trial blocks and from the early to late days of training, regardless of condition due to practice effects.*

To answer Hypothesis 1C, and using the same analyses as hypothesis 1A, each block of five trials was averaged for each of the dependent variables (mean velocity, mean SD velocity, and mean SampEn). Then, three separate 2 (condition) × 6 (block) × 7 (day) mixed ANOVAs with repeated measures on the last two factors were conducted for the dependent variables mean, SD, and SampEN velocity. We specifically examined the within-block and within-day differences for this hypothesis.

Resting-State Connectivity Analyses

Hypothesis 2a*: Those who practiced the dynamic balance task with an external focus of attention would demonstrate significantly less correlated brain activity amongst various motor and sensory regions when contrasting their brain activity at rest during retention with their brain activity at rest during baseline.*

To answer hypothesis 2a, we conducted region of interest (ROI) analyses to test our hypotheses that resting-state connectivity would change from baseline to retention for those training with an external focus. Specifically, we conducted two separate paired-samples *t* tests that contrasted participants resting-state connectivity at retention relative to baseline (retention > baseline) for the external focus and control groups. Following Demirakca et al. (2015), we only reported differences in connectivity for the external focus group that was not present in the control group. ROI-to-ROI results were reported when significant at a level of p <.05 false discovery rate (FDR) corrected (Chumbley, Worsley, Flandin, & Friston, 2010).

Hypothesis 2b: *Those who practiced the dynamic balance task with an internal focus would demonstrate significantly more correlated brain activity amongst various motor and sensory regions when contrasting their brain activity at rest during retention with their brain activity at rest during baseline.*

To answer hypothesis 2b, and like the approach used for hypothesis 2a, we conducted region of interest (ROI) analyses to test our hypotheses that resting-state connectivity would change from baseline to retention for those training with an internal focus. Specifically, we conducted a separate paired-samples *t* test that contrasted participants resting-state connectivity at retention relative to baseline (retention > baseline) for the internal focus group. Following Demirakca et al. (2015), we only reported differences in connectivity for the internal focus group that was not present in the control group (analyzed for hypothesis 2a). ROI-to-ROI results were reported when significant at a level of p <.05, FDR corrected (Chumbley et al., 2010).

Fractional Anisotropy Analyses

To calculate fractional anisotropy values for our specific brain regions of interest (prefrontal cortex, precentral gryus, and postcentral gyrus), we created binarized masks with a threshold of 10 using the Harvard Cortical Structural atlas within FSL. Using the FSLmaths multiply command, we multiplied each region brain mask by the mean fractional anisotropy skeleton mask. This allowed us to examine fractional anisotropy only in appropriate white matter tracts. Then, via the FSLstats command, we extracted the mean fractional anisotropy for each masked region and calculated a percent change score from baseline to retention ([mean retention FA – mean baseline FA] / mean baseline FA).

Hypothesis 3a: *Those who practiced with an external focus would elicit a significant negative relationship between percent change in fractional anisotropy in the prefrontal cortex and percent change in balance performance (decrease in FA and increase in balance performance; Taubert et al., 2010).*

To answer hypothesis 3a, we used Pearson product correlations to determine the relationship between percent change in fractional anisotropy in the prefrontal cortex and percent change in balance performance for the external focus condition. Percent change in balance performance was calculated by averaging the five trials on the baseline and retention day for each participant, subtracting the mean baseline value from the mean retention value, and dividing this value by the original mean baseline value.

Hypothesis 3b*: Those who practiced the balance task with an internal focus would elicit no significant relationship between percent change fractional anisotropy in the prefrontal cortex and percent change in balance performance.*

To answer hypothesis 3b, the same statistical approach as hypothesis 3a was used, however we used the percent change scores for the internal focus condition.

Hypothesis 3c*: Those who did not practice (control) would elicit no significant relationship between percent change in fractional anisotropy in the prefrontal cortex and percent change in balance performance.*

To answer hypothesis 3C, the same statistical approach as hypothesis 3a was used, however we used the percent change scores for the control condition.

CHAPTER IV

MANUSCRIPT I

Title

The extent to which attentional focus influences the performance and learning of a dynamic balance task over seven days.

Abstract

The purpose of this study was twofold; to examine the effects of attentional focus on the performance and learning of a dynamic balance task over seven training sessions, and to expand our understanding of attentional focus on balance control by integrating a metric derived from dynamical systems theory. Participants completed 30 trials on a dynamic balance board over seven consecutive days separated by 24 hours. Additionally, participants completed a baseline test prior to the training and a retention test 24 hours after the last session. Participants were randomly assigned to a control, internal focus, and external focus condition. For the internal focus trials, participants focused on their feet; whereas, for the external focus trials, participants focused on the balance board. Changes in postural control within each session and between the training days were measured using an inertial measurement unit attached to the center of the balance board. Classical attentional focus effects were observed for mean and standard deviation velocity, with an external focus displaying smaller values than the control and internal focus condition. We also observed that participants, regardless of condition, adopted a more patterned

behavior (measured using Sample Entropy) as each training session progressed. These findings complement the constrained-action hypothesis and provide novel insight into the dynamical changes exhibited within a single balance training session.

Introduction

Balance is a complex motor skill that relies on biomechanical and motor coordination (Horak, 1997; Winter, 1995; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). While some balance training interventions have been shown to be effective (Buchner et al., 1997; Davis et al., 2009; Wolfson et al., 1992), others have shown less positive results (Cadore, Rodríguez-Mañas, Sinclair, & Izquierdo, 2013; Landers et al., 2015). This balance training literature, however, has not fully integrated a motor behavior principle – the focus of attention – to explore how directing attention through instruction influences the performance and learning of complex balance tasks. Typically, practitioners in clinical settings provide instruction that directs individuals attention towards movement execution (Durham, Van Vliet, Badger, & Sackley, 2009; McNevin, Wulf, & Carlson, 2000), or may just ask individuals to 'do their best' with little guidance on where or what an individual should be focusing on. Initially defined by Wulf et al. (1998), attention directed towards movement execution is defined as an internal focus, whereas attention directed towards the effects of one's movement is defined as an external focus. Results from this research are robust in that focusing externally produces greater performance and enhanced learning relative to an internal focus, or when no specific focus instruction is provided (Wulf, 2007, 2013).

The first study exploring the effects of attentional focus on motor performance had participants stand on a ski simulator while their attention was directed internally or externally (Wulf et al., 1998) . Specifically, participants in the external focus condition where asked to focus on the ‘wheels’ of the ski simulator, whereas those in the internal focus were asked to focus on their ‘feet.’ Results from this study revealed that those who used an external focus displayed greater balance control throughout acquisition and during a retention test relative to those given internal focus instruction. Subsequently, the benefits of an external focus on balance control have been widely replicated (Chiviacowsky et al., 2010; Landers et al., 2005; Wulf, McNevin, et al., 2001; Wulf et al., 2003) with a consensus that an external focus is superior. According to the constrained action hypothesis (CAH) (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001), an external focus permits movement automaticity and reflexivity, whereas an internal focus disrupts previously learned motor movements by consciously interfering with automatic control processes. The CAH has been substantiated with neuromuscular measures, such as electromyography (EMG), in which an external focus reduced preparation time and integrated EMG activity in the upper arm during a dart-throwing task relative to an internal focus (Lohse et al., 2010). Further, evidence exists to support that an external focus permits more effective (Chiviacowsky et al., 2010; McKay & Wulf, 2012; McKay et al., 2015) and efficient movement (Stoate & Wulf, 2011; Zachry et al., 2005) than an internal focus or when no focus of attention is provided.

While the benefits of an external focus have been replicated in tasks ranging from basketball free-throw shooting (Al-Abood et al., 2002), dart-throwing (McKay et al., 2015), golf (Wulf & Su, 2007), to virtual target-shooting (Raisbeck & Diekfuss, 2016), the majority of studies examining attentional focus utilize balance tasks (Chiviacowsky et al., 2010; Laufer et al., 2007; Rotem-Lehrer & Laufer, 2007; Wulf et al., 1998, 2004; Wulf, Töllner, et al., 2007). While these studies are imperative to our understanding of attentional focus, they are limited by the short duration of practice time which minimize our understanding of the within and between day motor learning trajectories. The majority of studies exploring attentional focus have participants practice 20 – 100 trials over the course of one session (Chiviacowsky et al., 2010; Wulf et al., 1998, 2003), three sessions (Laufer et al., 2007), or five sessions (Porter, Makaruk, & Starzak, 2016) and assess learning via a retention test 24 hours later. Interestingly, however, there was a substantial jump in the attentional focus literature from the single or few session acquisition periods used, to large scale training studies of four weeks (Landers et al., 2015) and nine weeks (Makaruk, Porter, Czaplicki, Sadowski, & Sacewicz, 2012). While no benefits for an external focus were found for Landers et al.'s four-week study, benefits for an external focus on plyometrics were reported in the nine-week study conducted by Makaruk et al. One plausible explanation for the differences is that Landers et al. examined individuals with Parkinson's disease, while those in Makaruk et al.'s study were healthy adults. Another explanation is the differences in duration, frequency, and intensity of each training program, indicating further research into the effects of attentional focus during training programs is warranted.

Regardless of the reason for the differences in results exhibited in larger-scale training studies, there is a clear gap for our understanding of attentional focus on motor learning for periods longer than three sessions, yet shorter than four weeks. Except for the five sessions used by Porter et al. (2016), and the nine weeks of training used by Makaruk et al (2012), we are aware of no evidence that examines balance training with an external focus for more than three sessions. Thus, a natural progression to the literature would be to explore the performance and learning of a motor task over the course of one week. Since most attentional focus research has explored balance control, we elected to study the trajectory of learning in a dynamic balance task. The purpose of this study was to examine the effects of attentional focus on the performance and learning of a dynamic balance task over seven training sessions. A secondary purpose was to expand our understanding of attentional focus on balance control be integrating metrics derived from dynamical systems theory. This theory posits that individual behavior, such as balance control, is derived from the changing interaction amongst the individual, environment, and task (Newell, van Emmerik, Lee, & Sprague, 1993; Newell, Slobounov, Slobounova, & Molenaar, 1997). One metric that can be used to quantify this dynamic is sample entropy (Richman & Moorman, 2000) which has received notable attention in balance literature (Rhea et al., 2014). Sample entropy is used to quantify time-series data by examining the characteristics of its structure (i.e., assess how complex a time series is), but to our knowledge has not been integrated into the attentional focus literature.

Integrating a metric from the dynamical systems framework can expand our understanding of the influence of attentional focus on motor behavior. To examine this, we attached an inertial measurement unit to the center of a dynamic balance board and had participants practice 30 trials per day over the course of seven days. This included a baseline test before the training and a retention test 24 hours after the last session. Following previous research (e.g., Wulf et al., 2003), we predicted more favorable postural control characteristics throughout acquisition and during retention when participants adopted an external focus of attention compared to an internal focus or no focus of attention. Specifically, we predicted (1) a lower mean velocity, lower standard deviation (SD) velocity, and greater complexity (assessed via sample entropy [SampEn]) when participants adopted an external focus of attention compared to an internal focus or no focus of attention. Further, we predicted (2) significant improvements in balance control (lower mean and SD velocity and higher SampEn) from the early to late trial blocks and from the early to late days of training, regardless of condition due to practice effects.

Methods

Participants

Thirty-three healthy participants (16 males, age = 23.0 ± 3.7 yrs, height = 175.9 ± 5.8 cm, mass = 74.0 ± 12.7 kg; 17 females, age = 22.6 ± 3.9 yrs, height = 164.8 ± 6.0 cm, mass = 62.0 ± 10.6 kg) volunteered to participate in this study. Inclusion criteria included no lower extremity injury in the last 6 months, the right hand the preferred writing hand, and the left leg being the preferred stance limb when kicking a ball. Participants were excluded if they had: 1) a previous history of injury to the capsule, ligament, or menisci of either knee, 2) any inner ear or balance disorder, 3) undergone a previous balance training program, 4) were taking any medications that would affect balance, or 5) any neurological disorders. The institutional ethics committee approved the project and informed consent was obtained prior to commencing the study.

Apparatus

All balance testing was completed on a dynamic balance board (CanDo ®, NY, USA). The board is circular with a diameter of 76.2 cm. This board was attached to a half-sphere that was positioned underneath (height of 20.3 cm). When individuals stand on the circular board, it moves in all directions until they control their balance (see Figure 4.1). This specific board and other similar 'wobble boards' have been used extensively in balance training literature (e.g., Benson, Almonroeder, & O'Connor, 2017; Oliver & Di Brezzo, 2009). We attached an inertial measurement unit (IMU; Xsens; Xsens Technology, MA, USA) to the center of the board using Velcro. Importantly, this inclusion of the IMU allowed us to quantify velocity, our primary dependent variable of interest, at a rate of 100hz

Procedure

This was a nine-day study with each training session separated by 24 hours. On day one (baseline), participants stood on the board for 30 seconds for familiarization purposes. Participants then completed five separate 30-second trials on the balance board with a 30-second rest between trials. Participants were then randomly assigned to a control (n = 11), internal focus (n = 11), or external focus condition (n = 11). Participants in the internal and external focus conditions were asked to come back to the lab at the same time for the next seven consecutive days (training/acquisition). Participants in the control condition were asked to report back to the lab on day nine, but to not complete any balance training during the seven days in-between. On days two through seven, and only for those assigned to the internal or external focus condition, participants reported to the lab and completed six blocks of five separate 30-second trials (30 balance trials total per day). A 30-second rest was given between trials and a two-minute break was given between each block. For the internal focus trials, participants were asked to, '*focus on keeping your feet level;'* whereas, for the external focus trials participants were asked to, '*focus on keeping the board level.'* This attentional focus instruction was provided at the beginning of every test block throughout the seven days of training. No feedback or other instruction was provided throughout the training sessions. On day 9 (24 hour retention from day 8), and congruent with the baseline test, participants completed five separate 30-second trials on the balance board with a 30-second rest between trials. Importantly, no attentional focus instruction, feedback, or other information was provided during the baseline or retention tests.

Dependent Variables

All data were obtained through the IMU. The raw velocity time series (m/s) in the medial-lateral direction was extracted from the IMU and filtered with a 5th-order low-pass Butterworth filter using a 5 hz cut-off. This data was then entered into customized scripts in MATLAB (MathWorks, Inc., Natick, MA) to calculate the mean, SD, and SampEn of the velocity time series for each individual trial. For SampEn, a customized optimization script was used to extract optimal length (m) and tolerance (r) values (Lake et al., 2002). An $m = 2$ and $r = .15$ were used for this study.

Data Analyses

The five trials for baseline and retention were averaged and entered into separate between-subjects (three factors; control, internal, external) ANOVAs for each of the dependent variables mean, SD, and SampEN velocity. Tukey's post hoc procedure was used to identify significant between-group differences. For acquisition, each block of 5 trials was averaged and three separate 2 (condition) × 6 (block) × 7 (day) mixed ANOVA's with repeated measures on the last two factors were conducted for the dependent variables mean, SD, and SampEN velocity. Assessing baseline and retention data separately from acquisition data is consistent with others assessing motor performance and learning over separate days (Wulf et al., 2010). Bonferroni adjustments were used when appropriate and an alpha level of $p < .05$ was set a priori. Only the statistics for the significant or otherwise meaningful results are reported.

Results

Mean Velocity

At baseline, no differences were observed between the three groups for mean velocity ($p > .05$). During acquisition, however, there was a significant main effect for effect for trial block, Greenhouse-Geisser adjusted, F (3.10, 62.00) = 26.47, $p < .05$, partial $\eta^2 = .57$. As seen in Figure 4.2, there were significant reductions in mean velocity from trial block 1 to trial block 3, 4, 5, and 6, from trial block 2 to trial block 4, 5, and 6, and from trial block 3 to trial block 4, 5, and 6 (all $p < .05$; adjusted for multiple comparisons). There was also a significant main effect for day, F (6.00, 120.00) = 6.62, $p < .05$, partial $\eta^2 = .25$. There were significant reductions in mean velocity from day 1 to day 6 and 7, from day 2 to day 7, and from 3 to day 7 (all $p < .05$; adjusted for multiple comparisons). There was a main effect for condition with those in the external focus displaying lower mean velocity than those in the internal focus, F (1.00, 20.00) = 4.73, $p < .05$, partial $\eta^2 = .19$. There were no significant interactions during acquisition for mean velocity (all $p > .05$). At retention, there was a main effect for condition F (2.00, 30.00) = 4.76, $p < .05$, partial $\eta^2 = .24$, with Tukey's post hoc procedure revealing lower mean velocity for those in the external focus compared to the control ($p < .05$), with no significant differences when comparing the external focus to the internal focus or the internal focus to the control (all $p > .05$).

Standard Deviation Velocity

At baseline, no differences were observed between the three groups for SD velocity ($p > .05$). During acquisition, however, there was a significant main effect for effect for trial block, Greenhouse-Geisser adjusted, F (1.43, 28.54) = 9.51, $p < .05$, partial $\eta^2 = .32$. As seen in Figure 4.3, there were significant reductions in SD velocity from trial block 1 to trial block 6, from trial block 2 to trial block 5, and 6, and from trial block 3 to trial block 6 (all $p < .05$; adjusted for multiple comparisons). There was a significant main effect for day, F (3.02, 60.37) = 7.48, $p < .05$, partial $\eta^2 = .27$, with significant reductions in SD velocity from day 1 to day 6 and 7, from day 2 to day 7, and from day 3 to day 6 and 7 (all $p < .05$; adjusted for multiple comparisons). Also, there was a main effect for condition with those in the external focus displaying lower SD velocity than those in the internal focus, F (1.00, 20.00) = 4.49, $p < .05$, partial $\eta^2 = .18$. There were no significant interactions during acquisition for SD velocity (all $p > .05$). At retention, there was a main effect for condition F (2.00, 30.00) = 3.93, $p < .05$, partial $\eta^2 = .21$, with Tukey's post hoc procedure revealing lower SD velocity for those in the external focus compared to the control ($p < .05$), with no significant differences when comparing the external focus to the internal focus or the internal focus to the control (all $p > .05$).

Sample Entropy Velocity

At baseline, no differences were observed between the three groups for SampEn velocity ($p > .05$). In addition, there were no significant main effects for day, block, or condition for SampEn velocity ($p > .05$). There was, however, a significant block × day interaction, F (30.00, 600.00) = 5.20, $p < .05$, partial $\eta^2 = .21$. To follow up this significant interaction, separate univariate ANOVAs were conducted for each day with block (6 factors) as the repeated measures factor to isolate block × day differences. For day 1, there was a significant main effect for block, Greenhouse-Geisser adjusted, F (3.59, 75.93) = 6.98, $p < .05$, partial $\eta^2 = .25$, with a significant reduction in SampEn velocity from block 1 to block 5 and 6, from block 2 to block 5, and from block 3 to block 5 (all $p < .05$; adjusted for multiple comparisons). For day 2, there was also significant main effect for block, F (5.00, 105.00) = 9.89, $p < .05$, partial $\eta^2 = .32$, with a significant reduction in SampEn velocity from block 1 to block 4, 5 and 6, from block 2 to block 6, and from block 3 to block 4 and 5 (all $p < .05$; adjusted for multiple comparisons). For day 3, however, no differences were observed within the trial blocks for SampEn velocity ($p > .05$). For day 4, there was a significant main effect for block, F (5.00, 105.00) = 7.56, $p < .05$, partial $\eta^2 = .27$, with a significant reduction in SampEn velocity from block 1 to block 4, 5, and 6, and from block 2 to block 6 (all $p < .05$; adjusted for multiple comparisons). For day 5, there was a significant main effect for block, Greenhouse-Geisser adjusted, F (3.05, 64.09) = 6.58, $p < .05$, partial $\eta^2 = .25$, with a significant reduction in SampEn velocity from block 1 to block 5 and 6, from block 2 to block 6, and from block 3 to block 5 and 6 (all $p < .05$; adjusted for multiple comparisons). For day 6, there was a significant main effect for block, F (5.00, 105.00) = 5.06, $p < .05$, partial $\eta^2 = .19$, with a significant reduction in SampEn velocity only present from block 2 to block 5 ($p < .05$). For day 7, there was a significant main effect for block, Greenhouse-Geisser adjusted, F (2.35, 39.39) = 4.96, $p < .05$, partial $\eta^2 = .19$, with a significant reduction in SampEn velocity from block 2 to block 4, 5 and 6 (all $p < .05$; adjusted for multiple comparisons). No significant differences for SampEn velocity were observed at retention ($p > .05$). See figure 4.4.

Discussion

The purpose of this study was twofold; to examine the effects of attentional focus on the performance and learning of a dynamic balance task over seven training sessions, and to expand our understanding of attentional focus on balance control by integrating a metric derived from dynamical systems theory. We aimed to accomplish this by having participants practice a dynamic balance task over the course of seven days and assessed postural control changes via an inertial measurement unit. While we predicted more favorable postural control characteristics over the course of seven days regardless of condition due to practice effects, we expected those who were given external focus instruction to display superior balance control characteristics throughout acquisition and at retention relative to the internal focus and the control condition.

Congruent with our first hypothesis, those in the external focus displayed more favorable postural control characteristics during performance and at retention as measured by mean and SD velocity. This supports previous literature which has demonstrated superior balance performance when individuals adopt an external focus (Chiviacowsky et al., 2010; Jackson & Holmes, 2011; Landers et al., 2005; McNevin & Wulf, 2002; Shea et al., 1999; Wulf, Shea, et al., 2001). Further, this contributes to previous attentional focus literature (McNevin & Wulf, 2002; Wulf et al., 2003) as we have provided data extending the typical time frames of these studies to seven days. In conjunction with our second hypothesis that both groups would improve within and between days, both groups improved their performance from early to late trial blocks within each day, while also improving over the course of seven days. Importantly, however, those in the external focus group had greater improvements than those in the internal focus group, suggesting that attentional focus influences the trajectory in which novel motor tasks are learned. With no significant interactions, our data suggests that participants perform and learn at a superior rate when given external focus instruction.

Interestingly, however, similar results did not manifest when examining participants' balance control using SampEn. Specifically, no differences between the attentional focus conditions were observed for the structure of velocity complexity throughout performance or at retention. We did, however, find a block by day interaction for SampEn velocity that revealed significant reductions in SampEn velocity from early to late trial blocks. Following the framework proposed by Lipsitz (2002), reductions in SampEn reflect more rigid, patterned, and potentially less adaptive behavior. Our interpretation of this finding, however was task-dependent. Considering we also found reductions in mean and SD velocity from early to late trial blocks, we consider the reduction in SampEn velocity as an indicator that the system selected a patterned behavior as most appropriate for the novel task. For this task, participants may have started taking a patterned and rigid approach to reduce velocity and the magnitude of the variability to effectively keep the board (or their feet) level. This is an important contribution as it shows that learning a dynamic balance task using different instructional strategies influences the strategies performers adopt within a single training session.

One limitation of this study was that we did not have our control group practice the motor task with no focus instruction throughout the acquisition. We elected to do this, however, as we wanted to lay the foundation for longer training studies with similar control conditions that did not practice balance (e.g., Drijkoningen et al., 2015). We did not integrate any measure of muscular efficiency (e.g., EMG; Vance et al. 2004) to assess neuromuscular changes due to training. Follow up work, however, is warranted using these measurements, as well as extending this training to 2, 3, or 4 weeks. Future work could also examine variations in intensity or duration. For example, instead of completing 30 trials a day for 7 straight days, it would be interesting to increase the duration of training (e.g., 60 trials), but with longer rest periods between session (e.g., three times per week). It would also be important to integrate variations in practice schedules as this has been shown to interact with attentional focus (Raisbeck, Regal, Diekfuss, Rhea, & Ward, 2015).

Despite these limitations, this study makes two important contributions. First, our data supports the CAH and fills a gap in the literature by assessing balance performance and learning over the course of seven straight days. Classical attentional focus effects were confirmed supporting an external focus for training a dynamic balance task. Secondly, albeit our data did not reveal attentional focus differences for SampEn velocity, it furthered our understanding of how participants modify their dynamic balance strategy within-training sessions. Specifically, participants may adopt a patterned and rigid behavior to succeed with their respective instruction (feet or board level). The balance board used in this study is similar to a variety of attentional focus studies that have used stabilometer (e.g., Chiviacowsky et al., 2010) and it would be interesting to assess changes in SampEn on these or similar apparatuses. In conclusion, this research supports the use of an external focus for balance training and provides us with additional information pertaining to participants' postural control strategy within training sessions on a dynamic balance board.

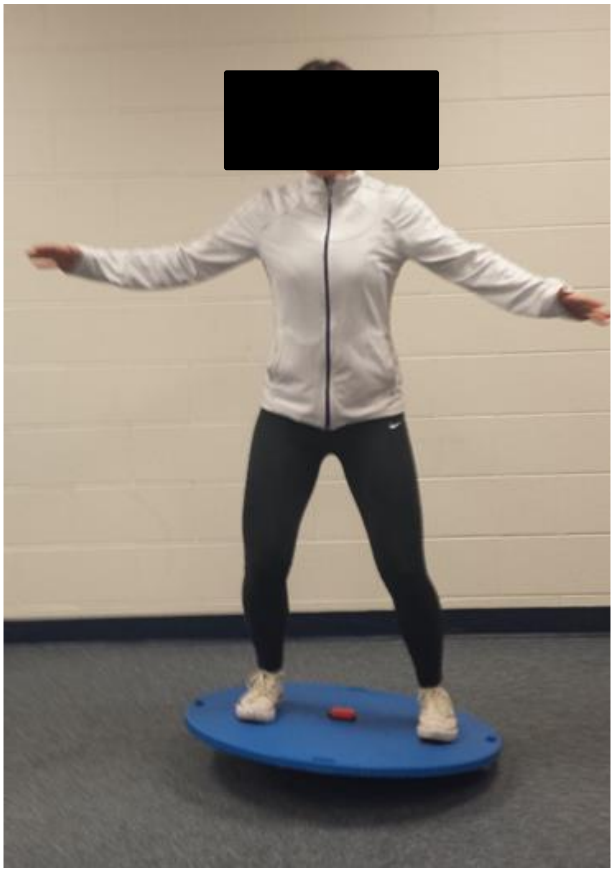

Figure 4.1. Balance Board and Inertial Measurement Unit.

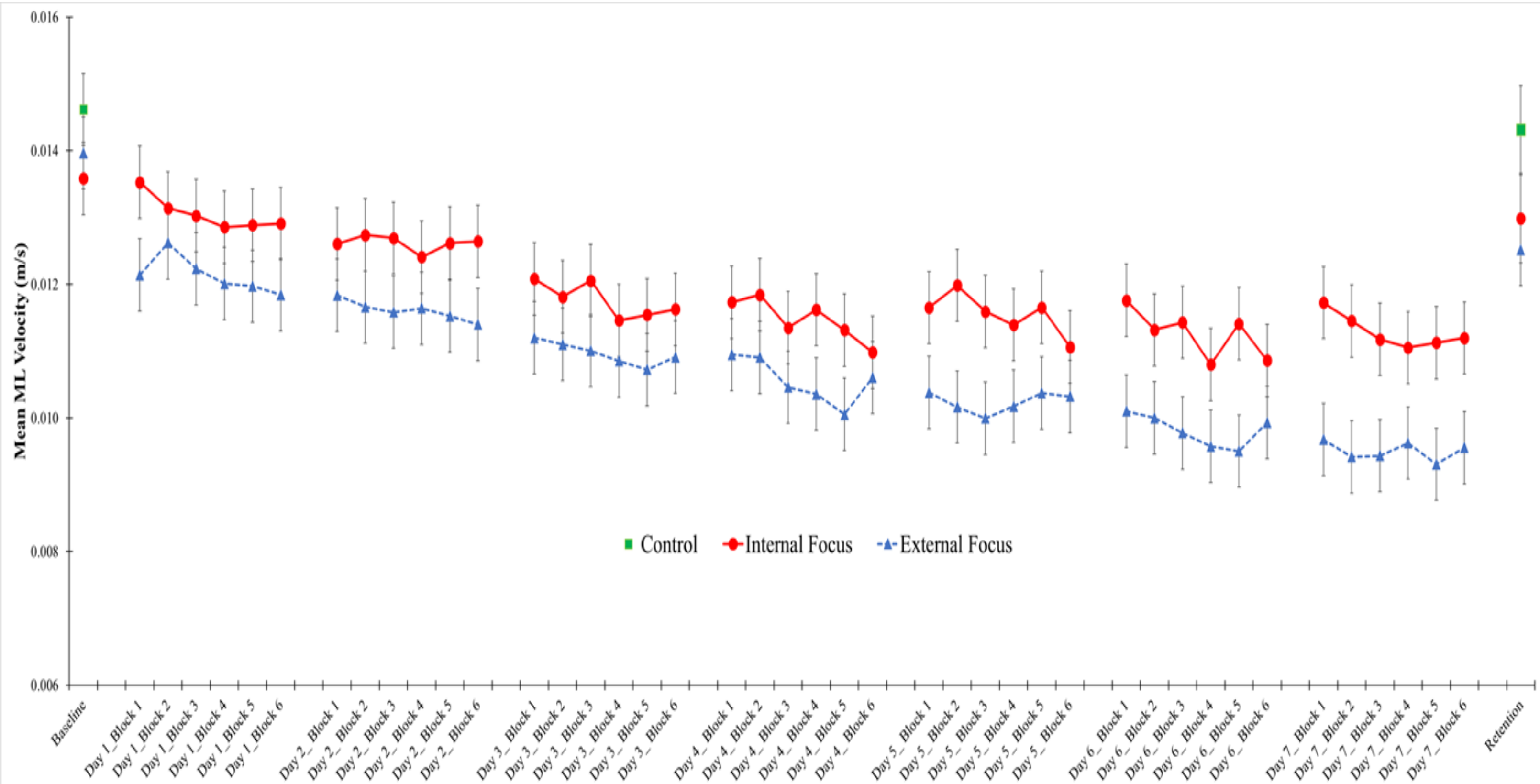

Figure 4.2. Mean Medial-lateral Velocity. Significant within-day and between-day effects with lower mean velocity from early to late trial blocks and early to late days, all $p < .05$. Significant main effect for condition throughout acquisition with a lower mean velocity for those in the external focus compared to the internal focus, $p < .05$. Significant main effect for condition at retention with a lower mean velocity for those in the external focus compared to the control, $p < .05$.

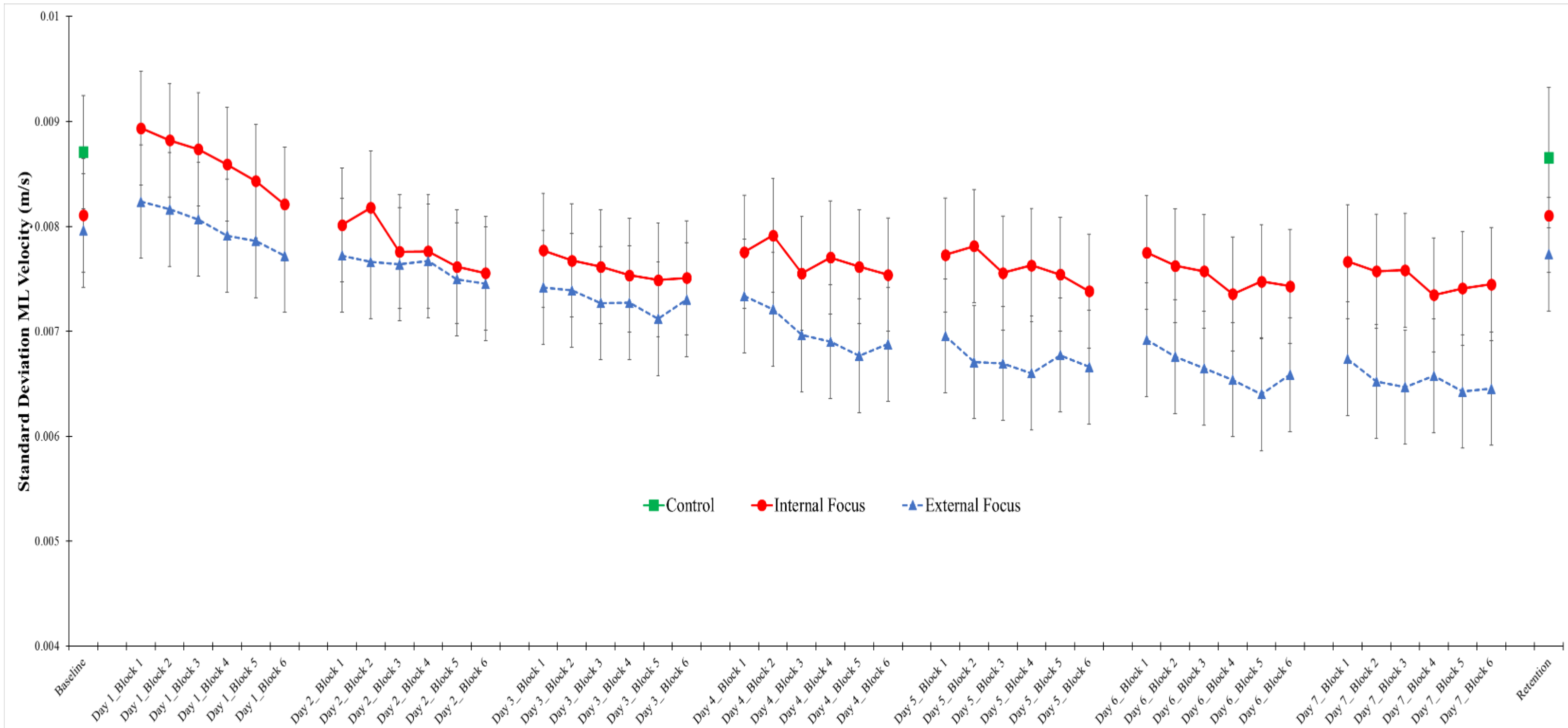

Figure 4.3. Standard Deviation (SD) Medial-lateral Velocity. Significant within-day and between-day effects with lower SD velocity from early to late trial blocks and early to late days, all $p < .05$. Significant main effect for condition throughout acquisition with a lower SD velocity for those in the external focus compared to the internal focus, $p < .05$. Significant main effect for condition at retention with a lower SD velocity for those in the external focus compared to the control, $p < .05$.

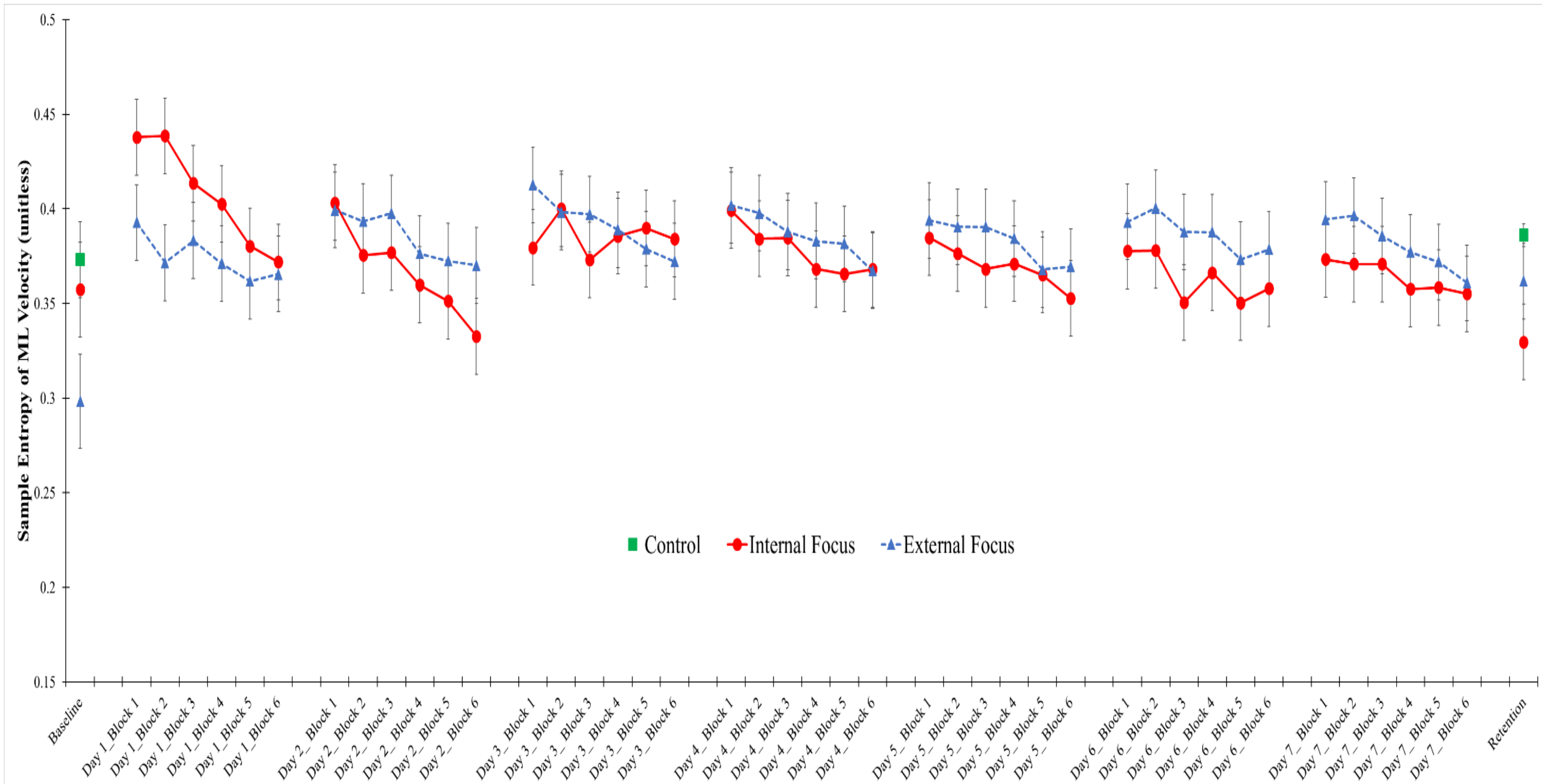

Figure 4.4. SampEn Medial-lateral Velocity. Significant block × day interaction (p < .05), with significant reductions in SampEn from early to late trial blocks for days 1, 2, 4, 5, 6, 7. No differences or interactions for the focus of attention, between days, or at retention, all $p > .05$.

CHAPTER V

MANUSCRIPT II

Title

The influence of attentional focus on resting-state brain connectivity following seven days of balance training.

Abstract

The purpose of this study was to examine the influence of attentional focus on resting-state brain connectivity. Participants were randomly assigned to a control (*n* = 11), internal focus (*n* = 11) or external focus (*n* = 11) condition. The internal and external focus groups practiced a dynamic balance task once a day for seven consecutive days while the control group did not complete any training. During training, participants in the internal focus condition were asked to, 'focus on keeping your feet level;' whereas, those in the external focus condition were asked to, 'focus on keeping the board level.' An inertial measurement unit was used to quantify changes in balance control and functional magnetic resonance imaging (fMRI) was used to collect resting-state data prior to (baseline) and following training (retention) for all three groups. Results revealed that both training groups improved balance control, with superiority evidenced for those in the external focus condition. Our data also revealed that those in the external focus group displayed less correlated brain activity amongst motor and sensory regions at the

retention test compared to baseline. While some similar connectivity results were exhibited for the internal focus group, this group showed increased correlated brain activity at the retention test between motor and sensory regions. We discuss these findings in the context of OPTIMAL theory, the constrained-action hypothesis, and the self-invoking trigger hypothesis.

Introduction

There is a strong association between motor learning, the relatively permanent changes in skilled behavior due to practice (Schmidt & Wrisberg, 2005), and neuroplasticity, changes in brain structure and (or) function (Chang, 2015). Evidence supports the concept that the human brain is capable of changing its structure (Jäncke et al., 2009; Pascual-Leone et al., 2005; Zilles, 1992) and can occur from specialized training (e.g., Amad et al., 2016). A classic study by Draganski et al. (2004) revealed that three months of juggling increased grey matter density in the intraparietal sulcus and the midtemporal area of the visual cortex relative to a control group. Similarly, 15 months of musical instrument training increased grey matter density in the precentral gyrus (Hyde et al., 2009) and 40 hours of golf training increased grey matter in various sensorimotor regions (Bezzola et al., 2011).

In addition to structural brain changes following training, there is accumulating evidence that there are functional changes within the brain attributed to motor learning (Albert et al., 2009). One specific area that has received considerable attention is resting-state brain connectivity (Biswal et al., 1995; Greicius et al., 2003), which refers to temporal correlations of spontaneous low frequency fluctuations of the blood oxygen dependent level (BOLD) signal between different brain regions at rest. Brain regions are believed to correlate at rest following a history of coactivation during active states (Corbetta, 2012), which in turn allows for the assessment of training-related changes in brain function in the resting-state (Lowe, 2012). Numerous studies exist pertaining to the effects of motor training on brain function (Ma et al., 2011; Vahdat et al., 2011) ranging from discrete fine motor tasks such as chopstick handling (Yoo et al., 2013) and finger pressing (e.g. (Floyer-Lea et al., 2006) to more complex tasks like balance board training (Taubert et al., 2011) and multimodal tasks that include both motor and cognitive training (Demirakca et al., 2015). This accumulating evidence suggests that the brain is functionally malleable and can change in response to the demands placed on the individual.

Recently, focus of attention has been theorized to contribute to the changes in resting-state brain connectivity (Wulf & Lewthwaite, 2016). Defined by Wulf et al. (1998), an internal focus directs an individual's attention towards movement execution, whereas an external focus directs an individual's attention towards the effects of his or her movement. For example, asking participants to focus on the 'flight of the dart' (an external focus) can improve dart throwing performance and learning relative to focus directed towards the hand (Lohse et al., 2010). The constrained action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001) suggests that an internal focus disrupts proceduralized knowledge by consciously interfering with automatized motor programs, whereas an external focus permits movement automaticity by allowing more reflexive behavior. The consensus is that an external focus permits more effective (Chiviacowsky et al., 2010; McKay & Wulf, 2012; McKay et al., 2015) and efficent movement (Stoate & Wulf, 2011; Zachry et al., 2005) with over 15 years of data to support (see Wulf, 2007 and 2013 for reviews).

Per OPTIMAL theory (optimizing performance through intrinsic motivation and attention for learning; Wulf & Lewthwaite, 2016), an external focus is a key contributor to enhanced learning by strengthening the coupling of goals with actions. Specifically, an external focus not only directs attention to the task and goal, but reduces the focus on one's self. Wulf and Lewthwaite (2016) theorized that an external focus aids in the development of more effective neural connections, partially based on the data comparing brain activity and networks of novice and expert performers (Di et al., 2012; Kim et al., 2015; Kim et al., 2014; Milton et al., 2007). While comparing brain connectivity in expert and novice performers is a plausible way to distinguish differences due to experience, this does not account for attentional focus. Current data suggests that athletes at both the Olympic (Porter, Wu, et al., 2010) and collegiate levels (Diekfuss & Raisbeck, 2016) minimally report using an external focus, which makes it difficult to conclude whether an external focus does in fact alter brain connectivity. Further, there are limited studies examining brain activity in conjunction with attentional focus (Zentgraf et al., 2009; Zimmermann et al., 2012), but these studies used task-based paradigms that minimize our understanding of attentional focus training on resting-state connectivity.

The purpose of this study was to extend OPTIMAL theory by directly examining the influence of attentional focus on resting-state brain connectivity. Since the majority of attentional focus literature has used balance tasks (Chiviacowsky et al., 2010; Laufer et al., 2007; Rotem-Lehrer & Laufer, 2007; Wulf et al., 1998, 2004; Wulf, Töllner, et al., 2007), with training sessions typically under one week (Chiviacowsky et al., 2010; Wulf et al., 1998, 2003), we elected to have participants learn a complex balance task over the course of one full week (seven days) while manipulating their attentional focus. To contribute to this area of research, we used functional magnetic resonance imaging (fMRI) to examine participants' resting-state brain connectivity prior to and after the training period. To our knowledge, no research has examined attentional focus training on resting-state brain connectivity which would make specific brain region predictions inappropriate. While it has been suggested that a history of coactivation during active states may increase connectivity at rest (Corbetta, 2012), we felt that the rich literature revealing that an external focus allows for more automatic and reflexive behavior would (1) lessen the amount of correlated brain activity amongst various motor and sensory regions, while improving balance performance, relative to those who did not undergo training (control). In contrast, since an internal focus is theorized to constrain the motor system (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001) and believed to elicit neural representations of one's self (McKay et al., 2015), we hypothesized (2) increased correlated brain activity for those training with an internal focus between various motor and sensory regions, with less improvements in balance performance, when comparing the retention test with their baseline test relative to the control group.

Methods

Participants

Thirty-three healthy participants (16 males, age = 23.0 ± 3.7 yrs, height = 175.9 ± 5.8 cm, mass = 74.0 ± 12.7 kg; 17 females, age = 22.6 ± 3.9 yrs, height = 164.8 ± 6.0 cm, mass = 62.0 ± 10.6 kg) volunteered to participate in this study. Inclusion criteria included no lower extremity injury in the last 6 months, the right hand the preferred writing hand, and the left leg being the preferred stance limb when kicking a ball. Participants were excluded if they had: 1) a previous history of injury to the capsule, ligament, or menisci of either knee, 2) any inner ear or balance disorder, 3) any metal or implanted medical device in the body that would be a contradiction to MRI assessment, 4) undergone a previous balance training program, 5) were taking any medications that would affect balance, or 6) any neurological disorders. The institutional ethics committee approved the project and informed consent was obtained prior to commencing the study.

Training and Experimental Procedure

Participants were randomly assigned to a control (n = 11), internal focus (n = 11), or external focus condition (n = 11). Participants in the internal and external focus condition were trained on a dynamic balance board (CanDo ®, NY, USA) once a day for seven consecutive days Each training session was separated by 24 hours and consisted of six blocks of five separate 30-second trials (30 balance trials total per day). A 30-second rest was given between trials and a two-minute break was given between each block. To manipulate attentional focus, participants in the internal focus condition were asked to, '*focus on keeping your feet level;'* whereas, those in the external focus condition were asked to, '*focus on keeping the board level.'* Participants in the control condition did not complete any training. Balance control was assessed via an inertial measurement unit (IMU; Xsens; Xsens Technology, MA, USA) attached to the center of the board which captured changes in medial-lateral velocity at a rate of 100hz (see Figure 5.1).

Neuroimaging for the internal and external focus conditions were performed one day prior to training (day one; baseline) and 24 hours after the last training session (day nine; retention). The same time frame for neuroimaging was used for those in the control condition (scans separated by seven days). Additionally, we asked all participants, including the control condition, to perform five trials on the dynamic balance board on day one and day nine to quantify behavioral changes. To assess the effects of attentional focus on learning, we averaged the mean medial-lateral velocity for the five trials and conducted a 3 (condition; control, internal focus, external focus) x 2 (time: baseline, retention) mixed ANOVA with repeated measures on the last factor. Results revealed a main effect for time, F (1.00, 30.00) = 4.40, $p < .05$, partial $\eta 2 = .13$, with participants reducing their medial-lateral velocity from baseline to retention. While no significant interaction was present, we elected to perform a univariate ANCOVA with condition (control, internal focus, external focus) as the between-subjects factor to account for individual differences in balance control at baseline. Results revealed a main effect for condition F (2.00, 29.00) = 4.21, $p < .05$, partial $\eta 2 = .23$, with post hoc analyses revealing lower mean velocity for those in the external focus compared to the control ($p < .05$). No significant differences were observed when comparing the external focus to the internal focus or the internal focus to the control (all $p > .05$; see Figure 5.2).

Scanning Protocol and fMRI Preprocessing

All scans were performed on a 3.0 T magnetic resonance imaging scanner using a 12-channel head coil (Siemens Tim Trio; Erlangen, Germany). First, a T1-weighted structural image was obtained using the following parameters: TR = 2000 ms; TE = 4.58ms, matrix field of view = 256mm; flip angle = 7°, voxel size = 1 × 1 × 1mm. Next, fMRI data was acquired with the following parameters: TR = 3000ms, TE = 28ms, matrix field of view = 212mm, flip angle = 73°, bandwidth = 2520 Hz, acquisition matrix = 64 × 64, slice thickness=3.3 mm, voxel dimensions = 3.3 × 3.3 × 3.3 mm, 48 slices, interleaved slice ordering. Participants were asked to look at a cross, remain motionless, and let their mind wander; the total time of the resting-state fMRI session was approximately 5.5 minutes. Preprocessing of fMRI data included slice-timing correction and realignment using the Statistical Parametric Mapping (SPM) 8 package (Wellcome Institute of Cognitive Neurology, London). Functional volumes were co-registered and re-sliced to a voxel size of 2 mm^3, normalized to the MNI template brain (Montreal Neurological Institute), and smoothed with an 8 mm3 isotropic Gaussian kernel.

Resting-State Connectivity Analyses

Resting-state connectivity analyses were implemented in MATLAB using the CONN toolbox (http://www.nitrc.org/projects/conn; Whitfield-Gabrieli & Nieto-Castanon, 2012). CONN implemented the CompCor method (Behzadi et al., 2007) to identify principal components associated with segmented cerebrospinal fluid (CSF) and white matter (WM). CSF, WM, and realignment parameters were entered as confounds in a first-level analysis (Behzadi et al., 2007) and the data was band-pass filtered to .008 Hz

- .09 Hz. The global signal was not regressed as CompCor addresses the confounding effects of subject movement without affecting intrinsic connectivity (Chai et al., 2012).

We then conducted exploratory region of interest (ROI) analyses to test our hypotheses that resting-state connectivity would change from baseline to retention for those undergoing training (internal and external focus). Specifically, to test our hypotheses that resting-state connectivity would change between motor and sensory regions, we conducted three separate paired-samples *t* tests that contrasted participants resting-state connectivity at retention relative to baseline (retention > baseline) for the internal focus, external focus, and control groups. Following Demirakca et al. (2015), we only report differences in connectivity for the training groups that were not present in the control group. This was to account for any changes in resting-state connectivity due to anxiety, stress, etc. from MRI scanning – we wanted to isolate changes associated to the training. ROI-to-ROI results are reported when significant at a level of p <.05 false discovery rate (FDR) corrected (Chumbley et al., 2010)

Results

External Focus

Significant differences in retention resting state connectivity relative to baseline resting-state connectivity for the external focus condition that were not present in the control group are reported in table 5.1 with a visual representation depicted in Figure 5.3.

Internal Focus

Significant differences in retention resting state connectivity relative to baseline resting-state connectivity for the internal focus condition that were not present in the control group are reported in table 5.2 with a visual representation depicted in Figure 5.4.

Discussion

This study investigated the impact of training with attentional focus on resting-state brain connectivity. The training consisted of a dynamic balance task similar to previous balance training literature (Taubert et al., 2010, 2016) in which participants learned the task over seven consecutive days while using an internal or external focus. The training groups improved their balance performance from baseline to retention, with classical attentional focus effects revealing superior performance for those in the external focus condition. The contribution of this study is the examination of changes in resting-state brain connectivity for those training with an internal or external focus relative to a control group.

Results for the external focus training group revealed significantly less correlated brain activity between a variety of motor (e.g., cerebellum) and sensory regions (e.g., occipital pole) when comparing their connectivity at the retention test relative to the baseline test. Our data revealed that the cerebellum 6 had significantly less correlated brain activity between the salience and visual network (bilaterally) and the left and right occipital pole. While the cerebellum has been attributed to a wide range of cognitive operations (Stoodley, 2012), it is highly involved in posture and balance stability (Morton & Bastian, 2004) which was specifically challenged in our study. Vision is one of the primary senses used to control balance (Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989) and our data revealed less correlated activity with the occipital pole, a region highly associated with vision (Epstein & Kanwisher, 1998; Grill-Spector et al., 1998; Winawer, Horiguchi, Sayres, Amano, & Wandell, 2010). The less correlated activity between the cerebellum and the visual network, specifically in the occipital pole, suggests that participants may have become less reliant on vision throughout the course of training. This is an important contribution as vision is a highly-debated topic within the attentional focus literature (Abdollahipour et al., 2016; Porter et al., 2016). Our results suggest that balance training using an external focus may lessen the functional connection between motor regions and visual regions as novel skills are learned. Similarly, we found significantly less correlated brain activity between the cerebellum 10 with the caudate nucleus at the retention test. The caudate plays a role in coordinating body limbs and posture (Villablanca, 2010) and supports the notion that motor and visual regions may become less correlated following external focus training. There was also significantly less correlated brain activity between the temporal occipital fusiform cortex and Heschl's gyrus. The temporal occipital fusiform cortex plays a role in integrating sensory information from the environment (Bracci, Caramazza, & Peelen, 2015) and Heschl's gyrus processes auditory sensory information (Da Costa et al., 2011), further suggesting that training with an external focus may minimize correlated activity of sensory systems at rest and may play a role in improving balance performance.

Like the external focus training group, and not initially predicted, the internal focus training group exhibited some similar neurophysiologic changes, particularly in cerebellar regions. Our results revealed significantly less correlated brain activity at the retention test relative to baseline between the anterior cerebellar network and the right planum polare, left and right central opercular cortex, and frontal medial cortex (bilateral). The planum polare is associated with auditory processing (Keenan, Thangaraj, Halpern, & Schlaug, 2001), the opercular cortex is linked with volitional movement (Hamdy, 2006), and the frontal medial cortex is linked with memory and decision making (Euston, Gruber, & McNaughton, 2012). Further, there was significantly less correlated activity at the retention test relative to baseline for the internal focus group between the temporal gyrus and the parietal operculum cortex and lateral occipital cortex and less correlated activity between the cerebellum 6 and the vermis 9, and between specific lobes of the cerebellum (cyrus 2 and cerebellum 8). We attribute these changes in resting-state connectivity to the improvements in balance control for those in the internal focus condition. Albeit this group was not significantly greater (i.e., less medial-lateral velocity) than the control or external focus group at the retention test, our evidence suggests that learning a complex motor skill, regardless of the focus of attention, changes resting state-connectivity and contributes to the growing evidence that motor learning changes the brain (Amad et al., 2016; Demirakca et al., 2015).

Congruent with our second hypothesis, our results revealed increased positively correlated activity between a variety of motor and sensory regions. Our data demonstrated increased connectivity at the retention test relative to baseline for the internal focus group between the cuneal cortex and the central opercular cortex and caudate nucleus. The caudate nucleus has received considerable attention within obsessive-compulsive disorder (OCD) research (Baxter et al., 1992; Szeszko et al., 2004; Whiteside, Port, & Abramowitz, 2004) as this region is believed to play a role in the excessive worry and obtrusive thoughts characterized by this disorder. This directly contributes to the self-invoking trigger hypothesis (McKay et al., 2015) which theorizes that an internal focus engages self-regulatory processes, neural access to the self, and self-evaluation. Our data suggest that training with an internal focus may activate this region throughout training, ultimately increasing correlated connectivity with regions attributed to volitional control (e.g., opercular cortex) and vision (cuneal cortex).

Further, our data revealed increased correlated activity between the left inferior frontal gyrus and the middle temporal gyrus and supramarginal gyrus for the internal focus training group. Both the left inferior frontal gyrus and middle temporal gyrus are associated with cognitive operations (Cabeza & Nyberg, 2000) with the left inferior frontal gyrus also contributing to inhibitory control (De Zubicaray, Andrew, Zelaya, Williams, & Dumanoir, 2000; Kawashima et al., 1996; Konishi et al., 1999) and the middle temporal gyrus also contributing to language and semantic memory (Chao, Haxby, & Martin, 1999; Tranel, Damasio, & Damasio, 1997). Considering that an internal focus is thought to constrain the motor system (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001), and the minimal improvements in balance performance for the internal focus group, this data suggests that an internal focus may engage self-regulatory control processes, disrupting proceduralized knowledge, and ultimately changing the brain’s correlated brain activity at rest.

Limitations from this study should be considered before concluding that attentional focus training makes changes within the brain's connectivity at rest. First, this study did not assess any brain activity throughout training, thus we cannot conclude that the regions with differing correlated activity at rest are due to areas coactivating (or deactivating) during training. Secondly, while participants were scanned at the same time of day for the baseline and retention scans, there is variability within a single resting-state run (Allen et al., 2012; Hutchison et al., 2013) and resting-state connectivity can be affected by participants keeping their eyes open or closed (Patriat et al., 2013). We attempted to control for this by providing all participants the same instruction and had participants look at a cross to keep participants' eyes open during both scans. Third, we did not directly contrast the internal focus with the external focus group at baseline and retention, but compared each group's changes from baseline to retention that were not evident in the control group. We elected this approach as it minimized interindividual differences amongst the groups for our relatively low sample size and for congruency with other research (Demirakca et al., 2015).

Despite these limitations, this study makes multiple contributions to the attentional focus and neurophysiology literature. First, this data directly complements OPTIMAL theory (Wulf & Lewthwaite, 2016) by providing neurophysiologic changes in the brain following balance training with an internal and external focus. Secondly, it contributes to both the self-invoking-trigger hypothesis and constrained-action hypothesis by providing data that an external focus may decrease correlated activity between motor and sensory regions, whereas an internal focus may increase correlated brain activity between these regions. This also contributes to the motor learning and resting-state connectivity research (Amad et al., 2016; Taubert et al., 2010, 2011, 2016) by revealing that instruction provided during training may influence changes. Lastly, we are careful to point out that this data only examined changes in correlated brain activity amongst different regions at rest, we did not examine any changes in network patterns. Network science is a growing discipline used to characterize brain structure and function (Börner, Sanyal, & Vespignani, 2007) that could be invaluable to our understanding of attentional focus on motor performance. Future work is warranted using techniques such as graph theory (see Bullmore & Sporns, 2009) to better understand the configuration of participants' brain networks following attentional focus training. Regardless of the analytical techniques used, this is the first study to examine changes in brain connectivity at rest following a specialized attentional focus training paradigm.

Figure 5.1. Balance Board and Inertial Measurement Unit.

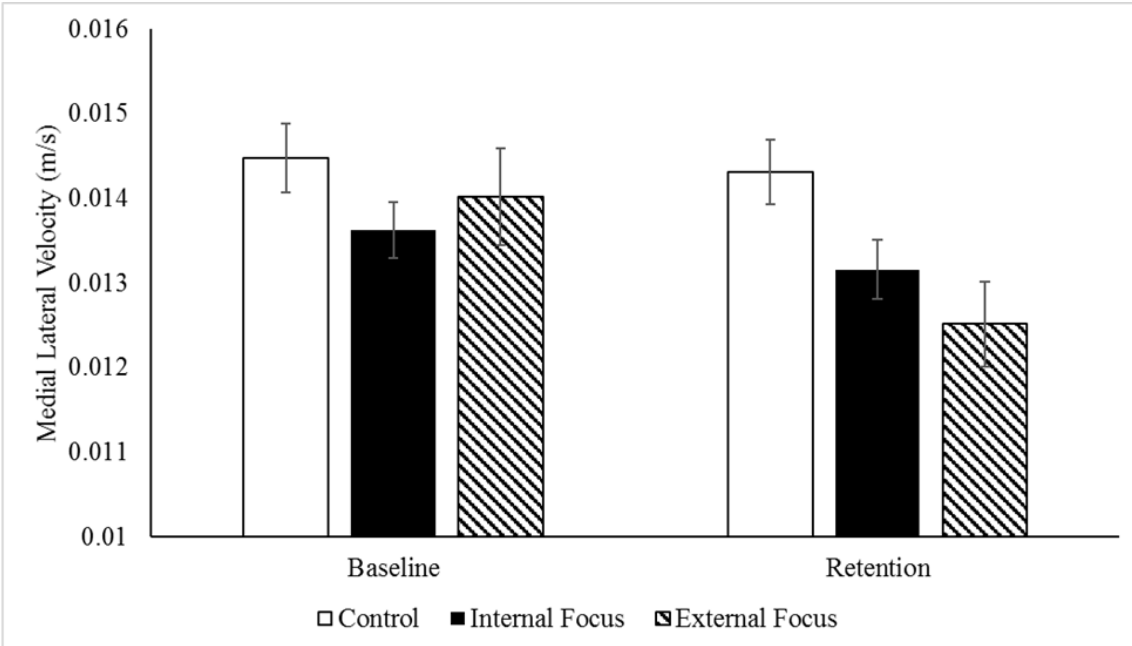

Figure 5.2. Behavioral Data Before (Baseline) and After (Retention) Training. Main effect for time with improvements in balance control (reductions in medial-lateral velocity) from baseline to retention ($p < .05$). Additional analyses revealed that those in the external focus condition had significantly lower medial-lateral velocity at retention compared to the control ($p < .05$).

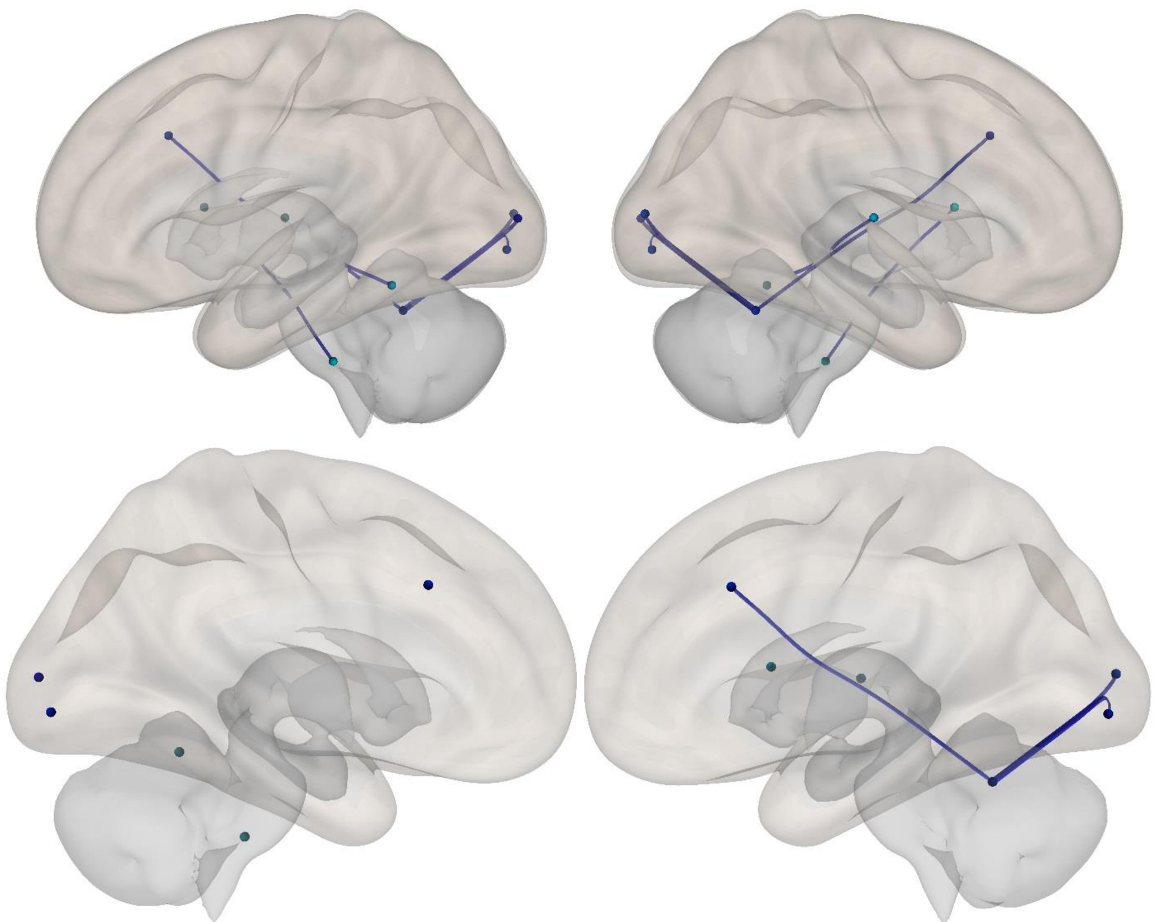

Figure 5.3. Resting-state Connectivity Differences for the External Focus Group. Retention > baseline contrast differences that were not present in the control group. Blue lines indicate significantly less correlation (*p* < .05; false discovery rate corrected)**.**

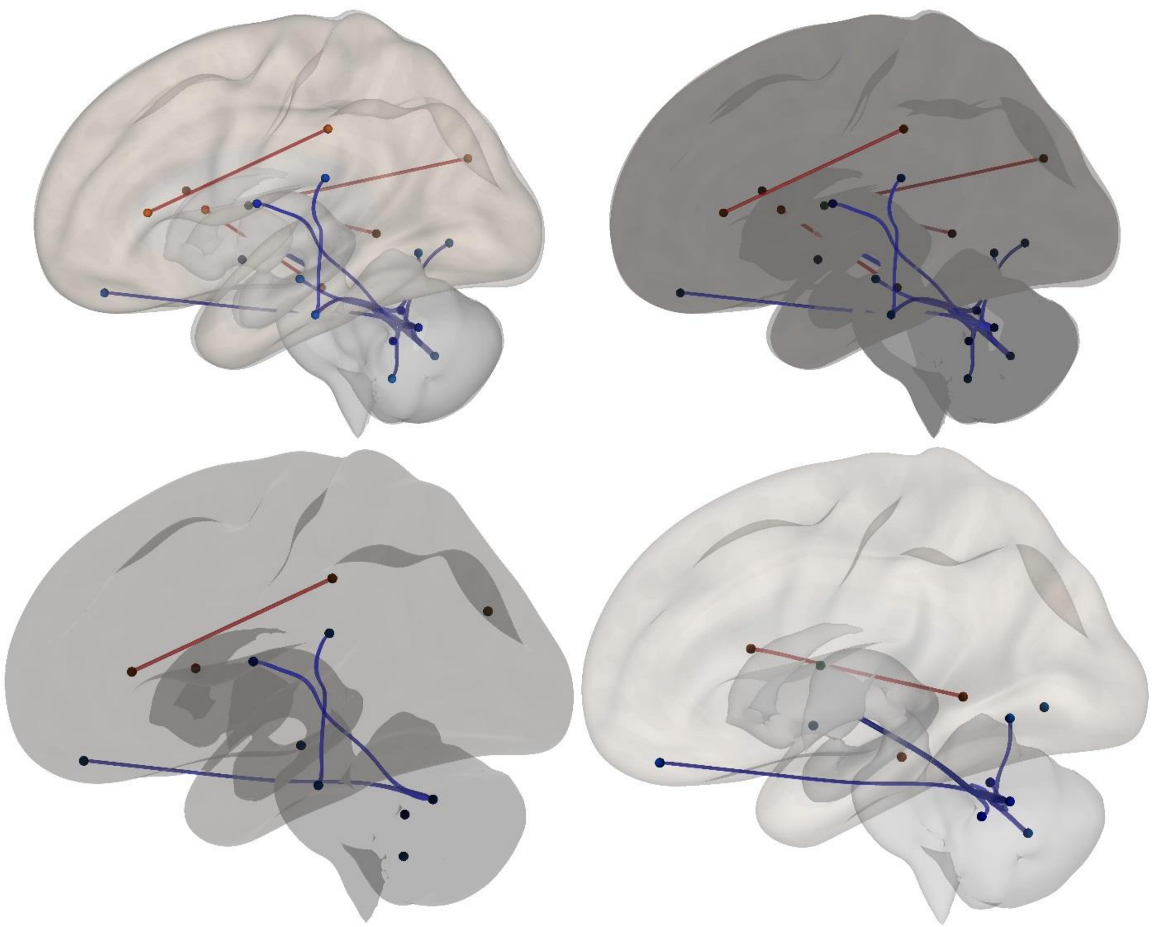

Figure 5.4. Resting-state Connectivity Differences for the Internal Focus Group. Retention > baseline contrast differences that were not present in the control group. Red lines indicate significantly higher correlations (*p* < .05; false discovery rate corrected). Blue lines indicate significantly less correlation (*p* < .05; false discovery rate corrected).

Table 5.1. Resting-state Connectivity Differences for the External Focus Group. Retention > baseline contrast differences that were not present in the control group.

Network 1	Seed Hemisphere	Result Region	Result Hemisphere	t (10)	p-FDR	p uncorrected
Cerebellum 6	Right	Salience Network (Anterior Cingulate Cortex)	Bilateral	-4.99	0.0401	0.0005
		Visual Network (Ventral)	Bilateral	-4.92	0.0401	0.0006
		Occipital Pole	Right	-4.74	0.0401	0.008
		Occipital Pole	Left	-4.6	0.0401	0.001
Network 2						
Cerebellum 10	Left	Caudate	Right	-6.12	0.0183	0.001
Network 3						
Temporal Occipital Fusiform Cortex	Left	Heschl's Gyrus	Right	-5.4	0.0491	0.0003

Table 5.2. Resting-state Connectivity Differences for the Internal Focus Group. Retention > baseline contrast differences that were not present in the control group.

Seed Region	Seed Hemisphere	Result Region	Result Hemisphere	*t*	p-FDR	p uncorrected
Network 1						
Cuneal Cortex	Left	Central Opercular Cortex	Right	5.49	0.0427	0.0003
Cerbellar Network (Anterior)	Bilateral	Planum Polare	Right	-5.6	0.0373	0.0002
		Central Opercular Cortex	Left	-5.14	0.0285	0.0004
		Central Opercular Cortex	Right	-5.02	0.0285	0.0005
		Frontal Medial Cortex	Bilateral	-4.46	0.0497	0.0012
Network 2						
Inferior Temporal Gyrus, Posterior Division	Left	Parietal Operculum Cortex	Left	-5.42	0.0476	0.003
		Lateral Occipital Cortex, Inferior Division	Right	-5.1	0.0378	0.005
Network 3						
Cerebellum Crus2	Right	Lingual Gyrus	Right	-5.36	0.028	0.003
		Cerebellum 8	Left	-5.23	0.028	0.004
		Hippocampus	Left	-5.03	0.028	0.005
Network 4						
Inferior Frontal Gyrus, Pars Opercularis	Right	Middle temporal Gyrus, Temporoccipital part	Right	6.04	0.0205	0.0001
Network 5						
Cerebellum 6	Right	Vermis 9	Bilateral	-5.98	0.022	0.001
Network 6						
Supramarginal Gyrus, Anterior Division	Left	Inferior Frontal Gyrus, Pars Triangularis	Left	5.81	0.0278	0.0002
Network 7						
Caudate	Left	Cuneal Cortex	Left	5.49	0.0434	0.0003

CHAPTER VI

MANUSCRIPT III

Title

The influence of attentional focus on fractional anisotropy following seven days of balance training.

Abstract

The purpose of this study was to examine the influence of attentional focus on white matter integrity within the human brain. Participants were randomly assigned to a control (n = 11), internal focus (n = 11) or external focus (n = 11) condition. The internal and external focus groups practiced a dynamic balance task once a day for seven consecutive days while the control group did not complete any training. During training, participants in the internal focus condition were asked to, 'focus on keeping your feet level;' whereas, those in the external focus condition were asked to, 'focus on keeping the board level.' An inertial measurement unit was used to quantify changes in balance control and functional magnetic resonance imaging was used to collect diffusion-weighted data prior to and following training for all three groups. We calculated percent change scores for balance performance and fractional anisotropy (a metric to quantify water diffusion with a brain voxel) within the frontal pole, precentral gyrus, and lingual gyrus and compared the resulting values using Pearson product correlations. While our

results did not reveal any significant relationships, these data make an important contribution as longer training programs or more rest may be needed to induce structural changes.

Introduction

The adult human brain is highly responsive to learning and is capable of changing its structure and function (Jäncke, 2009; Pascual-Leone et al., 2005; Zilles, 1992). Structural adaptations, specifically grey and white matter alterations can be observed after intensive long-term motor training (Draganski et al., 2004; Scholz et al., 2009) and functional changes, such as alterations in brain connectivity, have been documented following extended periods of motor skill training (Amad et al., 2016; Demirakca et al., 2015). Experience-dependent behavioral changes are associated with the formation of new synaptic connections and dendritic spine growth (DeBello, 2008; Trachtenberg et al., 2002; Xu et al., 2009) suggesting that the brain is malleable and highly plastic. Further, there is growing evidence that the brain may reorganize following a traumatic injury to the anterior cruciate ligament (Grooms et al., 2015), indicating a need for appropriate motor learning paradigms to not only improve biomechanical function, but also brain function and structure.

One area of motor behavior that has received considerable attention within the realm of rehabilitation is an external focus of attention (Benjaminse & Otten, 2011). Defined by Wulf et al. (1998), an external focus directs an individual’s attention towards the effects of his or her movement, whereas an internal focus directs an individual’s attention to the movement itself. For example, asking individuals who recently underwent

ACL reconstruction to adopt an external focus during a single-leg hop task produced safer landing mechanics relative to an internal focus (increased knee flexion; Gokeler et al., 2015). The constrained action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001) proposed that an external focus permits movement automaticity by allowing more reflexive behavior, whereas an internal focus disrupts proceduralized knowledge by consciously interfering with automatized motor programs. The behavioral and biomechanical improvements attributed to an external focus have been highly replicated in tasks such as golf (Wulf & Su, 2007), dart throwing (McKay & Wulf, 2012; McKay et al., 2015), virtual pistol shooting (Raisbeck & Diekfuss, 2016), and balance (McNevin et al., 2003).

Per OPTIMAL theory (optimizing performance through intrinsic motivation and attention for learning; Wulf & Lewthwaite, 2016) an external focus is a major component for optimizing skilled learning. Wulf and Lethwaite (2016) suggested that optimizing learning (i.e., using an external focus) may alter brain structure through synaptogenesis processes associated with dopamine changes. Long-term potentiation at the cellular level (Ashby & Isen, 1999; Shohamy & Adcock, 2010) and consolidation of motor memories from motor practice (Sugawara, Tanaka, Okazaki, Watanabe, & Sadato, 2012) have all been attributed to the motivational properties associated with dopamine. Considering an external focus facilitates motivation and increases dopamine (Wulf & Lewthwaite, 2016), and motor learning (without an external focus) alters brain structure (Draganski et al., 2004; Taubert et al., 2010, 2011), we reason that that motor training *with an external focus* may affect brain neuroplasticity.

We have previously reported the influence of a short-term balance training paradigm utilizing an external focus on resting-state brain connectivity (chapter 5). Briefly, our results showed that those in the external focus group displayed less correlated brain activity amongst motor and sensory regions at the retention test compared to baseline. We suggested that training with an external focus may lessen the reliance of the visual system and influence the connectivity between motor and visual regions at rest. While this provides the first information related to changes in brain function related to training with an external focus, we did not examine brain structure, nor did we directly tie changes in the brain with changes in performance Correlating changes in performance with changes in brain structure would provide more holistic neurophysiologic picture pertaining to the effects of balance training on neuroplasticity.

Using a diffusion MRI framework, diffusion tensor imaging (DTI) can be used to show tissue density and organization in white matter (Assaf & Pasternak, 2008). One commonly used parameter is fractional anisotropy (FA), which provides a simple and robust way to assess anisotropic diffusion with a brain region (Pfefferbaum et al., 2000) by quantifying the directionality of water diffusion within a voxel (Mori & Zhang, 2006). The diffusion of water molecules is constrained to the direction of fiber bundles allowing for fiber tracking algorithms to calculate length and orientation. FA is high in brain regions with high white matter organization, such as the corpus callosum, but FA is low in areas that consist of free fluid (e.g., cerebral spinal fluid). Typically, higher FA values are attributed to white matter integrity (Alexander et al., 2007) and FA positively correlates with executive function (O’Sullivan et al., 2004b); however, with respect to motor learning, decreases in FA are evidenced in highly trained musicians (Imfeld et al., 2009) and negative relationships between FA and balance improvements have been observed (Taubert et al., 2010), possibly due to plastic changes within the axonal membrane.

To our knowledge, minimal research has examined the influence of an external focus on FA in any brain region. The purpose of this study was to examine the influence of attentional focus on FA. To examine this, we asked participants to learn a complex balance task over seven straight days while using an internal or external focus of attention. We used DTI to examine the percent change in FA (baseline to retention) and its relationship with participants' percent change in balance performance via correlational analyses. Following Taubert et al. (2010), we predicted a significant negative relationship between percent change in FA in the prefrontal cortex and percent change in balance performance for those in the external focus condition (decrease in FA and increase in balance performance). We predicted no significant relationships for those learning the balance task with an internal focus or for our control group. Lastly, and somewhat exploratory we examined percent change in FA with percent change in balance performance in the precentral gyrus (M1) as this region contributes to motor control (Rao et al., 1993) and the lingual gyrus as this visual region showed changes in resting-state connectivity following attentional focus training (chapter 4) and was active during our previous task-based paradigms using attentional focus (Raisbeck et al., under review).

Methods

Participants

Thirty-three healthy participants (16 males, age = 23.0 ± 3.7 yrs, height = 175.9 ± 5.8 cm, mass = 74.0 ± 12.7 kg; 17 females, age = 22.6 ± 3.9 yrs, height = 164.8 ± 6.0 cm, mass = 62.0 ± 10.6 kg) volunteered to participate in this study. Inclusion criteria included no lower extremity injury in the last 6 months, the right hand the preferred writing hand, and the left leg being the preferred stance limb when kicking a ball. Participants were excluded if they had: 1) a previous history of injury to the capsule, ligament, or menisci of either knee, 2) any inner ear or balance disorder, 3) any metal or implanted medical device in the body that would be a contradiction to MRI assessment, 4) undergone a previous balance training program, 5) were taking any medications that would affect balance, or 6) any neurological disorders. The institutional ethics committee approved the project and informed consent was obtained prior to commencing the study.

Training and Experimental Procedure

Participants were randomly assigned to a control (*n* = 11), internal focus (*n* = 11), or external focus condition (*n* = 11). Participants in the internal and external focus condition were trained on a dynamic balance board (CanDo ®, NY, USA) once a day for seven consecutive days Each training session was separated by 24 hours and consisted of six blocks of five separate 30-second trials (30 balance trials total per day). A 30-second rest was given between trials and a two-minute break was given between each block. To manipulate attentional focus, participants in the internal focus condition were asked to, '*focus on keeping your feet level;'* whereas, those in the external focus condition were asked to, '*focus on keeping the board level.'* Participants in the control condition did not complete any training. Balance control was assessed via an internal measurement unit (IMU; Xsens; Xsens Technology, MA, USA) attached to the center of the board which captured changes in medial-lateral velocity at a rate of 100hz (see Figure 6.1). Training data is presented elsewhere (Chapter 4).

Neuroimaging for the internal and external focus conditions were performed one day prior to training (day one; baseline) and 24 hours after the last training session (day nine; retention). The same time frame for neuroimaging was used for those in the control condition (scans separated by seven days). Additionally, we asked all participants, including the control condition, to perform five trials on the dynamic balance board on day one and day nine to quantify behavioral changes. To determine the percent change in balance performance, we averaged the five trials on the baseline and retention day for each participant, subtracted the mean baseline value from the mean retention value, and divided this value by the original mean baseline value. The average percent change for each group is presented in figure 6.2 – lower values indicate a significant reduction in medial-lateral velocity which we interpreted as an improvement in balance control.

Scanning Protocol and fMRI Preprocessing

All scans were performed on a 3.0 T magnetic resonance imaging scanner using a 16-channel head coil (Siemens Tim Trio; Erlangen, Germany). First, a T1-weighted structural image was obtained using the following parameters: TR = 2000 ms; TE = 4.58ms, matrix field of view = 256mm; flip angle = 7°, voxel size = 1 × 1 × 1mm. Next, fMRI data (resting-state) were acquired with the following parameters: TR = 3000ms, TE

= 28ms, matrix field of view = 212mm, flip angle = 73°, bandwidth = 2520 Hz, acquisition matrix = 64 × 64, slice thickness=3.3 mm, voxel dimensions = 3.3 × 3.3 × 3.3 mm, 48 slices, interleaved slice ordering. Participants were asked to look at a cross, remain motionless, and let their mind wander; the total time of the resting-state fMRI session was approximately 5.5 minutes (results from the resting-state connectivity are reported in chapter 5). Finally, DTI data was acquired with the following parameters: TR = 9000ms, TE = 94ms, matrix field of view = 350mm, bandwidth = 1346 Hz, acquisition matrix = 64 × 64, slice thickness = 2.7 mm, voxel dimensions = 2.7 × 2.7 × 2.7 mm, 59 slices, diffusion mode = MDDW, noise level = 30, diffusion directions = 64, *b* value 1 = 0 s/mm^2, *b* value 2 = 1300 s/mm^2, interleaved slice ordering. The total time for the DTI scan was 10 minutes and 14 seconds.

DTI Analyses

DTI data was analyzed using FSL's (FMRIB [The Oxford Centre for Functional Magnetic Resonance Imaging of the Brain] Software Library) FDT toolbox (http://www.fmrib.ox.ac.uk/fsl/fdt/index.html). Images were first eddy current corrected to remove non-linear artifacts and distortions from the data sets (Jenkinson & Smith, 2001). Tensors were then fit using the *b*-factor and diffusion direction matrix with the DTIfit toolbox and brain extracted using FSL's brain extraction tool, BET (Smith, 2002). Eigenvalues, the resulting eigenvectors, and the FA indices were calculated for each voxel resulting in diffusion weighted brain maps. Tract-based spatial statistics (TBSS; (Smith et al., 2006) were then carried out using FSL. Using the nonlinear registration tool FNIRT (Andersson et al., 2007a, 2007b), all subjects' FA data was aligned to common

1x1x1mm MNI152 space and the subsequent mean FA image was created and thinned to produce a mean FA skeleton at a threshold value of 0.2 (see Figure 6.3).

To calculate FA values for our specific brain regions of interest (prefrontal cortex, percental gryus, and postcentral gyrus), we created binarized brain region masks with a threshold of 10 using the Harvard Cortical Structural atlas within FSL. Using the FSLmaths multiply command, we multiplied each mask by the mean FA skeleton mask. This allowed us to examine FA only in appropriate white matter tracts. Then, via the FSLstats command, we extracted the mean FA for each masked region and calculated a percent change score from baseline to retention in the same manner as described for the balance percent change score ([mean retention FA – mean baseline FA] / mean baseline FA). We then used Pearson product correlations to determine the relationship between percent change in FA and percent change in balance performance for each region. One outlier was removed from the control condition resulting in an *n* of 10, 11, & 11, for the control, internal focus, and external focus, respectively. This outlier showed a 3 standard deviation increase in FA from pre to post in the frontal pole.

Results

Prefrontal Cortex

There were no significant relationships between percent change FA for the frontal pole and percent change balance performance for any condition (all $p > .05$; see Figure 6.4). The percent variance (R^2) explained for the control, internal focus, and external focus was 22.9%, 4.1%, & .10%, respectively.

Precentral Gyrus

There were no significant relationships between percent change FA for the precentral gyrus and percent change balance performance for any condition (all $p > .05$; see Figure 6.5). The percent variance (R^2) for the control, internal focus, and external focus was 3.2%, 2.0%, & 3.8%, respectively.

Lingual Gyrus

There were no significant relationships between percent change FA for the precentral gyrus and percent change balance performance for any condition (all $p > .05$; see Figure 6.6). The percent variance (R^2) for the control, internal focus, and external focus was 17.3%, 2.2%, & 9.3%, respectively.

Discussion

The purpose of this study was to examine the influence of attentional focus on FA. We aimed to do this by having two groups of participants learn a complex balance task over the course of seven days while their attention was directed internally or externally. We also included a control condition in which participants did not undergo any balance training. We used a percent change score to ascertain the relationship between changes in balance performance and corresponding changes in FA within the frontal pole, precentral gyrus, and lingual gyrus. While our second and third hypotheses were confirmed in that no relationships would exist for the internal focus and control condition, this was not substantiated with a significant relationship between percent change FA and percent change balance performance in any region for the external focus condition. Thus, our data suggests that the behavioral improvements (i.e., largest percent change for the EF condition; also, see chapter 4) for those using an external focus did not correlate with FA changes in any region we explored.

We suspected FA changes in the frontal pole, percental gyrus, and lingual gyrus for several reasons. First, previous research has demonstrated a significant negative relationship between balance improvement and FA in the frontal pole using a similar paradigm (Taubert et al., 2010). While our study, and that of Taubert et al., required participants to learn a dynamic balance task, an important distinction between these two studies is the frequency and intensity of training. Taubert et al. had participants practice the task for approximately 45 minutes a day, once a week, for six weeks, totaling six training sessions. While our training session was similar in length (approximately 45 minutes to an hour), and culminated in more total training sessions (seven versus six), we had participants practice on *consecutive* days instead of once a week. We elected this training paradigm to naturally progress the attentional focus and balance training literature (chapter 4), but it appears to have minimized changes in FA in the frontal pole (as well as the other regions). Possible explanations are that more rest time is needed for structural changes to develop, or attentional focus training programs need to be longer (e.g., multiple weeks) to induce any structural changes. This opens unique follow-up work that could begin manipulating the frequency of rest between attentional focus training sessions and (or) extending attentional focus training programs to further assess the influence of attentional focus training on FA.

Our exploratory questions pertaining to changes in FA in the precentral gyrus and lingual gyrus were based on previous literature revealing the importance of the precentral gyrus for motor control (Porro et al., 1996) and the influence of the lingual gyrus for integrating visual information during movement (Grooms et al., 2015). Mostly, however, we examined the lingual gyrus as this region demonstrated changes in resting-state connectivity following attentional focus training (chapter 5) and is active during attentional focus (internal or external) instruction (Raisbeck et al., under review). Like the frontal pole, there were no significant relationships in percent change FA of the precentral gyrus or lingual gyrus with percent change balance performance for any condition. In view of our previous findings, this data suggests that the behavioral changes associated with seven days of attentional focus training are mostly functional, but longer training programs and (or) more rest may be needed to influence brain structure.

On the surface, it may appear that attentional focus has minimal influence on neuroplasticity. However, this data is unique in that it sheds light on how attentional focus may be influencing neural changes. Considering our resting-state connectivity data (chapter 5) and our previous work exploring task-based paradigms utilizing an internal and external focus (Raisbeck et al., under review), it appears that seven days of attentional focus training mostly influences functional changes, but variations in rest and training duration may be needed to influence brain structure. This is an important contribution as it disentangles the effects of attentional focus on neuroplasticity, by distinguishing the time frame for attentional focus functional changes, without influencing structural changes. Specifically, our data suggests that the behavioral results manifesting from those using an external focus may occur due to changes in correlated brain activity (chapter 5) possibly due to repeated coactivation throughout training.

This study examined changes in brain structure, specifically FA, and the corresponding relationship with balance performance. Our findings suggest that optimizing training via an external focus may not alter brain structure. Several limitations, however should be considered. First, while we carefully selected three brain regions to explore FA, it is possible that other regions' FA may have changed in response to the training. For example, Hofstetter et al. (2013) revealed that two hours of visuomotor training changed FA within the fornix and hippocampus, and Takeuchi et al. (2010) found changes in FA within the intraparietal sulcus and corpus callosum following two months of working memory training. The effects of attentional focus on the brain is still in its infancy, thus once there is a better understanding of how these manipulations specifically effect brain activity, it may warrant reexamination of FA in other regions, such as the hippocampus or fornix. Secondly, we only explored changes in FA. Other diffusion indices such as mean diffusivity, radial diffusivity, and axial diffusivity have been used in conjunction with FA to tell a more holistic neurophysiologic picture, but these indices were outside the scope of this project.

In conclusion, this is the first data that has tied changes in behavior (i.e., balance performance) resulting from attentional focus training with changes in brain structure, specifically FA within the frontal pole, precentral gyrus, and lingual gyrus. While our results were not congruent with our hypothesis that changes in FA would be associated with those training with an external focus, this data still contributes to the attentional focus literature. That is, training balance with specific attentional focus instructions may not influence FA, but seems to primarily affect resting-state connectivity (chapter 5) and brain activity (Raisbeck et al., under review). Further, this work reveals that it may take longer than seven days or more rest between sessions to alter FA within the brain using attentional focus instruction, but provides a foundation for those interested in using an external focus to alter brain structure.

Figure 6.1. Balance Board and Inertial Measurement Unit.

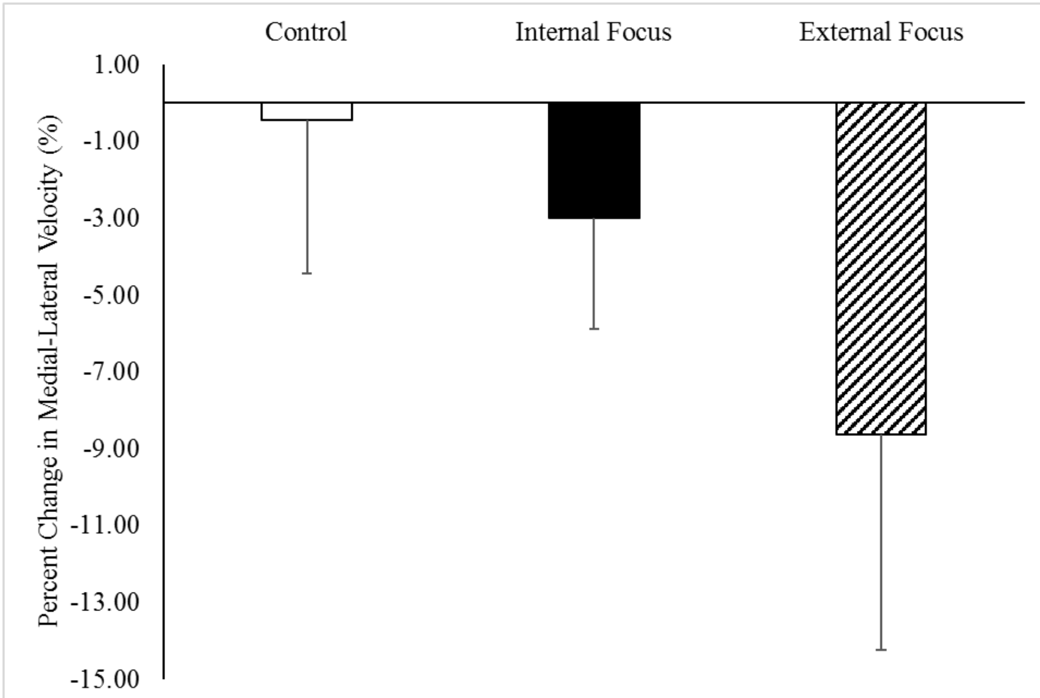

Figure 6.2. Percent Change in Medial-lateral Velocity Before and After Training. Lower percent change was deemed an improvement in balance performance.

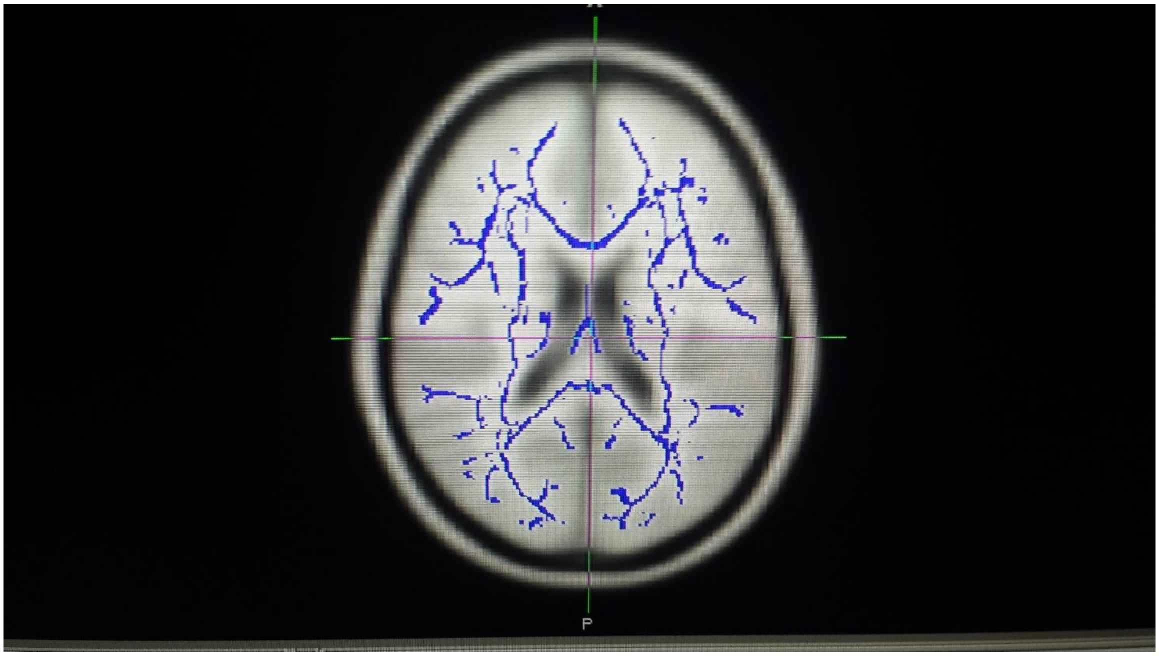

Figure 6.3. Mean FA Skeleton Mask. Mask overlaid on a 1x1x1mm MNI152 standard template (axial view). FA tracts are in blue.

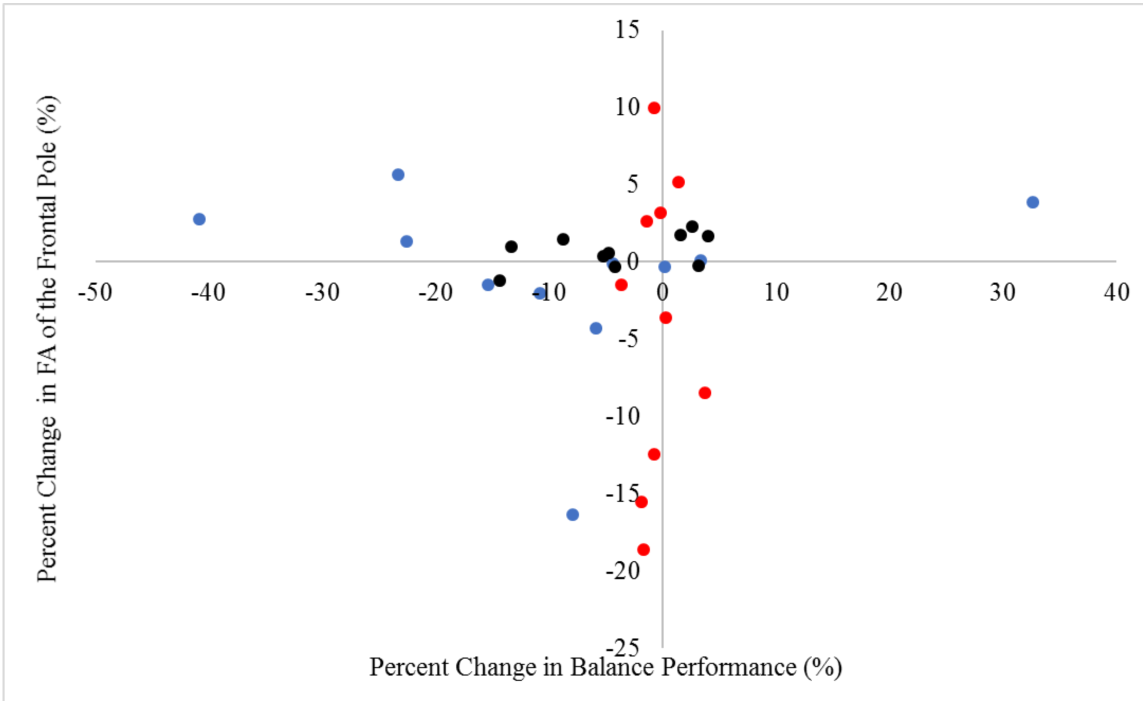

Figure 6.4. Percent Change FA and Balance Performance (Frontal Pole). Relationship between percent change in FA of the frontal pole and percent change in balance performance for each group – all non significant ($p > .05$). Black represents the control, blue represents the external focus, and red represents the internal focus.

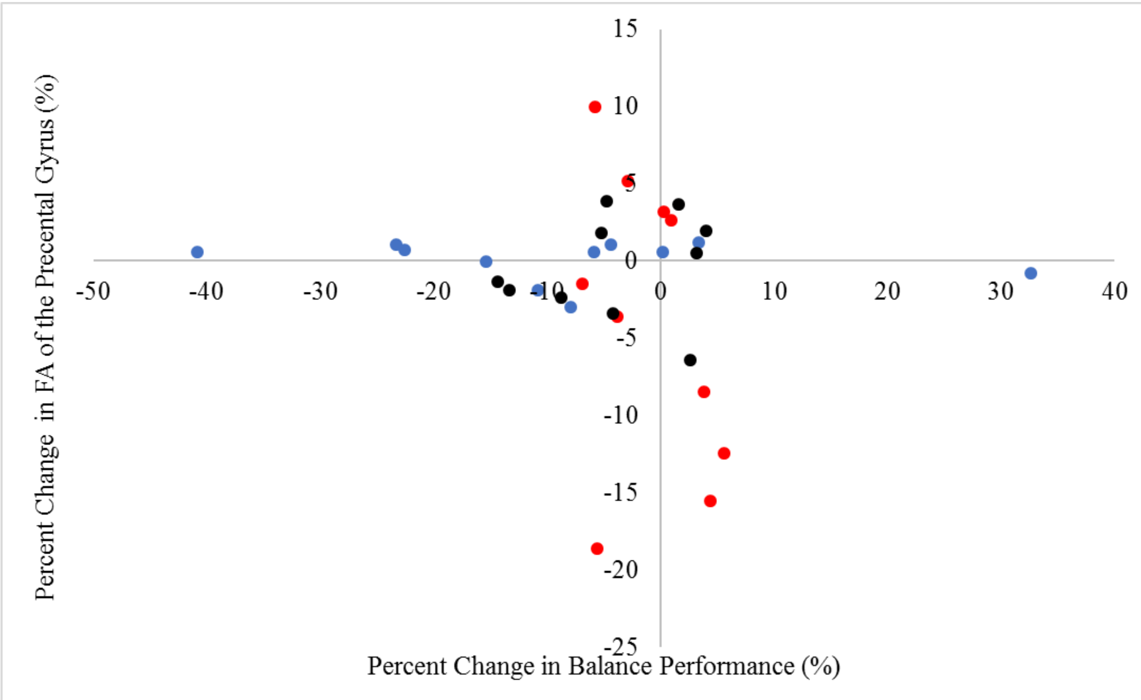

Figure 6.5. Percent Change FA and Balance Performance (Precentral Gyrus). Relationship between percent change in FA of the precentral gyrus and percent change in balance performance for each group – all non significant ($p > .05$). Black represents the control, blue represents the external focus, and red represents the internal focus.

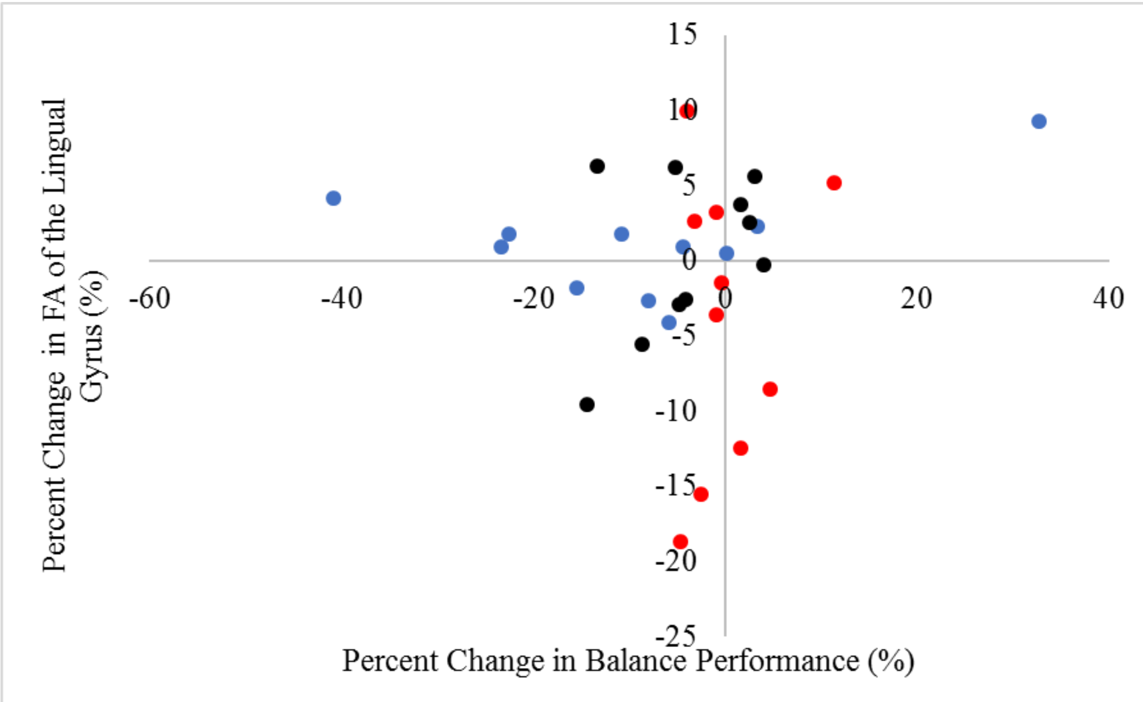

Figure 6.6. Percent Change FA and Balance Performance (Lingual Gyrus). Relationship between percent change in FA of the lingual gyrus and percent change in balance performance for each group – all non significant (p > .05). Black represents the control, blue represents the external focus, and red represents the internal focus.

CHAPTER VII

EXECUTIVE SUMMARY

Over 15 years of research has consistently demonstrated that an external focus (i.e., focusing on the effects of one's movement) relative to an internal focus (i.e., focusing on the movement itself) enhances performance and learning (see Wulf, 2013 for a comprehensive review). Per the constrained-action hypothesis (McNevin et al., 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001), an internal focus constrains the motor system, whereas an external focus frees the motor system by permitting more reflexive and automatic behavior. While there is a plethora of neuromuscular (e.g., Lohse et al., 2010; Vance et al., 2004) and behavioral data to support the benefits of an external focus (e.g., Al-Abood et al., 2002; McNevin & Wulf, 2002; Porter et al., 2016; Raisbeck & Diekfuss, 2016), the neural mechanisms underlying these differences are unclear. A few task-based paradigms using fMRI have begun to untangle the influence of attentional focus on brain activity (Raisbeck et al., under review; Zentgraf et al., 2009; Zimmermann et al., 2012), yet these studies do not explore the effects of training with attentional focus on functional (e.g., resting-sate fMRI) or structural changes (e.g., changes in the diffusion of water molecules) within the human brain while at rest.

Per OPTIMAL theory (Wulf & Lewthwaite, 2016) an external focus is theorized to contribute to changes in resting-state connectivity and structural changes within the human brain, potentially do to the synaptogenesis processes associated with changes in dopamine. While functional (e.g., Amad et al., 2016; Demirakca et al., 2015; Taubert et al., 2011) and structural (Draganski et al., 2004; Hofstetter et al., 2013; Taubert et al., 2010) changes in the human brain have been observed following training, these studies did not specifically manipulate attentional focus. The primary objective of this study was to determine the effects of balance training with attentional focus on neuroplasticity in a young healthy population. We hypothesized that those training with an external focus would exhibit more favorable postural control characteristics throughout acquisition and at retention, less correlated activity between motor and sensory region at retention relative to baseline, and a negative relationship between percent change balance improvement and percent change fractional anisotropy within the prefrontal cortex (Taubert et al., 2010). Further, we hypothesized that those training with an internal focus would exhibit less favorable postural control characteristics throughout acquisition and at retention, more correlated activity between motor and sensory region at retention relative to baseline, and no significant relationship between percent change balance improvement and percent change fractional anisotropy within the prefrontal cortex.

Classical attentional focus effects were revealed throughout acquisition with those practicing with an external focus displaying significantly less mean velocity and less SD velocity. These effects were also found when comparing the external focus with our control group at retention. Albeit we did not see between-group differences when assessing balance using SampEn, we did find within-day changes in SampEn suggesting that participants adopt a more patterned and rigid behavior to be successful in this specific dynamic balance board task. These findings may be explained by our changes in participants' resting-state connectivity when comparing each groups' data at retention relative to baseline. Specifically, we found less correlated brain activity amongst motor and sensory regions at the retention test compared to baseline for the external focus group. While some similar connectivity results were exhibited for the internal focus group, this group also showed increased correlated brain activity at the retention test relative to their baseline between motor and sensory regions. In conjunction with our behavioral findings, this data suggests that training with different foci of attention may influence the human brain's correlated activity at rest. Our final hypothesis, however, was not confirmed. We hypothesized to see a relationship between balance changes and fractional anisotropy changes within the prefrontal cortex, but this was not observed. We did examine two other regions (precentral gyrus, lingual gyrus), but no relationship was observed for these. The contribution of this finding is the understanding that the behavioral improvements observed with short motor learning paradigms may be due to functional changes as opposed to structural. We suggest that more rest time or longer training durations with attentional focus are needed to elicit structural changes congruent with other findings (Taubert et al., 2010).

Findings from this research warrant future investigation to continue our understanding of attentional focus training on neuroplasticity. First, other network measures (e.g., graph theory - see Bullmore & Sporns, 2009) would be useful to provide a more holistic picture of the underlying network differences resulting from attentional focus training. Second, replicating these findings in clinical populations could provide us with a deeper understanding of the influence of attentional focus on neuroplasticity by using populations that show alterations in connectivity at rest (e.g., Alzheimer's disease; Wang et al., 2007). Lastly, though we did not find a relationship between changes in fractional anisotropy and balance performance, it would be useful to examine other white matter tracts (e.g., corticospinal tract). Likewise, other metrics quantified via DTI, such as radial diffusivity and mean diffusivity, could reveal relationships to aid in our understanding of attentional focus balance training on brain structure.

In conclusion, this research takes an initial step in advancing our understanding of balance training with attentional focus on neuroplasticity. We replicated previous findings showing the short-term benefits of adopting an external focus on balance (McNevin & Wulf, 2002; Wulf, Töllner, et al., 2007) and extended this time frame to seven days. We further demonstrated that these behavioral changes may be associated with changes in correlated brain activity at rest (with less correlated activity for those training with an external focus), but are not associated with changes in water diffusivity in the prefrontal cortex, prefrontal gyrus, or lingual gyrus as measured by fractional anisotropy. This data suggests that a seven-day balance training program with attentional focus in a young healthy population may influence brain function (specifically correlated activity at rest), but longer training programs or more rest between training sessions may be needed to influence brain structure (as measured by fractional anisotropy). Neuroplasticity has become a highly studied topic in many cognitive and behavioral realms (Costandi, 2016) and our data adds to this growing area of research.

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APPENDIX A

INFORMED CONSENT FORM

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

CONSENT TO ACT AS A HUMAN PARTICIPANT

Project Title: The influence of attentional focus on neuroplasticity following a seven-day balance training intervention.

Principal Investigator: Jed A. Diekfuss

Faculty Advisor: Louisa D. Raisbeck

Participant Name: ____

What are some general things you should know about research studies?

You are being asked to take part in a research study. Your participation in the study is voluntary. You may choose not to join, or you may withdraw your consent to be in the study, for any reason, without penalty.

Research studies are designed to obtain new knowledge. This new information may help people in the future. There may not be any direct benefit to you for being in the research study. There also may be risks to being in research studies. If you choose not to be in the study or leave the study before it is done, it will not affect your relationship with the researcher or the University of North Carolina at Greensboro. Details about this study are discussed in this consent form. It is important that you understand this information so that you can make an informed choice about being in this research study.

You will be given a copy of this consent form. If you have any questions about this study at any time, you should ask the researchers named in this consent form. Their contact information is below.

What is the study about?

This is a research project. Your participation is voluntary. This is a research project to investigate how the brain changes following balancing training.

Why are you asking me?

Your participation in this study is entirely voluntary. To participant in this study, you must be right-handed and be between the ages of 18 and 35. You will be excluded if you: 1) have a previous history of injury to the capsule, ligament, or menisci of either knee, 2) have any inner ear or balance disorder, 3) have any metal or implanted medical device in the body that would be a contradiction to MRI assessment, 4) have undergone a previous balance training program, 5) are currently taking any medications that would affect balance or 6) have any neurological disorders.

MRI uses a very strong magnetic fields and powerful radio waves. While MRI an MRI exam is safe for most people, there are a number of instances when it is unsafe (even potentially fatal) for someone to be in or around a MRI scanner. In order to make sure the MRI procedure will be safe for you, you will be asked to fill out a screening form before starting the study. It is important that you tell the researchers in this study:

- if you have a heart pacemaker
- if you have metal in your head (not including dental work)
- if you have metal in your spine or heart
- if there is the possibility of metal in your eyes,
- if you have any implanted medical device in your body,
- if you have an implant in your body held in place with a magnet,
- if you have had surgery in the last 6 weeks,
- if you weigh more than 450 pounds,
- if you are pregnant or there is the possibility that you are pregnant.

What will you ask me to do if I agree to be in the study?

<u>This will be a 9-day study in total.</u>

Before your MRI exam is scheduled you will be asked to answer a series of questions about your medical history to determine if an MRI exam is safe for you as well as a series of questions about your physical activity history. We are interested in knowing if you have any metal inside your body that could results in injury during the MRI exam. You will also be asked your height, weight, sex, and birthdate. If it would be safe for you to be scanned, you will schedule a 1-hour testing session to occur at the Joint School of Nanoscience and Nanotechnology in Greensboro, NC.

Day 1:
Upon arrival to the Joint School of Nanoscience and Nanotechnology, you will again complete the screening questionnaire, complete a general demographics questionnaire, a questionnaire to determine handedness, a questionnaire to determine footedness, and a physical activity questionnaire. You will then complete then complete two tests: 1) 35 minute MRI scan. 2) 10 Minutes of Baseline balance measurements and two questionnaires.

1) 35 Minute MRI Scan 1
You will be asked to lay on a table and will be entered in the MRI scanner head first. You will lay quietly in this position for approximately 35 minutes. For your safety, you will be monitored the entire time you are in the scanner. The study team will be able to talk to you and hear you talk during the exam through an intercom. You will also be given a safety-ball to squeeze with your

hand if you want to stop the exam at any time for any reason.

2) Balance
You will be removed from the scanner and taken into a side laboratory within the MRI scanner suite. During this time, you will be asked to complete a series of quiet standing balance tasks upon a balance board and complete two questionnaires pertaining to the task. The balance tests use a circular board that is a few centimeters off the ground. You wil stand on it and it 'wobbles' forward and back and side to side. It is used often in physical therapy and rehabilitation settings to improve balance and stability. This is a very safe task with no risk of injury. This will take 10 minutes.:

Days 2-8:
If you are randomly assigned to the balance training group, you will need to meet the researcher in room 236 of the Coleman building for 7 consecutive days. During this time, you will complete a series of quiet standing balance tests on a balance board and complete two short questionnaires each day. Each testing session will take 1 hour.

If you are randomly assigned to the control group, you will not need to meet the researcher during this time.

Day 9:
The final testing day will require all participants and will occur at the Joint School of Nanoscience and Nanotechnology. This testing session will be identical to day 1, with the exclusion of the demographics, handedness, footedness, and physical activity questionnaire.

Is there any audio/video recording?
There will be no audio or video recording of any kind.

What are the dangers to me?

The Institutional Review Board at the University of North Carolina at Greensboro has determined that participation in this study poses minimal risk to participants. MRI scanners have been in clinical use for about 20 years. When the MRI is used properly, there are no known risks to having an MRI scan for most people. Unlike X-rays, CT scans, and nuclear medicine studies, the MRI machine does not use X-rays or other forms of ionizing radiation. Instead, the MRI scanner uses strong magnetic fields and radio waves to measure your brain activity when you lay on a bed in a tube.

Metal objects: Metal objects within or on your body and clothing can cause harm to you, in addition to distorting the quality of the MRI images. Such things as keys, watches, and credit cards will be kept safely away from the machine. We will ask you to take off all removable metal (e.g. jewelry, piercings, etc.). People with devices or objects inside their body that are affected by strong magnetic fields (i.e. metallic foreign bodies inside your head or in your eyes, incompatible medical implants, pacemakers, brain stimulators, blood vessel clips, etc.) will not be allowed to participate under any circumstances. Knowingly participating in this study with these types of metallic implants can lead to serious injury or death. Although metal objects sensitive to strong magnetic fields are not allowed in the MRI scanner, there are many metal objects that are not sensitive to strong magnetic fields, such as dental work, pins or screws used during surgery, and even some tattoos contain metal. People with these types of metal objects may safely participate in this study. You will go through an extensive screening process to determine if the MRI scanner is safe for you before allowing have your MRI exam

Burn risks: In extremely rare cases, metal in the body (e.g., in tattoos) exposed to the powerful radio waves used in MRI may heat up. This heating occurs gradually but if it goes unreported during the MRI exam it could lead to burns. Such burns are easily prevented by reporting any heating sensations that you have to the technologists immediately. For your safety, you will be monitored the entire time you are in the scanner. The study team will be able to talk to you and hear you talk during the exam through an intercom. You will also be given a ball to squeeze with your hand if you want to stop the exam immediately and for any reason.

Fear of small places: MRI machines require you to enter a tube about 2 feet in diameter and place your head in small helmet. For people with a fear of small spaces this can cause anxiety. If you experience anxiety during your MRI exam please let the technologist know. If you decide that you cannot complete the scan, you will be removed immediately from the scanner, and released from the study.

Hearing loss: MRI scanners when taking a picture are very loud. You will be required to wear earplugs during the exam. When the earplugs are used properly, the noise from the MRI scanner is as load as a garbage disposal or food blender. If the earplugs are not inserted into the ear canal then temporary hearing loss is possible. If at any time the noise from the MRI machine is too loud inform the technologist.

Muscle twitching and tingling: MRI machines turn magnetic fields on and off very quickly to make an image. In rare cases, this may cause your muscles to twitch and tingle. The muscle twitching and tingling are temporary and will stop as soon as the scanner stops. In some rare cases, some individuals find the muscle twitching and tingling to be uncomfortable and cannot continue with the MRI exam. If this happens to you let us know and you will be released from the study.

Other miscellaneous risks: There are other short-term effects that have been reported in very rare cases during the MRI exam. These effects range from dizziness, to taste sensations, to light flashes during the MRI exam. These effects are temporary and occur as you move in and out of the MRI machine. In most cases, these effects go away very quickly. If these sensations persist and you are unable to continue with the MRI exam, inform the researchers and you will be removed from the MRI exam and released from the study. The MRI images completed at our facility are part of a research study and are not for clinical diagnostic purposes. The MRI images in this study will not be reviewed by a physician. If you would like to review these images with your physician, we will give you a free copy of your images on a CD. In the case that we see a substantial deviation from normal anatomy we will notify you, provide you with a free copy of your data, and suggest that you contact your physician for follow up. The research team cannot diagnose conditions.

Pregnancy: It is unclear at this time whether strong magnets are a risk to unborn fetuses. Due to the unknown risk and potential harm to an unborn fetus from any MRI scan, pregnant women will be excluded. All women will be asked before entering the scanner if they are pregnant.

The MRI images completed as part of this study are not for clinical diagnostic purposes. The MRI images in this study will not be reviewed by a physician. If you would like to review these images with your physician, we will give you a copy of your images on a CD.

If you have questions, want more information or have suggestions, please contact Jed Diekfuss at (262) 364-6319 or jadiekfu@uncg.edu or Dr. Louisa Raisbeck at (336) 256-0280 or ldraisbe@uncg.du.

If you have any concerns about your rights, how you are being treated, concerns or complaints about this project or benefits or risks associated with being in this study please contact the Office of Research Integrity at UNCG toll-free at (855)-251-2351.

Are there any benefits to society as a result of me taking part in this research?
This study will benefit society by ascertaining information pertaining brain activity and leg movement. This could be beneficial for clinicians and therapists when constructing rehabilitation programs that require leg tasks.

Are there any benefits to *me* for taking part in this research study?
There are no direct benefits to participants in this study.

Will I get paid for being in the study? Will it cost me anything?
There is no compensation for participating in this study.

How will you keep my information confidential?
All information obtained in this study is strictly confidential unless disclosure is required by law. Confidentiality will be maintained by means of participant coding. Specifically, all information obtained from you (brain imaging data) will be assigned a random number; your name will never be associated with the information obtained (e.g., participant number 4). The researchers listed above will use this number when analyzing, reporting, and (or) summarizing the information obtained from you; your name will never be identified. Additionally, to further maintain your confidentiality; all obtained information (e.g., de-identified questionnaires) will remain in a file drawer in a locked office within Dr. Raisbeck's Kinesiology laboratory. Your obtained information will remain in this location for a minimum of three years after the completion of this study and will be destroyed (i.e., shredded) after this time. To be more specific, any information that can identify will be destroyed after three years, but de-identifiable data will be stored indefinitely. This de-identifiable data will be shared with an outside researcher who has expertise in brain imaging. Again, this person will have no knowledge of the person associated with the data. All electronic data will be stored on an external hard drive that will be password protected and stored in a locked file drawer within the VEAR lab. Some data will also be saved to UNCG's Box, but this data will all be de-identified and will require UNCG login passwords to access.

What if I want to leave the study?
You have the right to refuse to participate or to withdraw at any time, without penalty. If you do withdraw, it will not affect you in any way. If you choose to withdraw, you may request that any of your data which has been collected be destroyed unless it is in a de-identifiable state. The investigators also have the right to stop your participation at any time. This could be because

you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

What about new information/changes in the study?

If significant new information relating to the study becomes available which may relate to your willingness to continue to participate, this information will be provided to you.

What happens if you get injured during the study?

UNCG is not able to offer financial compensation nor to absorb the costs of medical treatment should you be injured as a result of participating in this research study. However, we will provide a referral to student health or to your primary care physician.

Voluntary consent by participant:

By signing this consent form you are agreeing that you read, or it has been read to you, and you fully understand the contents of this document and are openly willing consent to take part in this study. In addition, all of your questions concerning this study have been answered. By signing this form, you are agreeing that you are 18 years of age or older and are agreeing to participate, or have the individual specified above as a participant participate, in this study described to you by

____

Would you be like a copy of your images? Yes □ No □

Signature:__________________________Date: _________________

APPENDIX B

DEMOGRAPHICS QUESTIONNAIRE

SUBJECT DEMOGRAPHICS

Sex	________________
Age	________________
Height (cm)	________________
Mass (kg)	________________

HEALTH HISTORY

Do you have any General Health Problems or Illnesses? (e.g. diabetes, respiratory disease)

Yes____ No____ If Yes, please specify
____

Is there any chance you may be pregnant? Yes_______ No__________

Do you have any vestibular (inner ear) or balance disorders? Yes____ No____

Do you smoke? Yes____ No____ If yes, how often?____________________
____

Do you drink alcohol? Yes____ No____ If yes, how often?_______________________

Do you have any history of connective tissue disease or disorders? (e.g. Ehlers-Danlos, Marfan's Syndrome, Rheumatoid Arthritis) Yes____ No____

If Yes, please specify____

Please list any medications you take regularly:

____

____

____

Please list any previous injuries to your lower extremities. Please include a description of the injury (e.g. ligament sprain, muscle strain), severity of the injury, date of the injury, and whether it was on the left or right side.

Body Part	Description	Severity	Date of Injury	Side (L or R)
Hip				
Thigh				
Knee				
Lower Leg				
Ankle				
Foot				

Please list any previous surgery to your lower extremities (Include a description of the surgery, the date of the surgery, and whether it was on the left or right side)

Body Part	Description	Date of Surgery	Side(L or R)

APPENDIX C

EDINBURGH HANDEDNESS INVENTORY

Edinburgh Handedness Inventory - Short Form

Please indicate your preferences in the use of hands in the following activities or objects:

	Always right	Usually right	Both equally	Usually left	Always left
Writing	☐	☐	☐	☐	☐
Throwing	☐	☐	☐	☐	☐
Toothbrush	☐	☐	☐	☐	☐
Spoon	☐	☐	☐	☐	☐

Scoring:

For each item: Always right = 100; Usually right = 50; Both equally = 0; Usually left = -50; Always left = -100

To calculate the Laterality Quotient add the scores for the four items in the scale and divide this by four:

Writing score	
Throwing score	
Toothbrush score	
Spoon score	
Total	
Total ÷ 4 (Laterality Quotient)	

Classification:	Laterality Quotient score:
Left handers	-100 to -61
Mixed handers	-60 to 60
Right handers	61 to 100

APPENDIX D

WATERLOO FOOTEDNESS QUESTIONNAIRE

Appendix: Waterloo Footedness Questionnaire—Revised

Instructions: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

1.	Which foot would you use to kick a stationary ball at a target straight in front of you?	La	Lu	Eq	Ru	Ra
2.	If you had to stand on one foot, which foot would it be?	La	Lu	Eq	Ru	Ra
3.	Which foot would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4.	If you had to step up onto a chair, which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5.	Which foot would you use to stomp on a fast-moving bug?	La	Lu	Eq	Ru	Ra
6.	If you were to balance on one foot on a railway track, which foot would you use?	La	Lu	Eq	Ru	Ra
7.	If you wanted to pick up a marble with your toes, which foot would you use?	La	Lu	Eq	Ru	Ra
8.	If you had to hop on one foot, which foot would you use?	La	Lu	Eq	Ru	Ra
9.	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10.	During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?	La	Lu	Eq	Ru	Ra
11.	Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?	**YES**	**NO**	(circle one)		
12.	Have you ever been given special training or encouragement to use a particular foot for certain activities?	**YES**	**NO**	(circle one)		
13.	If you have answered **YES** for either question 11 or 12, please explain:					

APPENDIX E

UNCG MRI SCREENING FORM

Operator Scanning Check List

PWRB #: ______________ Acrostic: ____________________ Date: ___________________

To be filled out by PI or Study Coordinator:

Acrostic for Last Name Field : ______________________________

Participant ID : ______________________________

Accession Number : ______________________________

Date and Time : ______________________________

Height: _________ **Weight:** _________ **Birth Year:** _________ ☐ **Male** ☐ **Female**

MRI utilizes a very strong magnetic field, rapidly switching gradient magnetic fields and powerful radiofrequency transmissions. While having an **MRI is safe for most people, there are a number of instances when it can be dangerous (even fatal) for someone to have an MRI exam.** This screening form is used to identify which individuals can safely have an MRI exam.

Absolute Contraindications:

1.	☐ Yes	☐ No	Do you have a heart pacemaker?
2.	☐ Yes	☐ No	Is there a possibility of metal in your head? (e.g. aneurysm clips, metal ear tubes, etc.) for this question exclude dental work)
3.	☐ Yes	☐ No	Is there a possibility of metal in your eyes, have you ever needed an eyewash while working with metals, have you ever had an injury to the eye involving a metal object or fragment (e.g., metallic slivers, shavings, foreign body, etc.)
4.	☐ Yes	☐ No	Do you have any implanted medical devices in your body? (cochlear implant, metal ear tubes, bone stimulator, neurostimulator, biostimulator, medication pump, automatic defibrillator, internal pacing wires, etc). Exclude orthopedic hardware and dental work
5.	☐ Yes	☐ No	Do you have any implants held in by a magnet (dentures, posts, or crowns)?
6.	☐ Yes	☐ No	Have you had any bone, tendon, spine, or dental surgery **within the last 6 weeks**?
7.	☐ Yes	☐ No	Do you weigh more than 450 pounds (181 kg)?
8.	☐ Yes	☐ No	Are you pregnant or suspect you may be pregnant?

If you checked **Yes** to any of the questions above you do not need to complete the rest of the form. **<u>You cannot enter the MRI Exam room under any circumstances</u>** until you are able to answer No to all of these questions.

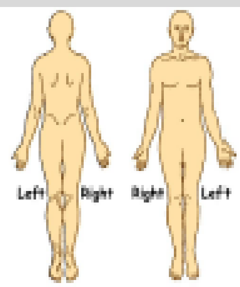
Operator Scanning Check List

PWRB #: ______________ Acrostic: ____________________ Date: ___________________

Potential Contraindications:

9.	☐ Yes ☐ No	Do you have an IUD that may contain copper, or a contraceptive diaphragm?
10.	☐ Yes ☐ No	Have you had any stents, clips or surgery to any of any of your vessels (carotid artery vascular clamp, coronary stent, aortic clips, IVC filter, coils for blocked arteries)
11.	☐ Yes ☐ No	Do you have metal anywhere else in your body? (screws, pins, plates, spinal rods, dental work - not including fillings and caps, piercings, shrapnel, buckshot, bullets) – please indicate where on your body on the diagram above.
12.	☐ Yes ☐ No	Do you have a cerebrospinal fluid (CSF) shunt? (treatment for hydrocephalus or water on the brain)
13.	☐ Yes ☐ No	Do you have any piercings that can't be removed?
14.	☐ Yes ☐ No	Do you have a transdermal medicated patch? (nicotine patch, contraceptive patch, medicated pain relief patch)
15.	☐ Yes ☐ No	Have you had any medical condition that has prevented you completing an MRI exam in the past?
16.	☐ Yes ☐ No	Do you wear a prosthetic device?
17.	☐ Yes ☐ No	Have you had any previous surgery? (give details, and indicate where on your body using the diagram below)

Details:



If you have answered Yes to any of the questions 10 through 19 then we need additional information and documentation before you may have your MRI exam. If possible, the items resulting in a Yes answer should be removed before your MRI exam. If this is impossible, the Principle Investigator/Study Coordinator needs to provide additional information that your device is MRI safe before you enter the MRI exam room.

Notes:

APPENDIX F

WORKLOAD QUESTIONNAIRE (HART & STAVELAND, 1988)

How mentally demanding was the task?

Very Low Very High

How physically demanding was the task?

Very Low Very High

How hurried or rushed was the pace of the task?

Very Low Very High

How successful were you in accomplishing what you were asked to do?

Perfect Failure

How hard did you have to work to accomplish your level of performance?

Very Low | Very High

How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low | Very High

APPENDIX G

ATTENTIONAL FOCUS COMPLIANCE CHECK

1.What were you focusing on during the previous balance tasks? If you did not focus on anything particular during the trial, please leave this question blank.