Journal of Sport Rehabilitation, 2020, 29, 441-447
https://doi.org/10.1123/jsr.2018-0026

Human Kinetics
ORIGINAL RESEARCH REPORT

The Effects of Attentional Focus on Brain Function During a Gross Motor Task

Louisa D. Raisbeck, Jed A. Diekfuss, Dustin R. Grooms, and Randy Schmitz

Context: Although the beneficial effects of using an external focus of attention are well documented in attainment and performance of movement execution, neural mechanisms underlying external focus' benefits are mostly unknown. ***Objective:*** To assess brain function during a lower-extremity gross motor movement while manipulating an internal and external focus of attention. ***Design:*** Cross-over study. ***Setting:*** Neuroimaging center ***Participants:*** A total of 10 healthy subjects (5 males and 5 females) ***Intervention:*** Participants completed external and internal focus of attention unilateral left 45° knee extension/flexion movements at a rate of 1.2 Hz laying supine in a magnetic resonance imaging scanner for 4 blocks of 30 seconds interspersed with 30-second rest blocks. During the internal condition, participants were instructed to "squeeze their quadriceps." During the external condition, participants were instructed to "focus on a target" positioned above their tibia. ***Main Outcome Measures:*** T1 brain structural imaging was performed for registration of the functional data. For each condition, 3T functional magnetic resonance imaging blood oxygenation level dependent data representing 90 whole-brain volumes were acquired. ***Results:*** During the external relative to internal condition, increased activation was detected in the right occipital pole, cuneal cortex, anterior portion of the lingual gyrus, and intracalcarine cortex ($Z_{\max} = 4.5–6.2$, $P < .001$). During the internal relative to external condition, increased activation was detected in the left primary motor cortex, left supplementary motor cortex, and cerebellum ($Z_{\max} = 3.4–3.5$, $P < .001$). ***Conclusions:*** Current results suggest that an external focus directed toward a visual target produces more brain activity in regions associated with vision and ventral streaming pathways, whereas an internal focus manipulated through instruction increases activation in brain regions that are responsible for motor control. Results from this study serve as baseline information for future prevention and rehabilitation investigations of how manipulating focus of attention can constructively affect neuroplasticity during training and rehabilitation.

Keywords: motor performance, motor learning, fMRI

A goal of the rehabilitation professional is to help their patients learn the successful execution of movements. Verbal instruction is one means by which learning movement can occur. In recent years, literature on the effects of instruction and performance has investigated focus of attention effects. Substantial evidence supports the premise that focusing attention on a specific body part related to movement or on the skill itself can affect performance and learning.[1–3] Instructional focus can be subdivided into an internal focus and an external focus of attention. An internal focus uses instruction to direct one's focus to specific aspects of one's body movement, whereas an external focus uses instruction to direct one's focus toward the effects of his or her movement on the environment.[4] For example, during balance-board training exercises, asking a participant to "focus on keeping their feet level" would be deemed an internal focus, whereas asking a participant to "focus on keeping the board level (ie, the effects of keeping their feet level)" would be an external focus.[5] While the change in instruction is subtle, a comprehensive review demonstrated that an external focus facilitates enhanced performance and greater skill learning relative to an internal focus.[3] One theoretical explanation for the skilled performance and learning changes resulting from an external focus is the constrained-action hypothesis.[6–8] This theory suggests that an external focus reduces the level of conscious interference in control processes allowing the body to behave automatically, whereas an internal focus is thought to require more conscious control over control processes disrupting the execution of motor skills.

Relevant findings from the attentional focus research have called for a consideration in rehabilitation in which practitioners may consider the potential benefits of using an external focus of attention.[9,10] For example, findings support that external focus facilitates safer biomechanics from an orthopedic injury perspective.[11,12] With respect to instruction the addition of visual stimuli has been shown to enhance performance when used with an external focus,[13] a technique that can easily be adopted in rehabilitation and sporting venues. The way we direct our attentional resources is considered the main mediator of cognition during visual searches.[14] In addition, research suggests that vision mediates the relationship between attentional focus and performance.[15] Therefore, integrating the visual stimuli with an external focus instruction would promote improved learning and performance.

A better understanding of the neural activity associated with attentional focus and motor skill may allow for more precise rehabilitation guidelines based on specific neural mechanisms. To date this has been done primarily using fine motor movements (key pressing tasks) due to the logistics of performing a gross motor movement using functional magnetic resonance imaging (fMRI). Zentgraf et al[16] provided specific instructions to direct subjects' attention internally (focus on their fingers when pressing the keys)

Raisbeck and Schmitz are with the Department of Kinesiology, School of Health and Human Sciences, University of North Carolina at Greensboro, Greensboro, NC. Diekfuss is with the Division of Sports Medicine, The SPORT Center, Cincinnati Children's Hospital Medical Center, Cincinnati, OH. Grooms is with Ohio Musculoskeletal & Neurological Institute, Ohio University, Athens, OH; and the Division of Athletic Training, School of Applied Health Sciences and Wellness, College of Health Sciences and Professions, Ohio University, Athens, OH. Raisbeck (ldraisbe@uncg.edu) is corresponding author.

or externally (focus on the keys being pressed). Results revealed that an external focus demonstrated a significantly higher blood oxygenation level dependent response in the primary motor cortex, somatosensory cortex, and insular region of the left hemisphere. The authors surmised from these regions that are associated with sensory function, that an external focus promoted task-adequate brain activity for movement execution by shifting focus toward exteroceptive information. However, it is important to clarify that these assumptions are speculative. The authors did not measure sensory function or assess participants' cognitive states, nor report the neural activation and key pressing behavioral data association. Thus, limiting our combined understanding of how differing neural activation resulting from attentional focus drives behavior or reflects participants' state of mind. Further, this work is limited by participants completing only fine motor movements, which are perceived as more cognitively demanding than gross motor movements,[17] practicing the task prior to receiving attentional focus instruction, the possibility that instructions given during the practice task may have biased attentional control,[18] and the brain data being obtained 1 day following training.

Given the lack of understanding of attentional focus and associated neural mechanisms during execution and learning of gross motor skills, the purpose of this study was to examine brain activation differences when participants performed a gross motor movement of the lower-extremity using an internal and external focus of attention. The integration of attentional focus instruction and neuroimaging during gross motor movement will help provide a mechanistic understanding for the effects of attentional focus for motor performance and learning. To better understand the role of vision and attentional focus, we added an additional visual stimuli to our external focus condition, as we wanted to maximize differences in brain activation congruent with manipulations that have demonstrated superior performance improvements with added visual stimuli.[13] We hypothesized that (1) when participants completed the gross motor movement using an external focus of attention with additional visual stimuli, there would be more activation in areas of the brain associated with vision, specifically regions that integrate sensory information from the environment and (2) when participants completed the gross motor movement using an internal focus of attention without a visual stimuli, the data would reveal significantly more activation in areas of the brain associated with motor control, such as the motor cortex, as an internal focus is believed to elicit conscious control over motor movements.[6–8]

Methods

Participants

A total of 10 healthy, recreationally active participants (5 males, age 27 [6.2] y, height 177.0 [10.8] cm, mass 65.3 [7.9] kg; 5 females, age 30 [15] y, height 167.0 [10.8] cm, mass 62.7 [12.2] kg) were recruited from local universities. Inclusion criteria included no lower-extremity injury in the last 6 months and the left leg being the preferred stance limb when kicking a ball. 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; and (3) any metal or implanted medical device in the body that would be a contraindication to magnetic resonance imaging (MRI) assessment. All participants read and signed an informed consent form approved by the University of North Carolina at Greensboro Institutional Review Board for the protection of human subjects. Each participant attended a single testing session consisting of structural and functional neuroimaging via MRI.

Task and Procedure

Prior to scanning, participants received no direct instructions of how to complete the tasks. For functional imaging a block design was implemented in the scanner where participants completed 1 run each of an internal focus condition and external focus condition in random order. Using a variety of blocking pads and straps, great care was taken to minimize head motion. A brace was applied to the ankle joint to minimize ankle joint motion. A wedge was placed under the knee to allow the limb to move from approximately 45° flexion to terminal extension (±5° depending on femur length; Figure 1).[19,20] Further, a mirror was attached to the head coil and positioned above the participants' eyes to allow the participant full view of their feet and the surrounding environment. Each run consisted 4 sets of 30 seconds of rest followed by 30 seconds of approximately 45° unilateral knee extension–flexion movements triggered by an auditory metronome at 1.2 Hz with each run ending after 30 seconds of rest (4:30 scan time for each run). Each attentional focus condition was performed in a separate run to avoid attentional focus confusion on behalf of the participant and to minimize pollution of instruction between conditions. While positioned in the scanner participants were familiarized to the extension–flexion movements. Attentional focus instructions on how to complete the knee movements were given only immediately prior to the specified run and immediately prior to each of the 30-second contraction blocks. For the external focus condition, a small external target (5 cm × 5 cm white piece of tape attached to a string) was placed directly above the participant's tibia. We elected to implement a visual target in our external focus manipulation as it has been demonstrated to further enhance performance relative to external focus instruction alone.[13] Care was taken to ensure that the participant could see the target the entire time through the mirror, but could not touch the target with their limb. In this external focus condition participants were instructed: "please focus on extending toward the target while moving your limb to the metronome." For the internal focus condition, participants were instructed: "please focus on squeezing your quadriceps while moving your limb to the metronome." Participants' field of view was constrained while in the scanner (ie, small window of vision), thus we deemed it appropriate to remove the target for the internal focus condition

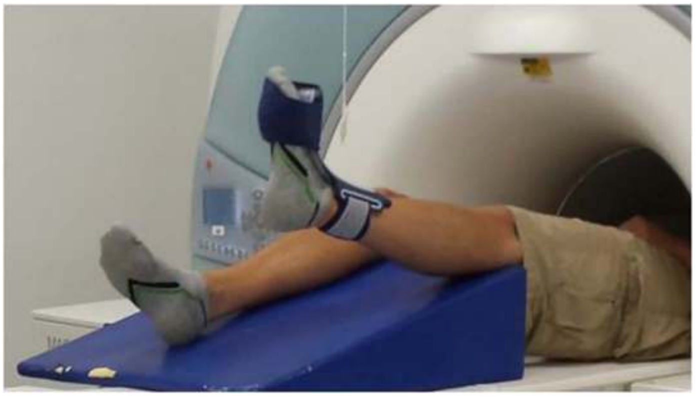

Figure 1 — Participant moving their leg in the external focus condition while inside an magnetic resonance imaging scanner. The hanging target was removed during the internal focus condition.

to isolate effects of internal focus instruction. The participant had the same field of view in both conditions, with the only difference being that there was no specific visual target during the rest and move blocks for the internal focus, whereas the visual target was present during all rest and move blocks for the external focus. We also acknowledge that asking participants to adhere to a metronome may have elicited a dual-task paradigm[21,22]; however, our contrast analyses allowed us to solely focus on instruction differences as the metronome sound and timing demands were present in both conditions.

fMRI Data Acquisition and Analysis

All scans were performed on a Siemens Magnetom Tim Trio 3.0 T MRI scanner using a 12-channel head coil (Siemens Medical Solutions; Erlangen, Germany). Following the methods of Grooms et al,[19] T1-weighted structural images were initially obtained (repetition time = 2000 ms; echo time = 4.58 ms, matrix field of view = 256 mm; voxel size = 1 mm × 1 mm × 1 mm). The fMRI imaging for each of the 3 runs included 93 whole-brain gradient-echo echoplanar scans (repetition time = 3000 ms; echo time = 28 ms, phase encoding direction = anterior to posterior; matrix field of view = 220 mm; voxel size = 2.5 mm × 2.5 mm × 2.5 mm). The first 3 volumes were discarded to account for scanner preparation and equilibration effects. This equated to 10 full-brain datasets per 30-second knee movement block, which resulted in 40 full-brain activation maps for knee movement (4 blocks) contrasted with 50 full-brain maps for rest (5 blocks) during each of the conditions.

The fMRI analyses were performed using the fMRI of the brain (FMRIB) software library (FSL: The Oxford Centre for Functional MRI of the Brain, Nuffield Department of Clinical Neurosciences, University of Oxford, Oxford, United Kingdom).[23] Standard processing was completed. This included 4Dmean intensity normalization, temporal filtering (90 s), spatial smoothing at 6-mm full width at half maximum (FWHM), FMRIB's improved linear model (FILM) prewhitening, interleaved slice timing correction, brain extraction, and fMRIB's linear image registration tool for motion correction (MCFLIRT).[23–25] Next, data were denoised with the independent component analysis-based automatic removal of motion artifacts (ICA-AROMA) pipeline. ICA-AROMA decomposes the data and automatically identifies and removes components related to head motion.[26] ICA-AROMA has been shown to be sensitive to motion artifacts while preserving task related data.[27] While this investigation had minimal motion artifact due to extensive participant restraint by using ICA-AROMA, we further decreased the probability of head artifact-related activation being present between the contrasts. There was no statistical difference in absolute (external: 0.33 [0.18]; internal: 0.33 [0.18]; $P = .93$) or relative (external: 0.12 [0.07]; internal: 0.13 [0.07]; $P = .45$) head motion between conditions. Lower level subject contrast (knee movement − baseline [rest]) and higher level (external − internal focus conditions) were completed with a z threshold of 2.3 and $P < .05$ Gaussian random field cluster corrected.[28–30] The higher level group analysis was completed with FMRIB's local analysis of mixed effects stage 1 and stage 2[31] using 2 separate paired samples t tests to contrast the external focus and internal focus conditions (external focus > internal focus and internal focus > external focus).

Results

When contrasting the external focus to the internal focus during left unilateral knee extension, several right side regions demonstrated significantly greater activation. Full details of brain regions with significantly greater activation in the external focus condition relative to the internal focus condition are presented in Table 1 with visual representations displayed in Figure 2. When contrasting the internal focus to the external focus during left unilateral knee extension, several left side regions demonstrated significantly greater activation. Full statistical details of the brain regions with significantly greater activation in the internal focus condition relative to the external focus condition are presented in Table 2 with visual representations displayed in Figure 2.

Discussion

This study examined brain function differences during a gross motor movement using an internal and external focus of attention. A primary purpose was to identify brain regions involved when following instructions specific to an external focus of attention when directed toward a visual target during a gross motor movement. We were specifically interested in the regions that integrate the sensory information from the environment. A secondary goal was to determine if regions of the brain associated with motor control activate more when individuals follow internal focus instructions. The importance of this experiment is the use of fMRI to study the regions of the brain that activate during different instructional foci. Currently, the literature hypothesizes that an external

Table 1 External Focus > Internal Focus Contrast

					Montreal Neurological Institute coordinate of peak voxel				Z center of gravity		
Cluster index	**Brain regions**	**Side**	**Voxels #**	***P* value**	***x***	***y***	***z***	**Z_{max}**	***x***	***y***	***z***
1	Occipital pole Cuneal cortex Lateral occipital cortex Intracalcarine cortex	Right	1048	<.001	12	−94	18	6.22	13.9	−86.4	22.7
2	Lingual gyrus (anterior) Temporal occipital fusiform cortex Parahippocampal gyrus (posterior)	Right	674	<.001	32	−46	−4	4.46	32.2	−41.6	−12.7
3	Lateral occipital cortex	Right	337	.01	46	−80	6	3.95	46.4	−78.9	5

Note: Brain regions with significant activation using a significance level set a priori at $P < .05$; Gaussian random field cluster corrected, and z threshold set at $z > 2.3$.

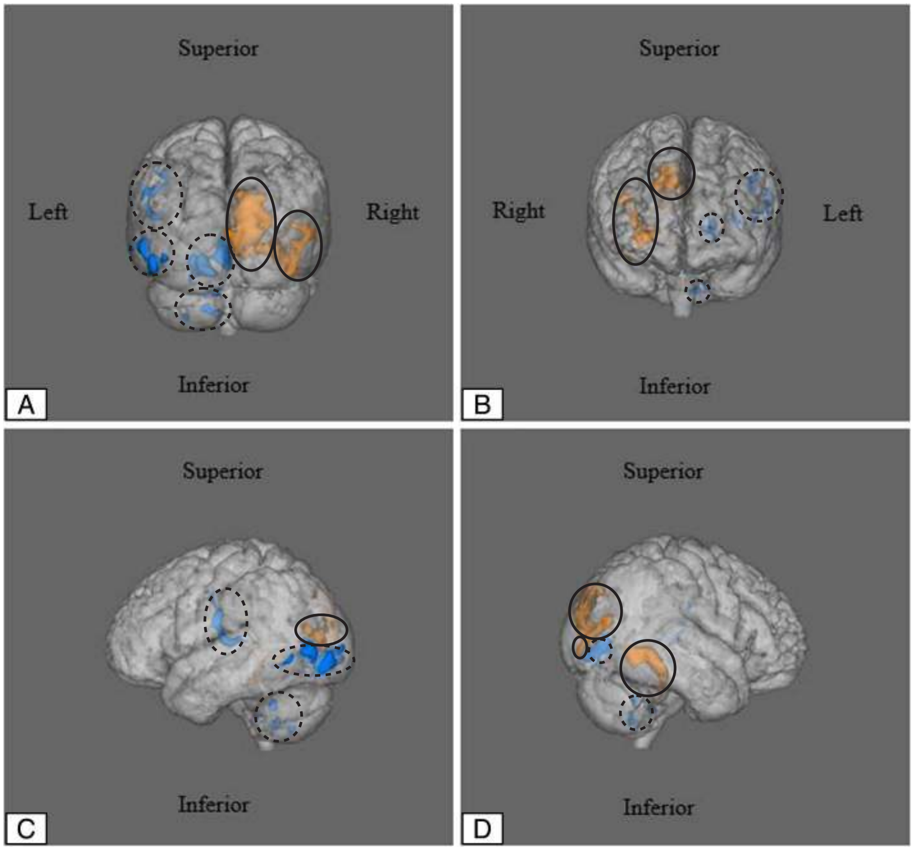

Figure 2 — Brain regions with increased activation ($P < .001$) during the external focus condition (colored orange and surrounded by solid circles) and internal focus condition (colored blue and surrendered by dashed circles). Note that the solid and dashed circles do not encompass the precise spatial characteristics of the activation clusters (to be used as a reference for black and white versions of the manuscript). (A) Posterior view, (B) anterior view, (C) left posterior–lateral view, and (D) right posterior–lateral view.

Table 2 Internal Focus > External Focus Contrast

					MNI coordinate of peak voxel				Z center of gravity		
Cluster index	**Brain regions**	**Side**	**Voxels #**	***P* value**	***x***	***y***	***z***	Z_{max}	***x***	***y***	***z***
1	Lingual gyrus Occipital pole Occipital fusiform gyrus	Left	725	<.001	2	−80	−6	4.28	−10.1	−82.1	−4.58
2	Lateral occipital cortex	Left	473	<.001	−54	−72	6	4.01	−50.1	−79.1	−1.27
3	Postcentral gyrus Heschl's gyrus Precentral gyrus	Left	301	<.001	−58	−14	20	3.54	53.7	−18	19.7
4	Cerebellum: IX, VIIb	Left	265	.01	−30	−65	−54	3.35	−14	−52.2	−48

Note: Brain regions with significant activation using a significance level set a priori at $P < .05$; Gaussian random field cluster corrected, and z threshold set at $z > 2.3$.

focus promotes automaticity and an internal focus elicits conscious control over motor movement, therefore, this study assessed this role of each type of focus on brain activity measured using fMRI.

Congruent with our first hypothesis, an external focus of attention directed toward a visual target, relative to an internal focus of attention directed purely through instruction, increased activation in areas of brain regions associated with vision. Increased activation was detected in the occipital pole, cuneal cortex, anterior portion of the lingual gyrus, and intracalcarine cortex. The cuneal cortex, lingual gyrus, and intracalcarine cortex are located within the occipital pole which is highly responsive to visual stimuli[32–34] and we believe that the added external target, relative to no visual target for internal focus, plausibly explains this increased activation. However, we did not include an external focus condition without a visual target to disentangle whether the increased visual region activation was a product of the external focus or the visual target. We also detected increased activation of the temporal-occipital fusiform gyrus cortex during the external focus condition directed toward a visual target. The occipital fusiform gyrus is highly involved with object recognition,[35] which may suggest that an external focus augments sensory streaming, but requires further investigations that incorporate behavioral and sensory measures.[36,37] Similarly, we found increased activation in the parahippocampal gyrus, which is associated with memory and encoding of environmental stimuli[38] and complements the findings of Zentgraf et al[16] that revealed increased somatosensory activation for an external focus.

Externally focused instructions can facilitate not only gross motor performance of a jumping task, but also kinematic values related to knee range of motion that could affect injury prevention.[12] Following externally focused instructions, individuals increased peak knee flexion during a single-leg hop compared with the internally focused group.[12] These differences can be explained by the constrained action hypothesis which states that when we pay attention (by using internal focus) to our movement output, we can disrupt the automaticity of a previously well-learned movement. Although the study is limited by lack of motor performance comparisons, our results provide information pertaining to the brain regions responsible for processing attentional focus instruction with and without additional visual stimuli within a controlled environment.

In support of our second hypothesis, we found that an internal focus increased activation in motor regions, specifically the precentral gyrus (ie, primary motor cortex or M1), the postcentral gyrus (ie, the supplementary motor cortex), and cerebellum. While participants performed the same motor task in both conditions under a controlled environment, the fMRI data revealed increased brain activity within motor regions when participants were given internal focus instruction. The primary role of the precentral gyrus is motor function, while integrating signals from the supplementary motor cortex to execute movement.[39] Similarly, the supplementary motor cortex responsible for the planning and coordination of complex movements and is activated during real or imagined movements.[40] The increased activation in motor regions for our internal focus condition is inconsistent with that of Zentgraf et al,[16] but may due to the controlled nature of our task (as opposed to self-paced). Alternatively, it may be due to the gross motor task used in this study, but highlights the differences in brain activation that occur depending on skill type and instructional demands. In addition, we detected increased activation in Heschl's gyrus during the internal focus condition. This region is located within the auditory cortex and contributes to auditory processing[41] and tentatively supports the concept that individuals will experience increased cognitive demands when processing internal focus instruction. While the cerebellum has traditionally been considered to be primarily involved in motor function, it is increasingly understood to have a much wider function due to parietal and prefrontal lobe connections.[42] Specifically Lobule VII of the cerebellum, which we demonstrate to be activated to a greater degree in the internal condition, has been associated with increased cognitive demands.[43,44] This may indicate that an internal focus of attention may increase cognitive demand relative to external focus and warrants future investigations with complementary psychometric measures to assess attentional resources. During our internal focus manipulation, we also found increased visual region activation, specifically in the occipital fusiform gyrus and posterior region of the lingual gyrus. The occipital fusiform gyrus is involved with body recognition (eg, face recognition)[45,46] and it is cautiously posited that internal focus instructions of "squeezing their quadriceps" engaged a similar neural recruitment strategy for limb recognition. However, it should be noted the blood oxygenation level dependent response captured here with fMRI is a secondary measure and has limitations and does not give complete insight into neural activity. It is possible other aspects of neurophysiology or individual cognitive states may contribute to the differences seen here.

Our choice of only including a visual target for our external focus condition may make it appear difficult to compare brain activation differences with the internal focus condition. While we are aware that standard attentional focus paradigms only manipulate instruction,[3] this was intentional due to the logistics of our design. When inside an MRI scanner, the field of view displayed through the mirror is small relative to the standard field of view participants have when engaging in typical attentional focus paradigms (ie, participants can look in any direction). Pilot testing revealed that the placement of our target encapsulated nearly the entire field of view for participants. Therefore, if the target remained hanging for the internal focus condition, participants may have ignored our instruction and visually relied on the target for movement control. Thus, we contend that our data were a satisfactory initial step in understanding brain activity associated with attentional focus and gross motor control, but further research is warranted that manipulates the presence of additional visual stimuli. We also acknowledge that the use of the metronome was more in line with attentional focus manipulations that utilize dual-task methodology,[2,17,47,48] but this was also intentional as attentional focus instruction can alter movement speed.[49,50] We did not want to confound our neuroimaging data with the effects of attentional focus on movement speed.

Conclusions

The results from this study are the first to show brain activation differences during a gross motor task when following specific attentional focus instructions. Relative to internal focus direction, an external focus directed toward a visual target produced more cortical activity in brain regions associated with vision and ventral streaming pathways. This increased activation may increase the important, relevant, and goal-oriented aspects of the task, which could be influential in the development of positive neuroplasticity and provide a partial explanation for the beneficial effects of an external focus for motor learning. In contrast, relative to an external focus, internal focus increased activation in brain regions that are responsible for motor control. We believe that this is the first neural mechanistic data showing that an internal focus engages brain regions associated with motor control furthering our understanding of the deleterious effects of an internal focus. We consider that previous reports of poor neuromuscular efficiency,[51] reduced maximal force production,[11] and overall poorer performance resulting from an internal focus[3] may be due to differences in cortical processing. Little attention has been given to positively affecting neurologic adaptations during orthopedic prevention and rehabilitation.[52] Results from this study serve as baseline information for future prevention and rehabilitation investigations of how manipulating the focus of attention can constructively affect neural control during training and rehabilitation.

References

1. Beilock SL, Carr TH, MacMahon C, Starkes JL. When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *J Exp Psychol Appl*. 2002;8(1):6–16. PubMed ID: 12009178 doi:10.1037/1076-898X.8.1.6

2. Gray R. Attending to the execution of a complex sensorimotor skill: expertise differences, choking, and slumps. *J Exp Psychol Appl*. 2004;10(1):42–54. PubMed ID: 15053701 doi:10.1037/1076-898X.10.1.42
3. Wulf G. Attentional focus and motor learning: a review of 15 years. *Int Rev Sport Exerc Psychol*. 2013;6(1):77–104. doi:10.1080/1750984X.2012.723728
4. Wulf G, Höß M, Prinz W. Instructions for motor learning: differential effects of internal versus external focus of attention. *J Mot Behav*. 1998;30(2):169–179. PubMed ID: 20037032 doi:10.1080/00222899809601334
5. Diekfuss JA, Rhea CK, Schmitz RJ, et al. The influence of attentional focus on balance control over seven days of training. *J Mot Behav*. 2019;51(3):281–292. doi:10.1080/00222895.2018.1468312
6. McNevin NH, Shea CH, Wulf G. Increasing the distance of an external focus of attention enhances learning. *Psychol Res*. 2003;67(1):22–29. PubMed ID: 12589447
7. Wulf G, McNevin N, Shea CH. The automaticity of complex motor skill learning as a function of attentional focus. *Q J Exp Psychol A*. 2001;54(4):1143–1154. PubMed ID: 11765737 doi:10.1080/713756012
8. Wulf G, Shea C, Park J-H. Attention and motor performance: preferences for and advantages of an external focus. *Res Q Exerc Sport*. 2001;72(4):335–344. PubMed ID: 11770783 doi:10.1080/02701367.2001.10608970
9. Benjaminse A, Gokeler A, Dowling AV, et al. Optimization of the anterior cruciate ligament injury prevention paradigm: novel feedback techniques to enhance motor learning and reduce injury risk. *J Orthop Sports Phys Ther*. 2015;45(3):170–182. PubMed ID: 25627151 doi:10.2519/jospt.2015.4986
10. Gokeler A, Benjaminse A, Hewett TE, et al. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. *Sports Med*. 2013;43(11):1065–1074. PubMed ID: 24062274 doi:10.1007/s40279-013-0095-0
11. Ducharme SW, Wu WFW, Lim K, Porter JM, Geraldo F. Standing long jump performance with an external focus of attention is improved as a result of a more effective projection angle. *J Strength Cond Res*. 2016;30(1):276–281. PubMed ID: 26691415 doi:10.1519/JSC.0000000000001050
12. Gokeler A, Benjaminse A, Welling W, Alferink M, Eppinga P, Otten B. The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. *Phys Ther Sport*. 2015;16(2):114–120. PubMed ID: 25443228 doi:10.1016/j.ptsp.2014.06.002
13. Porter JM, Anton PM, Wu WFW. Increasing the distance of an external focus of attention enhances standing long jump performance. *J Strength Cond Res*. 2012;26(9):2389–2393. PubMed ID: 22067252 doi:10.1519/JSC.0b013e31823f275c
14. Gottlieb J. Attention, learning, and the value of information. *Neuron*. 2012;76(2):281–295. PubMed ID: 23083732 doi:10.1016/j.neuron.2012.09.034
15. Al-Abood SA, Bennett SJ, Hernandez FM, Ashford D, Davids K. Effect of verbal instructions and image size on visual search strategies in basketball free throw shooting. *J Sports Sci*. 2002;20(3):271–278. PubMed ID: 11999481 doi:10.1080/026404102317284817
16. Zentgraf K, Lorey B, Bischoff M, Zimmermann K, Stark R, Munzert J. Neural correlates of attentional focusing during finger movements: a fMRI study. *J Mot Behav*. 2009;41(6):535–541. PubMed ID: 19567364 doi:10.3200/35-08-091
17. Raisbeck LD, Diekfuss JA. Fine and gross motor skills: the effects on skill-focused dual-tasks. *Hum Mov Sci*. 2015;43:146–154. PubMed ID: 26296039 doi:10.1016/j.humov.2015.08.007
18. Knight HC, Smith DT, Knight DC, Ellison A. Altering attentional control settings causes persistent biases of visual attention. *Q J Exp Psychol*. 2016;69(1):129–149. doi:10.1080/17470218.2015.1031144
19. Grooms DR, Page SJ, Onate JA. Brain activation for knee movement measured days before second anterior cruciate ligament injury: neuroimaging in musculoskeletal medicine. *J Athl Train*. 2015;50(10):1005–1010. PubMed ID: 26509775 doi:10.4085/1062-6050-50.10.02
20. Kapreli E, Athanasopoulos S, Papathanasiou M, et al. Lower limb sensorimotor network: issues of somatotopy and overlap. *Cortex*. 2007;43(2):219–232. PubMed ID: 17405668 doi:10.1016/S0010-9452(08)70477-5
21. Beilock SL, Carr TH. On the fragility of skilled performance: what governs choking under pressure? *J Exp Psychol Gen*. 2001;130(4):701–725. PubMed ID: 11757876 doi:10.1037/0096-3445.130.4.701
22. Castaneda B, Gray R. Effects of focus of attention on baseball batting performance in players of differing skill levels. *J Sport Exerc Psychol*. 2007;29(1):60–77. PubMed ID: 17556776 doi:10.1123/jsep.29.1.60
23. Smith SM, Jenkinson M, Woolrich MW, et al. Advances in functional and structural MR image analysis and implementation as FSL. *NeuroImage*. 2004;23:S208–S219. PubMed ID: 15501092 doi:10.1016/j.neuroimage.2004.07.051
24. Jenkinson M, Bannister P, Brady M, Smith S. Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage*. 2002;17(2):825–841. PubMed ID: 12377157 doi:10.1006/nimg.2002.1132
25. Smith SM. Fast robust automated brain extraction. *Hum Brain Mapp*. 2002;17(3):143–155. PubMed ID: 12391568 doi:10.1002/hbm.10062
26. Pruim RHR, Mennes M, van Rooij D, Llera A, Buitelaar JK, Beckmann CF. ICA-AROMA: a robust ICA-based strategy for removing motion artifacts from fMRI data. *NeuroImage*. 2015;112:267–277. PubMed ID: 25770991 doi:10.1016/j.neuroimage.2015.02.064
27. Pruim RHR, Mennes M, Buitelaar JK, Beckmann CF. Evaluation of ICA-AROMA and alternative strategies for motion artifact removal in resting state fMRI. *NeuroImage*. 2015;112:278–287. PubMed ID: 25770990 doi:10.1016/j.neuroimage.2015.02.063
28. Beckmann CF, Jenkinson M, Smith SM. General multilevel linear modeling for group analysis in FMRI. *NeuroImage*. 2003;20(2):1052–1063. PubMed ID: 14568475 doi:10.1016/S1053-8119(03)00435-X
29. Woolrich MW, Ripley BD, Brady M, Smith SM. Temporal autocorrelation in univariate linear modeling of FMRI data. *NeuroImage*. 2001;14(6):1370–1386. PubMed ID: 11707093 doi:10.1006/nimg.2001.0931
30. Worsley KJ. Statistical analysis of activation images. In: Jezzard P, Matthews PM, Smith SM eds. *Functional Magnetic Resonance Imaging*. Oxford University Press; 2001:251–270. http://www.oxfordscholarship.com/view/10.1093/acprof:oso/9780192630711.001.0001/acprof-9780192630711
31. Woolrich M. Robust group analysis using outlier inference. *NeuroImage*. 2008;41(2):286–301. PubMed ID: 18407525 doi:10.1016/j.neuroimage.2008.02.042
32. Epstein R, Kanwisher N. A cortical representation of the local visual environment. *Nature*. 1998;392(6676):598–601. PubMed ID: 9560155 doi:10.1038/33402
33. Grill-Spector K, Kushnir T, Hendler T, Edelman S, Itzchak Y, Malach R. A sequence of object-processing stages revealed by fMRI in the human occipital lobe. *Hum Brain Mapp*. 1998;6(4):316–328. doi:10.1002/(SICI)1097-0193(1998)6:4<316::AID-HBM9>3.0.CO;2-6

34. Winawer J, Horiguchi H, Sayres RA, Amano K, Wandell BA. Mapping hV4 and ventral occipital cortex: the venous eclipse. *J Vis*. 2010;10(5):1–1. PubMed ID: 20616143 doi:10.1167/10.5.1
35. Tyler LK, Chiu S, Zhuang J, et al. Objects and categories: feature statistics and object processing in the ventral stream. *J Cogn Neurosci*. 2013;25(10):1723–1735. PubMed ID: 23662861 doi:10.1162/jocn_a_00419
36. Bracci S, Caramazza A, Peelen MV. Representational similarity of body parts in human occipitotemporal cortex. *J Neurosci*. 2015; 35(38):12977–12985. PubMed ID: 26400929 doi:10.1523/JNEUROSCI.4698-14.2015
37. Peelen MV, Caramazza A. Conceptual object representations in human anterior temporal cortex. *J Neurosci*. 2012;32(45):15728–15736. PubMed ID: 23136412 doi:10.1523/JNEUROSCI.1953-12.2012
38. Takahashi E, Ohki K, Miyashita Y. The role of the parahippocampal gyrus in source memory for external and internal events. *NeuroReport*. 2002;13(15):1951–1956. PubMed ID: 12395098 doi:10.1097/00001756-200210280-00024
39. Rao SM, Binder JR, Bandettini PA, et al. Functional magnetic resonance imaging of complex human movements. *Neurology*. 1993; 43(11):2311–2311. PubMed ID: 8232948 doi:10.1212/WNL.43.11.2311
40. Porro CA, Cettolo V, Francescato MP, et al. Functional activity mapping of the perirolandic cortex during motor performance and motor imagery. In: Pavone P, Rossi P eds.*Functional MRI* (Bracco Education in Diagnostic Imaging). Springer Milan; 1996:49–51. doi:10.1007/978-88-470-2194-5_11/a>
41. Da Costa S, van der Zwaag W, Marques JP, Frackowiak RSJ, Clarke S, Saenz M. Human primary auditory cortex follows the shape of Heschl's Gyrus. *J Neurosci*. 2011;31(40):14067–14075. PubMed ID: 21976491 doi:10.1523/JNEUROSCI.2000-11.2011
42. O'Reilly JX, Beckmann CF, Tomassini V, Ramnani N, Johansen-Berg H. Distinct and overlapping functional zones in the cerebellum defined by resting state functional connectivity. *Cereb Cortex*. 2010;20(4):953–965. doi:10.1093/cercor/bhp157
43. Allen G, Buxton RB, Wong EC, Courchesne E. Attentional activation of the cerebellum independent of motor involvement. *Science*. 1997;275(5308):1940–1943. PubMed ID: 9072973 doi:10.1126/science.275.5308.1940
44. Desmond JE, Gabrieli JD, Wagner AD, Ginier BL, Glover GH. Lobular patterns of cerebellar activation in verbal working-memory and finger-tapping tasks as revealed by functional MRI. *J Neurosci*. 1997;17(24):9675–9685. PubMed ID: 9391022 doi:10.1523/JNEUROSCI.17-24-09675.1997
45. Iidaka T. Role of the fusiform gyrus and superior temporal sulcus in face perception and recognition: an empirical review. *Jpn Psychol Res*. 2013;56(1):33–45. doi:10.1111/jpr.12018
46. Kanwisher N, Yovel G. The fusiform face area: a cortical region specialized for the perception of faces. *Philos Trans R Soc Lond B Biol Sci*. 2006;361(1476):2109–2128. PubMed ID: 17118927 doi:10.1098/rstb.2006.1934
47. Diekfuss JA, Ward P, Raisbeck LD. Attention, workload, and performance: a dual-task simulated shooting study. *Int J Sport Exerc Psychol*. 2016;15(4):423–437. doi:10.1080/1612197X.2015.1121508
48. Raisbeck LD, Suss J, Diekfuss JA, Petushek E, Ward P. Skill-based changes in motor performance from attentional focus manipulations: a kinematic analysis. *Ergonomics*. 2016;59(7):941–949.
49. Ille A, Selin I, Do M-C, Thon B. Attentional focus effects on sprint start performance as a function of skill level. *J Sports Sci*. 2013;31(15):1705–1712. PubMed ID: 23710928 doi:10.1080/02640414.2013.797097
50. Porter JM, Wu WF, Crossley RM, Knopp SW, Campbell OC. Adopting an external focus of attention improves sprinting performance in low-skilled sprinters. *J Strength Cond Res*. 2015;29(4):947–953. PubMed ID: 25811269 doi:10.1097/JSC.0000000000000229
51. Vance J, Wulf G, Töllner T, McNevin N, Mercer J. EMG activity as a function of the performer's focus of attention. *J Mot Behav*. 2004; 36(4):450–459. PubMed ID: 15695233 doi:10.3200/JMBR.36.4.450-459
52. Grooms DR, Myer GD. Upgraded hardware horizontal line—What about the software? Brain updates for return to play following ACL reconstruction. *Br J Sports Med*. 2017;51(5):418–419. doi:10.1136/bjsports-2016-096658