

A distal external focus of attention facilitates compensatory coordination of body parts

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Abstract

Many studies have shown that focusing on an intended movement effect that is farther away from the body (distal external focus) results in performance benefits relative to focusing on an effect that is closer to the body (proximal external focus) or focusing on the body itself (internal focus) (see Chua, Jimenez-Diaz, Lewthwaite, Kim, & Wulf, 2021). Furthermore, the advantages of a distal external focus seem to be particularly pronounced in skilled performers (Singh & Wulf, 2020). The present study examined whether such benefits of more distal attentional focus may be associated with enhanced functional variability. Volleyball players ($n = 20$) performed sixty overhand volleyball serves to a target. Using a within-participants design, the effects of a distal external focus (bullseye), proximal external focus (ball), and an internal focus (hand) were compared. The distal focus condition resulted in significantly higher accuracy scores than did the proximal and internal focus conditions. In addition, uncontrolled manifold analysis showed that functional variability (as measured with the index of synergy) was greatest in the distal focus condition. These findings suggest that a distal external focus on the task goal may enhance movement outcomes by optimizing compensatory coordination of body parts.

Key words: Attentional focus, functional variability, volleyball, distance effect, coaching

Introduction

The ability to control the motor system's many degrees of freedom to produce consistent, accurate, and effective coordination is a distinguishing characteristic of skilled performance. Across repetitions of the same motor task, it is well known that there are numerous different movement strategies the performer can employ to achieve a task goal (Davids, Bennett, & Newell, 2006; Davids, Glazier, Araujo, & Bartlett, 2003; Riley & Turvey, 2002). For example, when shooting a free throw in basketball, the same velocity-angle combination at ball release can result from various combinations of joint motions and muscle activations. Insight into movement variability suggests that motor elements can compensate each other to control for a particular movement outcome (Arutyunyan, Gurfinkel, & Mirskii, 1968; Bootsma & Wieringen, 1990; Cohen & Sternad, 2009; Edelman & Gally, 2001; Gelfand & Latash, 1998; Latash, 2012, Latash, 2021). How a particular coordination pattern emerges is a fundamental question of motor control (Bernstein, 1967; Turvey, 1990; Latash 1996).

The coupling of intended goals to movement actions (goal-action coupling) is influenced, among other things, by what the performer focuses on during the preparation of movement execution (Wulf & Lewthwaite, 2016). Over the past two decades, considerable evidence has shown that the type of a performer's focus of attention can result in distinct differences in performance and learning outcomes (for reviews, see Lohse, Wulf, & Lewthwaite, 2012; Wulf, 2013; Wulf & Lewthwaite, 2016; Wulf & Prinz, 2001). Specifically, an external focus on the intended movement effect or task goal, such as the motion of an implement, planned trajectory of a ball, or simply hitting a target, results in performance benefits compared to an internal focus on body movements. Recent meta-analyses (Chua, Jimenez-Diaz, Lewthwaite, Kim, & Wulf, 2021) confirmed the superiority of an external focus for both immediate performance and learning (retention, transfer), regardless of age, health condition, or level of expertise. Since the pioneering work by Wulf, Höß, and Prinz (1998), adopting an external focus has been found to enhance fluency in movement execution (e.g., Kal, van der Kamp, & Houdijk, 2013; Lohse, 2012), lead to

greater neuromuscular efficiency (e.g., Greig & Merchant, 2014; Zachry et al., 2005), produce kinematic changes (i.e., movement form) typical of skilled performers (e.g., An, Wulf, & Kim, 2013; Parr & Button, 2009), and facilitate more economical neural strategies (Kuhn, Keller, Ruffleux, & Taube, 2017; Kuhn, Keller, Lauber, & Taube, 2018, Kuhn, Keller, Eggar, & Taube, 2021). In contrast, an internal focus leads to conscious control attempts and interferes with the motor system's automatic control processes (Wulf, McNevin, & Shea, 2001).

Differences in movement kinematics show that coordination strategies are different as a function of attentional focus. In general, there are indications that an internal focus may lead to “freezing” of the body's degrees of freedom (i.e., reduced joint range of motion along with tightly coupled motion of different joints) (van Ginneken et al., 2018). For example, Ford et al. (2009) found that an internal focus resulted in higher cross-correlations between various joint pairs compared to an external focus when performing soccer kicks. Along the same times, Vidal et al. (2018) performed a vector coding technique to examine the effects of focus of attention on interlimb coordination during a standing long jump. In their study, an internal focus constrained the motor system by predominantly using the knees and reducing movement of the hip and ankle joints. In contrast, an external focus may help to “free” the body's degrees of freedom to produce “functional” couplings of joints and body segments (see also Hossner & Ehrlenspiel, 2010; Tuller & Turvey, 1982; Vereijken, van Emmerik, Whiting, & Newell, 1992; Wulf & Dufek, 2009). Wulf and Prinz (2001) first speculated that focusing on the movement effect (i.e., external focus) may facilitate compensatory variability such that the motor system adjusts the various degrees of freedom (e.g., kinematic) to ensure the desired movement effect is achieved, whereas focusing on the movement themselves (i.e., internal focus) interferes with this process. Indeed, several studies provide support for this idea (Fietzer, Winstein, & Kulig, 2018; Lohse, Jones, & Healy, 2014; Lohse, Sherwood, & Healy, 2010). For example, in a series of dart throwing studies, higher accuracy and consistency was accompanied by increased kinematic variability at the joint level

(i.e., freeing degrees of freedom) when instructed with an external relative to an internal focus (Lohse et al., 2010, 2014).

The above-described increase in kinematic variability coupled to increased consistency in movement outcome is indicative of enhanced *functional variability*, or the compensatory mechanism in which degrees of freedom coordinate action execution without relying on conscious adaptations (Bernstein, 1967; Edelman & Gally, 2001; Gelfand & Latash 1998; Latash, 2012; Newell, 1986). Functional variability is a key property exhibited by skilled individuals (Buszard et al., 2020; Hiley, Zuevsky, & Yeadon, 2013; Müller & Loosch, 1999; Williams et al., 2020; Wilson et al., 2008). For example, Button et al. (2003) showed that an increase in skill level in basketball free-throw shooting was associated with increased movement variability at the elbow and wrist joint, with deviations in these joint angles seemingly compensating one another to reduce variability in release parameters that are critical to performance outcome (e.g., release velocity). It thus seems that an external focus promotes performance by enhancing a performer's ability to exploit a variety of movement patterns to produce stable motor output ("execution redundancy") (Ranganathan & Newell, 2013).

However, most studies so far have only inferred the effects of an external focus on functional variability using indirect methods, by simultaneous assessment of performance accuracy and correlations between joint kinematics, providing a relative magnitude of variability. For example, when pitching a fast ball in baseball to a target location (e.g., catcher's glove), the optimal pitching velocity can be achieved through a simultaneous increase in elbow extension and wrist flexion at ball release (Pappas, Zawacki, & Sullivan, 1985). What is undetected by such approach is the degree to which compensatory variability in joint kinematics contributes to stabilizing task variables that are essential determinants to the performance outcome. In other words, it is unclear what combinations of elbow and wrist kinematics resulted in achieving the same pitching velocity (e.g., decrease in elbow extension and increase in wrist flexion)?

Therefore, a more valid approach to quantify functional variability is the uncontrolled manifold (UCM) analysis (Scholz & Schöner, 1999; Schöner & Scholz, 2007).

According to the UCM hypothesis, for each repetition of a motor task, the controller (central nervous system) selects a manifold within the joint space that corresponds to a fixed instantaneous value of the selected task-relevant performance variable that ensures appropriate motor output (Latash, Scholz, Danion, & Schöner, 2001). Therefore, its methodology is based on how much variance in combinations of different joint angles contributes to variance in the task-relevant performance variable of interest. When specific performance variables are to be stabilized (e.g., angle of velocity of a ball release in a throwing task), the trial-to-trial co-variation or compensatory behavior among *elemental* variables (e.g., variables directly affecting performance, such as shoulder, elbow, and wrist joint angles) is divided into two components. The first (V_{UCM}) is considered performance-stabilizing variability, where the variance of elemental variables does not affect the value of a particular performance variable. The second (V_{ORT}) is considered performance-destabilizing, where variance of the elemental variables does affect the value of the performance variable, leading to inconsistent movement outcomes. Combined, V_{UCM} and V_{ORT} can be used to gauge the strength of synergistic control that aids in stabilizing the performance variable. That is, relatively greater V_{UCM} versus V_{ORT} indicates a higher index of synergy (and hence greater functional variability), as this points to coordinated compensatory activity to overall maintain movement outcome consistency. The UCM analysis has been utilized to investigate tasks such as shooting (Scholz, Shöner, & Latash, 2000), throwing (Yang & Scholz, 2005), and stone knapping (Rein, Bril, & Nonaka, 2013). A few studies have investigated differences in skill level when performing a golf swing (Morrison, McGrath, & Wallace, 2016), table tennis forehand (Lino, Yoshioka, & Fukashiro, 2017), robotic teleoperation (Nisky, Hsieh, & Okamura, 2014), and running (Möhler et al., 2020). For example, skilled golfers showed higher values of V_{UCM} compared to lower skilled players when performing a golf swing (Morrison,

McGrath, & Wallace, 2016). Fietzer et al. (2018) compared three different attentional foci (control, internal, external) during the performance of a unipedal hopping task using the UCM. The authors found that an external focus enhanced functional variability by increasing leg length stabilization (i.e., increase V_{UCM}) such that the leg was able to orient differently at takeoff and landing to compensate for any perturbation during the hopping movement. These changes in motor control associated with an external focus (i.e., increased functional variability) reflect movement coordination patterns and movement outcomes typically seen at higher skill levels and suggest enhanced goal-action coupling (Wulf & Lewthwaite, 2016).

While experimental evidence shows that an external focus results in superior performance, some external foci may be more effective than others. McNevin, Shea, and Wulf (2003) first showed that the spatial distance between an action and its effect is a critical factor in determining the advantage associated with an external focus. That is, distal external foci located at farther distances from the body result in greater performance benefits than proximal external foci located closer or in greater proximity to the body (e.g., Banks et al., 2020; Coker, 2016; Duke, Cash, & Allen, 2011; Kearney, 2015; Raisbeck & Yamada, 2019). For example, in a series of standing long jump studies by Porter et al. (2012, 2013), participants jumped farther when instructed with a distal focus (“jump as close to the cone as possible”) relative to a proximal focus (“jump as fast past the start line as possible”). A recent meta-analysis on the distance effect confirmed the greater effectiveness of distal relative to proximal external foci (Chua et al., 2021). One reason for the distance effect might be that distal foci are more easily distinguishable from body movements compared to proximal foci (McNevin et al., 2003). Furthermore, a distal focus might trigger the whole movement pattern necessary to achieve the desired outcome, particularly in skilled performers for whom movement control has become largely automatic, whereas a proximal focus might disrupt the fluidity of their movements (Singh & Wulf, 2020).

On the basis of the assumption that an external focus increases functional variability and recent evidence suggesting that skilled performers are more accurate with a distal relative to a proximal external focus (Singh & Wulf, 2020), the purpose of the present study was to examine whether a distal focus would increase functional variability in skilled performers. Using an overhand volleyball serve, the effects of internal, proximal external, and distal external foci were compared. The UCM analysis was used to quantify the functionality of movement variability under each attentional focus condition. We hypothesized that a distal external focus would result in higher accuracy scores as well as increased functional variability compared to a more proximal or internal focus.

Methods

Participants

An estimated effect size of $\eta^2_p = .11$ (Stambaugh, 2017; Zarghami et al., 2012) was utilized to conduct a power analysis using G*Power 3.1 (Faul, Erdfelder, Land, & Buchner, 2007). For a repeated measures ANOVA, with an α -level set at .05 and 90% power, a sample size of 19 participants was estimated. Twenty skilled volleyball players (7 males, 13 females) with a mean age of 25.2 years (SD = 4.71) participated in the study. Participants were current or former collegiate and professional volleyball players with up to 4 years of collegiate varsity playing experience who had a basic understanding of the overhand volleyball serve. All participants reported no musculoskeletal injury in the previous 6 months, played an average of 10-20 hours of competitive volleyball each week, and gave their informed consent before beginning the experiment. All participants also reported being right hand dominant when serving, meaning they perform the overhand volleyball serve using their right arm when striking the ball. The study was approved by the university's institutional review board.

Apparatus and task

Participants were asked to serve a volleyball (Molten Flistatec V5M5000-3N) towards a target, using a standing overhand serve. The target was a bullseye that was located 6.09 m away. A regulation size volleyball net was located 3.04 m in front of the participant. Consistent with both National (NCAA) and international regulations (FIVB), the net height was adjusted to 2.24 m for female participants and 2.43 m for male participants. The target itself consisted of four concentric circles with diameters of 30, 60, 90, and 120 cm, respectively. Four points were awarded if the ball landed in the bullseye. For each progressively larger circle, three, two, and one points was awarded, while zero points were given if participants missed the target completely. A video recorder mounted on a tripod directly facing the target was used to record the points scored on each trial. All trials were scored offline by the experimenter. A schematic of the lab set up and apparatus can be seen in Figure 1.

Participants were outfitted with a modified VICON Plug-in Gait upper body marker set (Figure 2). Reflective markers were placed at the following landmarks: C7, T10, jugular notch of sternum, xiphoid process of sternum, right back, acromio-clavicular joint, upper arm (3 markers), medial and lateral epicondyle of humerus, forearm, styloid process of the radius, styloid process of the ulna, proximal interphalangeal joint of the third digit (middle finger) and head (4 markers attached to a headband). 3D kinematic data was collected by a 12-camera VICON motion capture system at a 250Hz sampling rate. The lab coordinates corresponded to the individual with the x axis indicating mediolateral, y axis indicating anteroposterior, and z axis indicating superiorinferior directions.

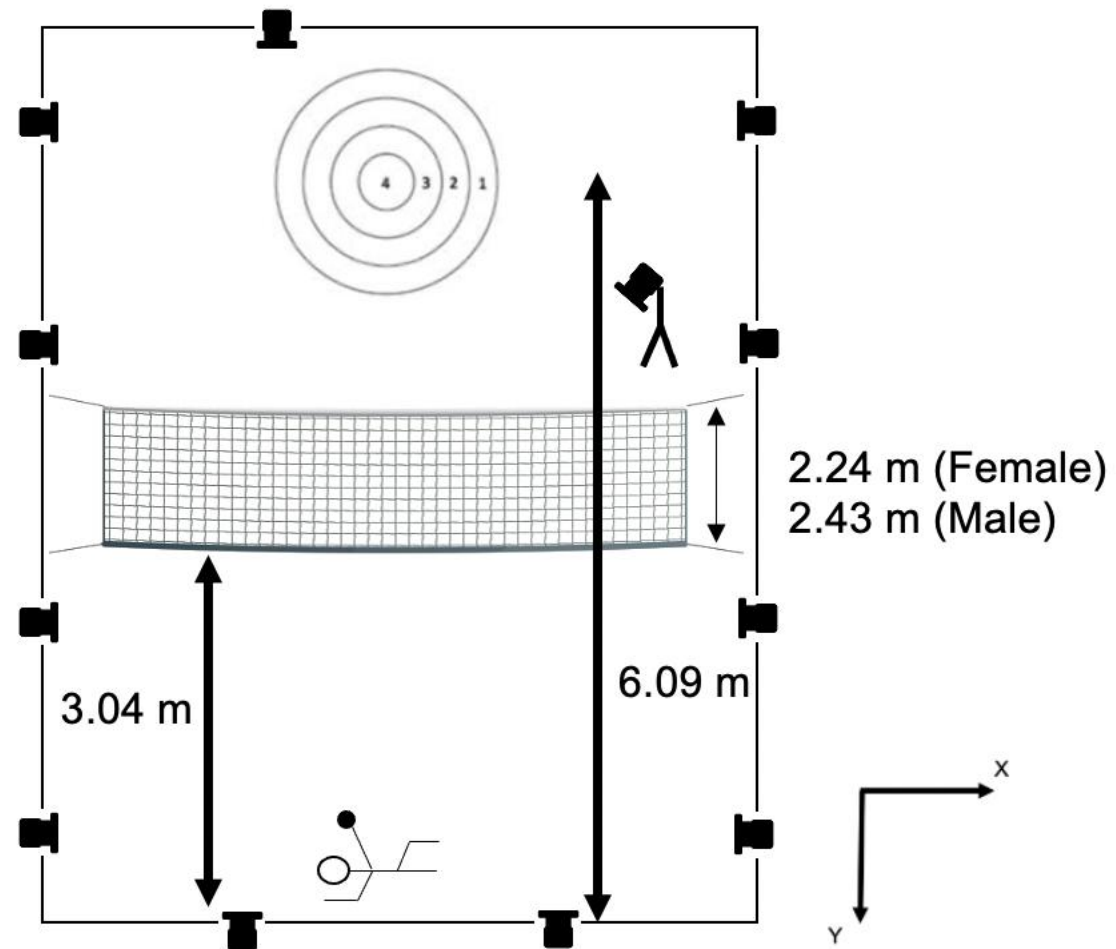


Figure 1. Schematic of lab and apparatus

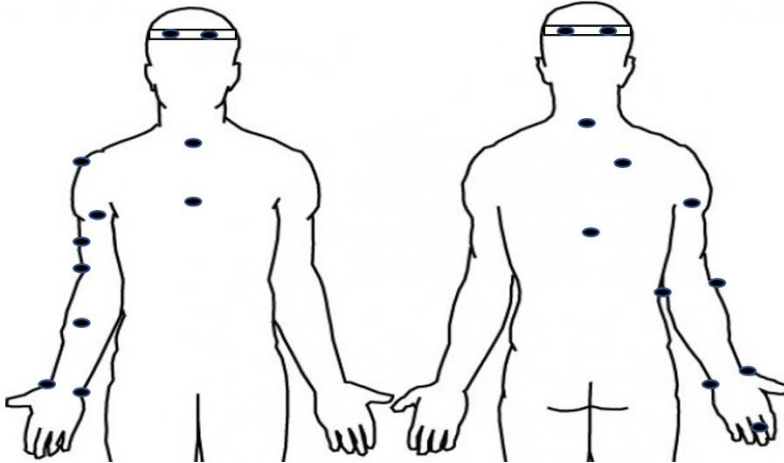


Figure 2. Upper body marker set

Procedure

Prior to performing a practice trial, participants performed a dynamic stretch on their own. All participants were informed that the task goal was to achieve the highest possible score on each serve (referring to the score that corresponded to the circle in which the ball landed). After completing a static standing trial and five warm-up trials with no instructions, participants performed 20 trials under each of the three attentional focus conditions (internal focus, proximal external, distal external) for a total of 60 serves. The order of conditions was counterbalanced, using all six possible orders. (As the study included 20 participants, the orders internal focus – proximal external focus – distal external focus and proximal external focus – distal external focus – internal focus were used four times.) In the internal focus condition, participants were instructed to “focus on your hand while contacting the ball.” In the proximal external focus condition, participants were instructed to “focus on contacting the middle of the ball.” In the distal external focus condition, participants were instructed to “focus on hitting the bullseye.” Each trial started with the experimenter repeating the instruction followed by a verbal “go” command to assure

kinematic data collection had started. A 15- second rest period was given after each trial followed by a 2-minute rest period after each block of 20 trials.

Dependent Variables and Data Analysis

Accuracy scores were averaged across all 20 trials in each focus condition. In addition, all trials were labeled and further processed using Visual 3D (C-Motion, Rockville, MD, USA). Kinematic data were lowpass-filtered using a 4th order Butterworth filter with a cutoff frequency of 6Hz (Bartlett, 2007; Cho & Ju, 2006; Delp et al., 2007). Trials were cut into the window of interest, from the frame that the marker on the dominant (serving side) acromio-clavicular joint started moving forward in sagittal plane to the frame that the ball had the peak acceleration in y direction. Each trial was normalized to 100 frames for uncontrolled manifold analysis (UCM) representing 100 chronological time slices (Scholz & Schöner, 1999). For the UCM analysis, shoulder, elbow, and wrist joint angles in the sagittal plane were extracted as the elemental variables ($n = 3$). The magnitude and angle of ball velocity in the sagittal plane at peak acceleration were calculated as the performance variables ($d = 1$). Using a custom MATLAB (The MathWorks Inc., Natwick, MA) code, a relationship between the joint angles and ball velocity was estimated by the Jacobian matrix (J), which is the linear approximation of the uncontrolled manifold. Specifically, the Jacobian matrix determines how deviations in the respective joint angles from the average configuration affect ball velocity, a key determinant for better serving performance (Mackenzie et al., 2012; Paulo et al., 2016). All variables including both elemental and performance variables were transformed to be mean-free ($\theta - \theta^0$) before entering to null space of the Jacobian matrix. Within the null space is the performance-stabilizing variability (V_{UCM}) and the space orthogonal to it is the performance-destabilizing variability (V_{ORT}). Performance variables were then regressed on elemental variables and regression coefficients (B) were obtained. The precision with which this linearization approximates the forward kinematics can be assessed by computing the deviation between the values of the task variables predicted by the linearized model and those predicted from the full forward kinematics. The linearized forward kinematics around the reference

configuration (θ^0) is represented by equation 1, where r^0 is the value of the task variable corresponding to the reference configuration of joint angles, θ^0 . $J(\theta^0)$ is the $d \times n$ Jacobian matrix obtained from the reference configuration. The computation of the UCM is approximated linearly using the null space of the Jacobian, which is spanned by basis vectors ε_i , computed numerically at each time slice using equation 2. There were $n-d$ basis vectors, so that the null space has $n-d$ dimensions. The deviations of joint vectors from the mean joint configuration at each trial, $(\theta - \theta^0)$, were resolved into their projection onto the null space as parallel (V_{UCM}) and perpendicular (V_{ORT}) according to equations 3 and 4 (see Appendix 1). Using equations 5 and 6, both components were then calculated. Lastly, the index of synergy (IOS) was computed using equation 7 for each respective attentional focus condition to measure how much of the variance relative to the total amount is compatible with the mean trajectory of the performance variable. The resultant index of synergy was Fisher's Z transformed using equation 8 for statistical analysis consistent with previous studies (Krishnan et al., 2013; Robert et al., 2009).

$$r - r^0 = J(\theta^0) \cdot (\theta - \theta^0) \quad (1)$$

$$0 = J(\theta^0) \cdot \varepsilon_i \quad (2)$$

$$\theta_{para} = \sum_{i=1}^n \varepsilon_i \cdot (\theta - \theta^0) \quad (3)$$

$$\theta_{perp} = (\theta - \theta^0) - \theta_{para} \quad (4)$$

$$V_{UCM} = \frac{\sum \theta_{para}^2}{(n-d) * N_{trials}} \quad (5)$$

$$V_{ORT} = \frac{\sum \theta_{perp}^2}{d * N_{trials}} \quad (6)$$

$$\Delta V = (n + d) * \frac{V_{UCM} - V_{ORT}}{d * V_{ORT} + (n-d) * V_{UCM}} \quad (7)$$

$$\Delta V_z = \frac{1}{2} \log \left[\frac{\frac{n}{d} + \Delta V}{\frac{n}{n-d} - \Delta V} \right] \quad (8)$$

For all dependent variables, a one-way analysis of variance (ANOVA) with repeated measures on the attentional focus condition was used to determine if there were significant differences between accuracy scores, V_{UCM} , V_{ORT} , and IOS. Significant main effects were followed up by Bonferroni-adjusted pairwise post-hoc paired t-tests.

Results

Accuracy Scores

As seen in Figure 3, participants served more accurately with the distal external ($M = 1.82$, $SD = .32$) relative to the proximal external ($M = 1.42$, $SD = .39$) or internal focus ($M = 1.27$, $SD = .37$). The difference between focus conditions was significant, $F(2,38) = 21.43$, $p < .001$, $\eta^2_p = 0.53$. Post-hoc analysis revealed that accuracy scores were significantly higher in the distal compared to the proximal ($p < .001$) and internal focus conditions ($p < .001$). There was no statistically significant difference between proximal external and internal focus conditions ($p = .302$).

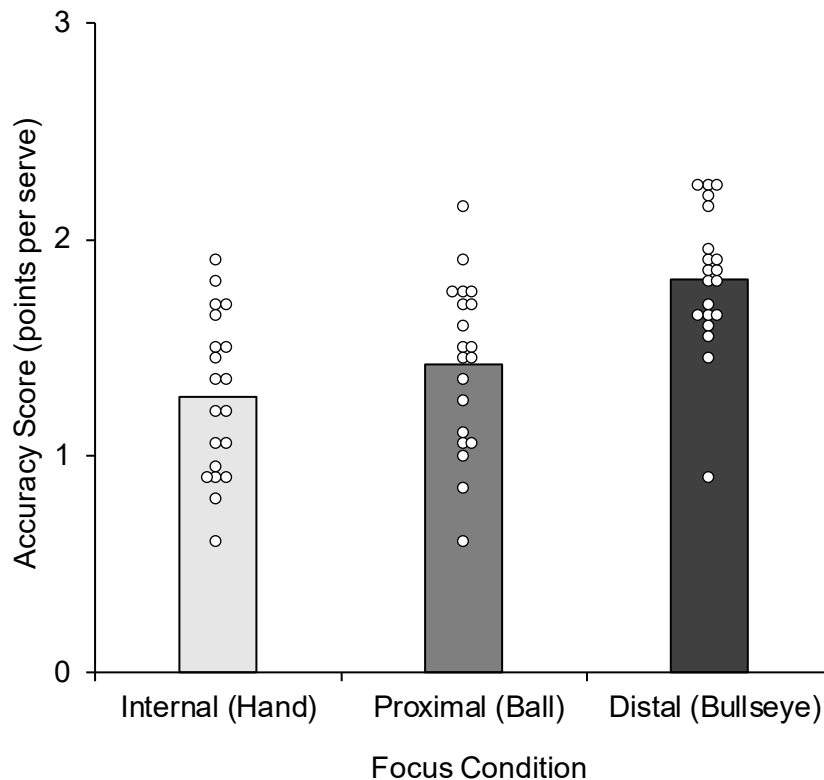


Figure 3. Average accuracy scores in the internal, proximal external, and distal external focus conditions. Error bars represent standard errors.

UCM Analysis

Figure 4 illustrates the source of variance (V_{UCM} vs. V_{ORT}) grouped by attentional focus condition. For V_{UCM} , there was a significant difference between focus conditions, $F(2,38) = 3.34$, $p < .05$, $\eta^2_p = 0.15$. Post hoc analysis showed V_{UCM} was significantly higher in the distal focus condition compared to the internal focus condition ($p < .05$), but that there was no significant difference between the internal focus and proximal focus condition ($p = .521$), or the proximal focus and distal focus condition ($p = .888$). Similarly, for V_{ORT} , there was a significant difference between focus conditions, $F(2,38) = 3.60$, $p < .05$, $\eta^2_p = 0.16$. Post hoc analysis revealed that V_{ORT} was significantly higher in the internal focus condition relative to the distal focus condition (p

< .05), but that there was no significant difference in V_{ORT} between the internal focus and proximal focus condition ($p = 1.00$), or the proximal focus and distal focus condition ($p = .385$).

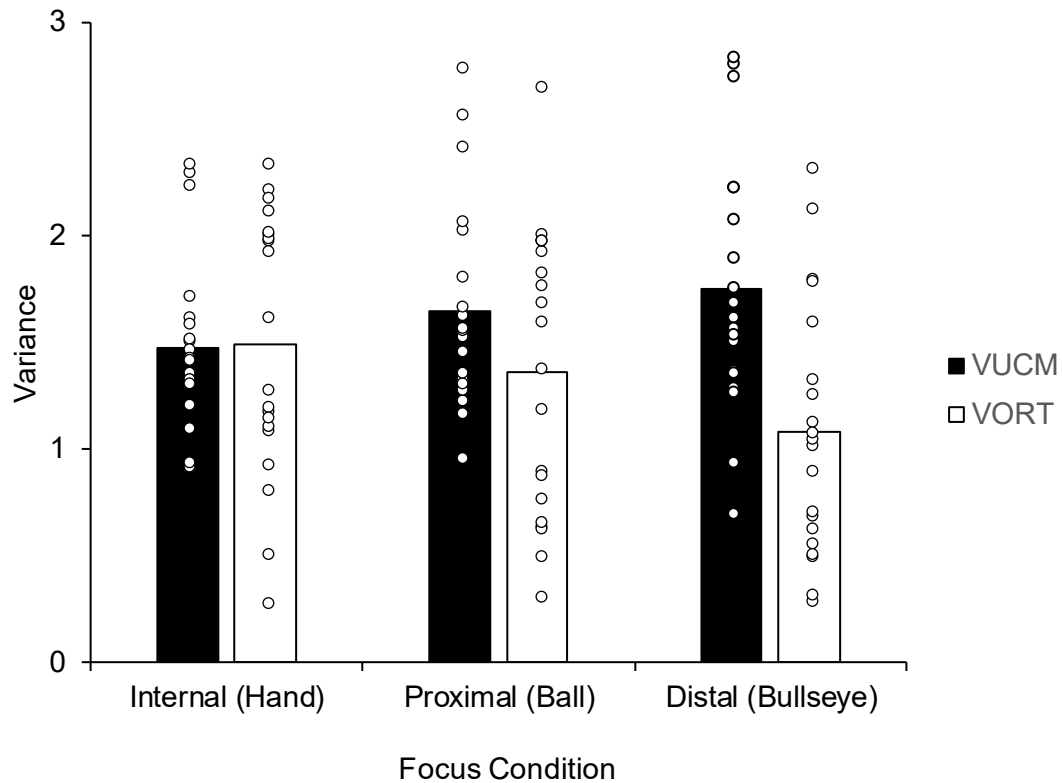


Figure 4. Log-normalized V_{UCM} and V_{ORT} values for internal, proximal external, and distal external focus conditions. Error bars represent standard errors.

Index of Synergy

The index of synergy was computed for all participants and averaged across attentional focus condition to identify the degree to which the elemental variables stabilized the performance variable. A larger and more positive index of synergy indicates that V_{UCM} is bigger than V_{ORT} , meaning that most of the variance that occurred still allowed for consistent magnitude and angle of ball velocity. Negative values indicate an absence of a stabilizing synergy. As seen in Figure 5, an external focus in general had a higher index of synergy (IOS). There was a significant effect of focus condition, $F(2,38) = 8.52$, $p < .001$, $\eta^2_p = .31$. Utilizing a Fisher's z-transformed IOS (ΔV_z)

to indicate the cutoff value for when a synergy could be present, it was identified that ΔV_z was .09, .27, and .54 for the internal, proximal, and distal focus conditions, respectively. Restricting the analysis to proximal ($M = .51$) and distal focus conditions, as they were the only ones to meet the cutoff value ($\Delta V_z = .15$) a paired samples t-test showed a statistically significant difference, $t(19) = 2.22, p < .05$. In other words, a distal external focus resulted in a higher degree of coordinated compensation of elemental variables to stabilize the performance variable.

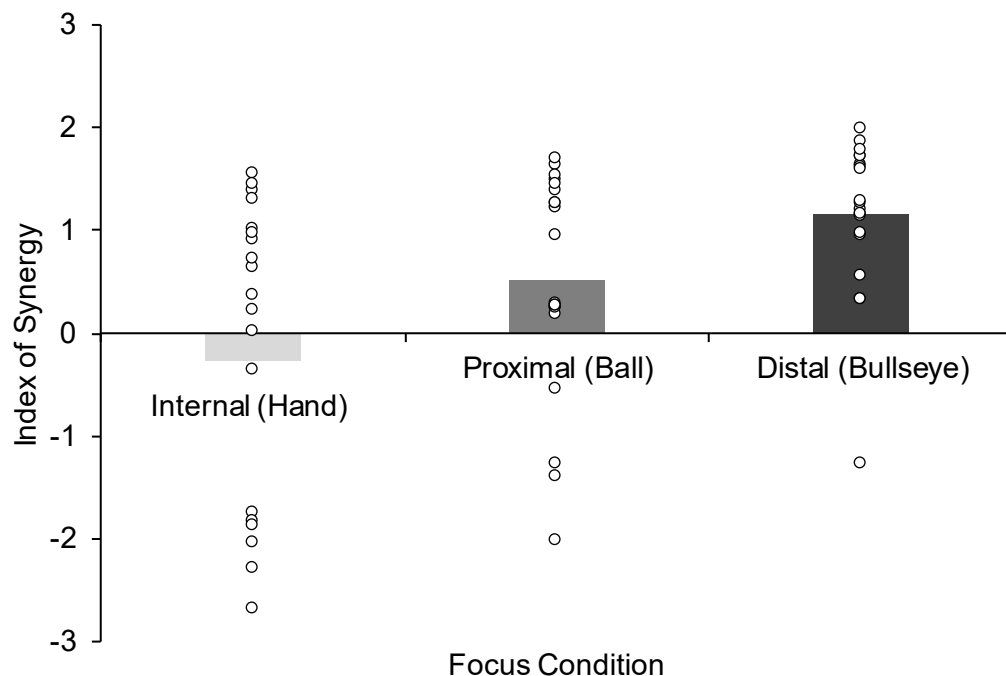


Figure 5. Index of synergy values for internal, proximal external, and distal external focus conditions. Error bars represent standard errors.

Discussion

The aim of the present study was to determine the effects of different attentional foci on functional variability. We compared the effectiveness of three attentional foci – internal, proximal external, and distal external – for the performance of a complex motor task requiring the

coordination of multiple degrees of freedom. Even though we did not use manipulations checks to determine the degree to which participants used the instructed attentional foci, the results were in line with our hypothesis: Skilled volleyball players performed overhand serves more accurately when asked to adopt a distal focus compared to proximal or internal foci. These findings are also in line with those of previous studies showing benefits of external relative to internal foci, and distal external relative to proximal external foci for all skill levels (see Chua et al., 2021), including skilled performers (e.g., Banks et al., 2020; Bell & Hardy, 2009; Singh & Wulf, 2020). Results of the UCM analysis, which measured how variability in the shoulder, elbow, and wrist joints co-varied to stabilize the performance variable (magnitude and angle of ball velocity), revealed that a distal external focus also resulted in increased functional variability relative to proximal and internal foci. That is, when asked to concentrate on the bullseye, the same volleyball players displayed movement coordination patterns that were characterized by a significant increase in V_{UCM} (performance-stabilizing) and significant decrease in V_{ORT} (performance-destabilizing) compared to when they focused on the ball or hand. Finally, the index of synergy showed that while only the external focus conditions displayed synergies for the performance variable (only proximal and distal foci surpassed the cutoff value), the distal focus condition displayed a higher proportion of V_{UCM} compared to V_{ORT} . These findings suggest that a distal external focus on the task goal facilitated compensatory variability among joint angles relevant to movement execution, thereby optimizing movement outcomes in skilled performers.

According to the OPTIMAL theory (Wulf & Lewthwaite, 2016), directing attention externally to the task goal contributes to goal-action coupling, or the fluidity with which the intended goal is translated into action. In general, the changes in motor control associated with an external focus, and in particular a distal external focus, showed an increase in V_{UCM} , decrease in V_{ORT} , and an increase in IOS. This suggests greater flexibility in coupling *action* (different configurations of the shoulder, elbow, and wrist joint angles) to *goal*-relevant parameters (magnitude and angle of ball

velocity, which largely determine task success). However, with an internal focus (attention directed to the hand), there was a pronounced increase in performance-destabilizing variability (V_{ORT}). This might be due to performers constraining the variance in performance-stabilizing and performance-destabilizing directions to minimize error in the attended dimension (hand movement) or specific stage of movement execution (“nodal point”), potentially due to underlying inefficiencies in neuromuscular control (e.g., increased co-contractions; Hossner & Ehrlenspiel, 2010; Lohse et al., 2010).

For skilled performers, the neural basis of motor coordination is also reflected in greater functional connectivity between task-related neural networks (Di et al., 2012; Bernardi et al., 2013; Kim et al., 2015; Milton et al., 2007). For example, higher IOS values have been found to be associated with greater intermuscular coherence reflecting functional coordination amongst elemental variables (Laine & Valero-Cuevas, 2017; Vries et al., 2016). In fact, McNevin et al. (2003) showed that a distal focus led to increased high-frequency, small amplitude adjustments (mean power frequency) while balancing on a stabilometer compared to a proximal external or internal focus. Increases in mean power frequency reflects a higher number of active degrees of freedom working together in a synergistic way to maintain performance (Newell & Slifkin, 1996). The results of the present study extend these findings linking a distal focus to an increase in functional variability (Barris, Farrow, & Davids, 2014; Vereijken, Van Emmerik, Whiting, & Newell, 1992). Thus, maintaining focus on clear distal movement effects compared to proximal movement effects facilitates goal-action coupling.

The optimal external focus depends not only on the distance from the body, but also on the performer’s level of expertise. While novices performing complex skills can benefit from a proximal external focus, skilled individuals have been found to produce more effective performance with a more distal focus (Singh & Wulf, 2020, 2021). In the present study, a proximal focus on the middle of the ball decreased serve accuracy for skilled performers. For these

experienced volleyball players, focusing on the ball (e.g., for optimal ball trajectory) might be something that they do relatively automatically and without conscious attention. Asking them to specifically concentrate on the ball presumably disrupted their typical movement fluidity and produced less efficient coordination patterns. Instead, the distal focus on the bullseye, representing the highest hierarchical movement goal, enhanced goal-action coupling. Despite skilled performers often adopting a less-optimal focus (e.g., Mornell & Wulf, 2018), maintaining a distal external focus when performing a complex motor task involving multiple degrees of freedom is important, as it results in significantly more effective movement outcomes relative to other attentional foci.

Disclosure Statement

The authors report there are no competing interests to declare.

References

- An, J., Wulf, G., & Kim, S. (2013). Increased carry distance and x-factor stretch in golf through an external focus of attention. *Journal of Motor Learning and Development*, 1, 2-11.
- Arutyunyan, G. A., Gurfinkel, V. S., & Mirskii, M. L. (1968). Investigation of aiming at a target. *Biophysics*, 13, 642-645.
- Banks, S., Sproule, J., Higgins, P., & Wulf, G. (2020). Forward thinking: When a distal external focus makes you faster. *Human Movement Science*, 74, 102708.
- Barris, S., Farrow, D., & Davids, K. (2014). Increasing functional variability in the preparatory phase of the takeoff improves elite springboard diving performance. *Research Quarterly For Exercise And Sport*, 85, 97-106.
- Bartlett, R. (2007). *Introduction to sports biomechanics: Analysing human movement patterns*. London: Routledge.
- Bell, J. J., & Hardy, J. (2009). Effects of attentional focus on skilled performance in golf. *Journal of Applied Sport Psychology*, 21(2), 163-177.
- Bernardi, G., Ricciardi, E., Sani, L., Gaglianese, A., Papisogli, A., & Ceccarelli, R. et al. (2013). How skill expertise shapes the brain functional architecture: an fMRI study of visuo-spatial and motor processing in professional racing-car and naïve drivers. *Plos ONE*, 8, e77764
- Bernstein, N. A. (1967). *The coordination and regulation of movement*. London: Pergamon Press.
- Bootsma, R., & van Wieringen, P. (1990). Timing an attacking forehand drive in table tennis. *Journal Of Experimental Psychology: Human Perception and Performance*, 16, 21-29.
- Button, C., Macleod, M., Sanders, R., & Coleman, S. (2003). Examining movement variability in the basketball free-throw action at different skill levels. *Research Quarterly for Exercise and Sport*, 74, 257-269.

- Buszard, T., Garofolini, A., Reid, M., Farrow, D., Oppici, L., & Whiteside, D. (2020). Scaling sports equipment for children promotes functional movement variability. *Scientific Reports*, *10*(1), 1-8.
- Christina, B., & Alpenfels, E. (2014). Influence of attentional focus on learning a swing path change. *International Journal of Golf Science*, *3*, 35-49.
- Chua, L.-K., Jimenez-Diaz, J., Lewthwaite, R., Kim, T., & Wulf, G. (2021). Superiority of external attentional focus for motor performance and learning: Systematic reviews and meta-analyses. *Psychological Bulletin*, *147*, 618-645.
- Cohen, R. G., & Sternad, D. (2009). Variability in motor learning: relocating, channeling and reducing noise. *Experimental Brain Research*, *193*(1), 69-83.
- Coker, C. (2016). Optimizing external focus of attention instructions: The role of attainability. *Journal of Motor Learning and Development*, *4*, 116-125.
- Daivids, K., Glazier, P., Araujo, D., & Bartlett, R. (2003). Movement systems as dynamical systems. *Sports Medicine*, *33*, 245-260.
- De Vries, I. E., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, *116*(6), 2576-2585.
- Di, X., Zhu, S., Jin, H., Wang, P., Ye, Z., Zhou, K., Rao, H. (2012). Altered resting brain function and structure in professional badminton players. *Brain Connectivity*, *2*, 225-233.
- Duke, R., Cash, C., & Allen, S. (2011). Focus of attention affects performance of motor skills in music. *Journal of Research in Music Education*, *59*, 44-55.
- Edelman, G., & Gally, J. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences*, *98*, 13763-13768.
- Faul, F., Erdfelder, E., Lang, A., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175-191.

- Fietzer, A., Winstein, C., & Kulig, K. (2018). Changing one's focus of attention alters the structure of movement variability. *Human Movement Science, 62*, 14-24.
- Ford, P., Hodges, N. J., Huys, R., & Williams, A. M. (2009). An evaluation of end-point trajectory planning during skilled kicking. *Motor Control, 13*, 1-24.
- Gelfand, I., & Latash, M. (1998). On the Problem of Adequate Language in Motor Control. *Motor Control, 2*, 306-313.
- Greig, M., & Marchant, D. (2014). Speed dependent influence of attentional focusing instructions on force production and muscular activity during isokinetic elbow flexions. *Human Movement Science, 33*, 135–148.
- Hiley, M., Zuevsky, V., & Yeadon, M. (2013). Is skilled technique characterized by high or low variability? An analysis of high bar giant circles. *Human Movement Science, 32*, 171-180.
- Hossner, E.-J., & Ehrlenspiel, F. (2010). Time-referenced effects of an internal vs. external focus of attention on muscular activity and compensatory variability. *Frontiers in Psychology, 1*, 230.
- Iino, Y., Yoshioka, S., & Fukashiro, S. (2017). Uncontrolled manifold analysis of joint angle variability during table tennis forehand. *Human Movement Science, 56*, 98-108.
- Kal, E., van der Kamp, J., & Houdijk, H. (2013). External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Human Movement Science, 32*, 527-539.
- Kearney, P. (2015). A distal focus of attention leads to superior performance on a golf putting task. *International Journal of Sport and Exercise Psychology, 13*, 371-381.
- Kim, J. H., Han, J. K., Kim, B.-N., & Han, D. H. (2015). Brain networks governing the golf swing in professional golfers. *Journal of Sports Sciences, 33*, 1980–1987.
- Krishnan, V., Rosenblatt, N., Latash, M., & Grabiner, M. (2013). The effects of age on stabilization of the mediolateral trajectory of the swing foot. *Gait & Posture, 38*, 923-928.

- Kuhn, Y., Keller, M., Egger, S., & Taube, W. (2021). Effects of an external compared to an internal focus of attention on the excitability of fast and slow(er) motor pathways. *Scientific Reports*, 11.
- Kuhn, Y.-A., Keller, M., Lauber, B., & Taube, W. (2018). Surround inhibition can instantly be modulated by changing the attentional focus. *Scientific Reports*, 8, 1–10.
- Kuhn, Y.-A., Keller, M., Ruffieux, J., & Taube, W. (2017). Adopting an external focus of attention alters intracortical inhibition within the primary motor cortex. *Acta Physiologica*, 220, 289–299.
- Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, 118, 1775-1783.
- Latash, M. L. (1996). The Bernstein problem: how does the central nervous system make its choices. *Dexterity and its development*, 277-303.
- Latash, M. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental Brain Research*, 217, 1-5.
- Latash, M. L., Scholz, J. F., Danion, F., & Schöner, G. (2001). Structure of motor variability in marginally redundant multifinger force production tasks. *Experimental Brain Research*, 141, 153-165.
- Latash, M. L. (2021). One more time about motor (and non-motor) synergies. *Experimental Brain Research*, 239(10), 2951-2967.
- Lohse, K. (2012). The influence of attention on learning and performance: Pre-movement time and accuracy in an isometric force production task. *Human Movement Science*, 31, 12-25.
- Lohse, K. R., Jones, M. C., Healy, A. F., & Sherwood, D. E. (2014). The role of attention in motor control. *Quarterly Journal of Experimental Psychology: General*, 143, 930–948
- Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2010). How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Human Movement Science*, 29, 542–555

- Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2011). Neuromuscular effects of shifting the focus of attention in a simple force production task. *Journal of Motor Behavior*, *43*, 173–184.
- Lohse, K. R., Wulf, G., & Lewthwaite, R. (2012). Attentional focus affects movement efficiency. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport: Research, theory and practice* (2nd ed.). London: Routledge.
- MacKenzie, S., Kortegaard, K., LeVangie, M., & Barro, B. (2012). Evaluation of two methods of the jump float serve in volleyball. *Journal of Applied Biomechanics*, *28*, 579-586.
- Marchant, D. C., Greig, M., & Scott, C. (2009). Attentional focusing instructions influence force production and muscular activity during isokinetic elbow flexions. *Journal of Strength and Conditioning Research*, *23*, 2358–2366.
- McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research*, *67*, 22-29.
- Milton, J., Solodkin, A., Hluštík, P., & Small, S. (2007). The mind of expert motor performance is cool and focused. *Neuroimage*, *35*, 804-813.
- Möhler, F., Marahrens, S., Ringhof, S., Mikut, R., & Stein, T. (2020). Variability of running coordination in experts and novices: A 3D uncontrolled manifold analysis. *European Journal of Sport Science*, *20*, 1187-1196.
- Mornell, A., & Wulf, G. (2019). Adopting an external focus of attention enhances musical performance. *Journal of Research in Music Education*, *66*, 375-391.
- Morrison, A., McGrath, D., & Wallace, E. S. (2016). Motor abundance and control structure in the golf swing. *Human Movement Science*, *46*, 129-147.
- Müller, H., & Loosch, E. (1999). Functional variability and an equifinal path of movement during targeted throwing. *Journal of Human Movement Studies*, *36*, 103-126.
- Newell, K. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341–360). The Hague: Nijhoff.

- Newell, K.M., & Slifkin, A.B. (1996). The nature of movement variability. In J. Piek (Ed.). *Motor Control and Human Skill: A Multidisciplinary Perspective*. Champaign: Human Kinetics.
- Nisky, I., Okamura, A. M., & Hsieh, M. H. (2014). Effects of robotic manipulators on movements of novices and surgeons. *Surgical Endoscopy*, *28*, 2145-2158
- Osu, R., Franklin, D., Kato, H., Gomi, H., Domen, K., Yoshioka, T., & Kawato, M. (2002). Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface EMG. *Journal of Neurophysiology*, *88*, 991-1004.
- Pappas, A., Zawacki, R., & Sullivan, T. (1985). Biomechanics of baseball pitching. *The American Journal of Sports Medicine*, *13*, 216-222.
- Paulo, A., Zaal, F., Fonseca, S., & Araújo, D. (2016). Predicting volleyball serve-reception. *Frontiers in Psychology*, *7* (Article 1694).
- Parr, R., & Button, C. (2009). End-point focus of attention: Learning the “catch” in rowing. *International Journal of Sport Psychology*, *40*, 616–635.
- Porter, J. M., Anton, P. M., Wikoff, N. M., & Ostrowski, J. B. (2013). Instructing skilled athletes to focus their attention externally at greater distances enhances jumping performance. *Journal of Strength and Conditioning Research*, *27*, 2073–2078.
- Porter, J. M., Anton, P. M., & Wu, W. F. W. (2012). Increasing the distance of an external focus of attention enhances standing long jump performance. *Journal of Strength and Conditioning Research*, *26*, 2389–2393.
- Profeta, V., & Turvey, M. (2018). Bernstein’s levels of movement construction: A contemporary perspective. *Human Movement Science*, *57*, 111-133.
- Raisbeck, L. D., & Yamada, M. (2019). The effects of instructional cues on performance and mechanics during a gross motor movement. *Human Movement Science*, *66*, 149–156.
- Ranganathan, R., & Newell, K. (2013). Changing up the routine: intervention-induced variability in motor learning. *Exercise and Sport Sciences Reviews*, *41*, 64-70.
- Reed, E. (1996). *Encountering the world*. New York: Oxford University Press.

- Rein, R., Bril, B., & Nonaka, T. (2013). Coordination strategies used in stone knapping. *American Journal of Physical Anthropology*, *150*, 539-550.
- Riley, M., & Turvey, M. (2002). Variability and determinism in motor behavior. *Journal of Motor Behavior*, *34*, 99-125.
- Robert, T., Bennett, B., Russell, S., Zirker, C., & Abel, M. (2009). Angular momentum synergies during walking. *Experimental Brain Research*, *197*, 185-197.
- Schöner, G., & Scholz, J. (2007). Analyzing variance in multi-degree-of-freedom movements: uncovering structure versus extracting correlations. *Motor Control*, *11*, 259-275.
- Scholz, J., & Schöner, G. (1999). The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research*, *126*, 289-306.
- Scholz, J. P., Schöner, G., & Latash, M. L. (2000). Identifying the control structure of multijoint coordination during pistol shooting. *Experimental Brain Research*, *135*, 382-404.
- Schutts, K. S., Wu, W. F. W., Vidal, A. D., Hiegel, J., & Becker, J. (2017). Does focus of attention improve snatch lift kinematics? *Journal of Strength and Conditioning Research*, *31*, 2758-2764.
- Singh, H., & Wulf, G. (2020). The distance effect and level of expertise: Is the optimal external focus different for low-skilled and high-skilled performers? *Human Movement Science*, *74*. DOI: [10.1016/j.humov.2020.102663](https://doi.org/10.1016/j.humov.2020.102663)
- Singh, H., & Wulf, G. (2021). Mind over body: Creating an external focus for sport skills. *European Journal for Sport Science*, Feb. 28; 1-7. DOI: [10.1080/17461391.2021.1887367](https://doi.org/10.1080/17461391.2021.1887367).
- Stambaugh, L. A. (2017). Effects of internal and external focus of attention on woodwind performance. *Psychomusicology: Music, Mind, and Brain*, *27*, 45-53. <https://doi.org/10.1037/pmu0000170>.
- Tuller, B., Fitch, H. L., & Turvey, M. T. (1982). The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. In J. A. S. Kelso, *Human Motor Behavior: An Introduction*. London: Psychology Press.

- Turvey, M. (1990). Coordination. *American Psychologist*, *45*, 938-953.
- Turvey, M. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, *4*, 173–187.
- Vance, J., Wulf, G., Töllner, T., McNevin, N. H., & Mercer, J. (2004). EMG activity as a function of the performers' focus of attention. *Journal of Motor Behavior*, *36*, 450–459.
- van Ginneken, W. F., Poolton, J. M., Capio, C. M., van der Kamp, J., Choi, C. S., & Masters, R. S. (2018). Conscious control is associated with freezing of mechanical degrees of freedom during motor learning. *Journal of Motor Behavior*, *50*, 436-456.
- Vereijken, B., Emmerik, R., Whiting, H., & Newell, K. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior*, *24*, 133-142.
- Vidal, A., Wu, W., Nakajima, M., & Becker, J. (2018). Investigating the constrained action hypothesis: a movement coordination and coordination variability approach. *Journal of Motor Behavior*, *50*, 528-537.
- Williams, B., Sanders, R., Ryu, J., Graham-Smith, P., & Sinclair, P. (2020). The kinematic differences between accurate and inaccurate squash forehand drives for athletes of different skill levels. *Journal of Sports Sciences*, *38*, 1115-1123.
- Wilson, C., Simpson, S., Van Emmerik, R., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, *7*, 2-9.
- Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *International Review of Sport and Exercise Psychology*, *6*, 77–104.
- Wulf, G., & Dufek, J. S. (2009). Increased jump height with an external focus due to enhanced lower extremity joint kinetics. *Journal of Motor Behavior*, *41*, 410–409.
- Wulf, G., Dufek, J.S., Lozano, L., & Pettigrew, C. (2010). Increased jump height and reduced EMG activity with an external focus of attention. *Human Movement Science*, *29*, 440–448.
- Wulf, G., Höß, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of Motor Behavior*, *30*, 169–179.

- Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review*, 23, 1382-1414.
- Wulf, G., McNevin, N. H., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *Quarterly Journal of Experimental Psychology* 54A, 1143–1154.
- Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin & Review*, 8, 648-660.
- Yang, J. F., & Scholz, J. P. (2005). Learning a throwing task is associated with differential changes in the use of motor abundance. *Experimental Brain Research*, 163, 137-158.
- Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as a result of adopting an external focus of attention. *Brain Research Bulletin*, 67, 304–309.
- Zarghami, M., Saemi, E., & Fathi, I. (2012). External focus of attention enhances discus throwing performance. *Kinesiology*, 44, 47–51.

Appendices

Appendix 1. Sample UCM MATLAB code

```

%Use the coefficients (B) of multiple linear regression between mean free joint
%angles (x1, x2, x3 etc) and mean free output variable (devY) to calculate the
%Jacobian (J)

%The basis vectors are in matrix Z which is null(J)

%The following snippet of code aligns with equation 3 and 4 in the manuscript
%VUCM (equation) = UCM (appendix) and VORT (equation) = UCMperp (appendix)

%The deviations of the joint vectors from the mean joint configuration at
%each trial are resolved into their projection onto the null space
for i = 1:N
    UCM(:,i) = Z*(Z'*dev(:,i));
end

% and the component perpendicular to the null space
UCMperp = dev-UCM;

```