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EDITORIAL

Mind over muscle: the role of gaze control, spatial cognition, and the quiet eye in motor expertise

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Abstract In the course of all motor behavior, the brain is limited in how much information it can process and act upon at a time. Performers must constantly decide where to look, what to attend to, and how to time fixated information with precisely controlled actions. The gaze can be directed to only one location at a time and information central to success must be selected from spatially complex environments, most often under severe time constraints. The coordination of these processes is explored in this Special issue in a number of motor tasks, including golf, soccer, law enforcement, and ballet. The papers describe the visual information and quiet eye characteristics that underlie the ability to make decisions under complex task conditions and the relationship between control of the gaze and task outcomes. With the attainment of motor expertise, measureable changes occur within the gaze, cognitive, and neural systems that are useful in training, rehabilitation, and the treatment of motor deficits.

The papers in this Special issue of Cognitive Processing are the result of a Symposium on Gaze and Cognitive Control presented at the International Conference on Spatial Cognition in Rome, September, 2009. The goal of the Symposium was to further understanding of the nature of gaze control, spatial cognition, and the quiet eye during the performance of complex motor skills. I want to thank all of the authors and reviewers who took part in the Symposium and this Special issue, as well as Marta Olivetti Belardinelli, Editor-in-Chief and Thomas Hünefeldt, Managing Editor.

As the title of this editorial suggests to reach the highest levels of expertise in a sport or any other motor domain, it takes more than superior physical skill. While previously it was difficult, if not impossible, to research how human's control their gaze in complex spatial environments, all of the authors in this Special issue have found ways to research real world events and test individuals under experimentally rigorous conditions. All have done this by harnessing mobile eye tracking technology that provides new insights into how the visual system functions in physically challenging spaces and time frames. All present evidence that shows how the gaze is controlled in space is a critical factor in motor expertise requiring precise cue selection, optimal timing, and the ability to focus for surprisingly long durations under all conditions of performance. The greater or more intense the pressure then the more the gaze must be precisely controlled in space and timed relative to specific phases of the motor skill.

They further show that expert performers have gaze control abilities distinct from those with lower skill levels in being able to acquire the most optimal spatial information thus allowing the neural structures underlying the action to optimally organize. When the spatial information is insufficient or incomplete, then the action is only partially organized and performance suffers. Paradoxically, the type of gaze control that accompanies excellence in dynamic motor skills is not itself rapid and dynamic, but instead just the opposite; it is calm, cool, and collected, meaning fixation onsets are early, of long duration and focussed intently on critical external locations well before the final phase of the movement begins. Since the human brain is a relatively slow visual processor, it is incumbent on the performer to find ways to access complex spatial

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information that is often very difficult to access. The authors of this Special issue all show how expert performers do this, potentially opening new avenues for training, rehabilitation, and the treatment of motor deficits.

Study of the gaze behaviors of motor experts and non-experts also provides new insights into how the brain changes as a result of the development of expertise. Hommel (2010) states that instead of trying to define an attention system, which has been the goal of many in cognitive science, a more productive approach is to "focus on the attentional processes, that is, to ask what attention does rather than what it is" (p. 121). Such an approach seems appropriate in light of fMRI evidence showing the neural structures subserving the different forms of attention (vision, audition and so on) are widely distributed in the brain making the identification of a single attention system, per se, highly unlikely. A more approachable goal, according to Hommel, is to "appreciate the importance of attentional processes for action (selection of action)." His thesis is that "attention not only subserves action-control problems but may actually have emerged to solve action-control problems in a cognitive system that relies on distributed representations and multiple, loosely connected processing streams" (p. 121).

When the gaze is optimally controlled in space then a state of "motor resonance" is achieved. I have borrowed the term "motor resonance" from Aglioti et al. (2008, p. 1109) who found that "achieving excellence in sports may be related to the fine-tuning of specific anticipatory 'resonance' mechanisms that endow elite athletes' brains with the ability to predict others' actions ahead of their realization." Building on the evidence of Aglioti et al. (2008) and others I would like to suggest that when the gaze is controlled optimally in space, then energy is transferred from the information being fixated to the neural networks and finally to the motor system resulting in performances that are not only more successful, but also possess the quality of effortlessness that is symptomatic of optimal energy transfer. What is new about the notion of motor resonance is that the energy originates, in part, from the spatial information being fixated or tracked in space. Expressions such as "being one with the target" and "being in the zone" are common and reflect, at some level, an awareness of an elusive energy source that is universally accompanied by a sense of complete motor control.

One measureable source of motor resonance is the quiet eye. It has been 15 years since the first quiet eye paper was published (Vickers 1996), and in the intervening years, over 70 papers have been published, with many listed in the reference lists of this Special issue. The quiet eye is recorded with a mobile eye tracker that is coupled with an external motor camera or cameras. It is defined as the final fixation or tracking gaze that is located on a specific object or location in the task environment within three degrees of visual angle (or less) for a minimum duration of 100 ms. The quiet onset occurs prior to the final movement, and thus the quiet eye is a perception–action variable; it contains measures of both the gaze in space and the physical movements of the performer (Vickers 1996, 2007).

From a cognitive neuroscience perspective, a long duration quiet eye period provides the time the brain needs to organize the neural structures underlying the planning and control of the action. Mann et al. (this volume) provides evidence in support of this idea using the golf putt. They explain that the bereitschaftspotential (BP) is an aspect of the event-related potential (ERP) that reflects the activation of the supplementary motor area that begins approximately 1500 ms prior to movement onset. Since the BP precedes an actual, intended, or imagined action by 1.0–1.5 s, it serves as an index of anticipatory attention and movement preparation. Prior to this study, there was speculation that the BP played a role in the detection and pairing of task relevant environmental visual features with the requisite elements of response execution. They found that "prolonged fixations, particularly during the final fixation that defines the QE, apparently permit the detailed processing of information and cortical organization necessary for effective motor performance".

An optimal quiet eye period also acts like a GPS system that feeds into the brain the specific x, y, and z spatial coordinates needed for the action to be organized optimally in space over time. A long duration fixation on a specific location contributes to better body positioning, a more balanced stance and the timing of limb actions that are efficient and economical. Evidence supporting the efficacy of testing individuals in realistic spatial environments where GPS-like gaze coordinates can be accessed comes from a paper by Button et al. (this volume) and Dicks et al. (2010) who tested elite soccer goaltenders in five experimental conditions: two using video simulations of penalty kicks with verbal and joystick responses, and three carried out on the field with verbal, step, and real world responses. Not only did the goalkeepers make more saves in the real world condition, but their fixation locations changed significantly across the five conditions. It is apparent that the visual control of experts cannot be fully appreciated until they are studied in experimental settings that access the actual spatial x, y, and z visual coordinates used to control the mind and body.

This concept is also illustrated in Piras and Vickers (this volume) in a soccer goaltending study using the penalty kick. They show there is a cognitive cost associated with shifting the gaze in a time pressured environment like the penalty kick. In order to be successful, the goalkeeper's gaze has to be controlled precisely during the run-up on a "visual pivot," which is located between the ball and kicking action. When fixations are located on the visual pivot, this allows the goaltender to "read" the type of kick being delivered while at the same time anticipate the moment of ball-foot contact. Since there is initially considerable distance between the ball and kicking action in terms of visual angle, the limits of focal vision are a factor, as is the need for fixation transitions between the visual pivot and ball. More important, when the final fixation on the ball is too long, then valuable information is missed of the leg/foot action and the chances of being scored against increases.

Once the quiet eye characteristics in a motor task are known, this allows the teaching of the gaze control and visual focus characteristics of expert performers. Wood and Wilson (this volume) used quiet eye information to train soccer players in the penalty kick. They found that during acquisition and retention, QE training led to making shots that were more accurate, further from the goalkeeper's reach and less likely to be saved. They also found significant improvements in quiet eye/gaze control and suggest the longer QE periods minimized distractions. Theoretically, Wood and Wilson and Vine and Wilson (2011) argue that a long duration quiet eye prevents a disruption in the balance of the goal-directed (top-down dorsal) system and the stimulus-driven (ventral) systems. Since anxiety disrupts the balance between these two systems, a long duration quiet eye provides performers an extended duration of response programming (dorsal processing), while blocking unwanted stimulus-driven ventral processing.

Neuwenhuyns and Oudejans (this volume) used a novel training method to train police officers under conditions of high stress and anxiety. How officers are trained to shoot has not changed over the past 100 years and is carried out almost exclusively on ranges where officers achieve high levels of accuracy but later perform poorly when faced with a violent offender on the street. Using a pretest, posttest and four month retention interval they report that positive changes in movement speed and accuracy could only be explained by the observed changes in gaze behavior. Compared to a control group, officers who were trained under high anxiety developed gaze characteristics that were "relatively calm" and characterized by a long final fixations on the targets which indicated control of goal-directed attention after training. When performance was poor, this was accompanied by relatively short final fixations on the targets, indicating that goal-directed attentional control was not achieved to the same degree.

The ability to control the gaze in space is also critical for ballet dancers (Panchuk and Vickers, this volume) who must not only move with grace and assurance along choreographed travel paths but do this under complete control. They determined the gaze and stepping behaviors of elite ballet dancers and controls as they walked along progressively narrower 3 m lines (2.5, 10 cm). The ballet dancers fixated into far space delaying their first step before stepping quickly onto the lines which they exited slowly and under control. In contrast, the controls stepped immediately and looked down at the lines which they exited with greater speed and less control. These results suggest that with the acquisition of expertise in dance neural control shifts forward from somatosensory sensory inputs arising from the feet and legs to greater use of visual feedback from external sources.

Control of the gaze in space is also central to decision making as shown by Ward et al. (this volume) who investigated the gaze and decision making abilities of elite (SWAT) and regular police officers as they responded to video simulations of crimes that officers typically face. Their research question centered on whether police officers with extensive experience used an exhaustive search strategy in which a number of likely alternatives are considered, or do they go right to the final decision with little consideration of alternatives? Ford et al. found the SWAT officers have developed superior long-term memory skills that support both an exhaustive search of alternative decisions and rapid decision making, depending on the context. When the time constraints were greatest and associated with complex and dynamic situations, the SWAT officers limited the extent to which they engaged in additional higher order evaluations.

Roca et al. (this volume) investigated the gaze and verbal reports of low- and high-skilled soccer players after viewing complex 11 versus 11 tactical plays. Skilled players employed a quantitatively different visual search strategy when compared to lower skilled players and also had more advanced memory representations that enabled them to retrieve task-specific information with greater ease and make better superior decisions. The skilled players generated a higher proportion of evaluation, prediction, and planning statements in comparison with the less skilled players, while the less skilled players recalled more current actions and events. In time-constrained sporting tasks, skilled players' advanced memory representations enable them to anticipate and predict upcoming events to a greater extent information than their less skilled counterparts. The papers in the current volume not only provide an overview of past studies but also provide a glimpse of new studies that need to be pursued.

Although the quiet eye effect is described by Mann et al. as a "remarkably robust finding with a rapidly expanding body of literature," there is a need for replication and extension of current findings. Future studies need to continue to explore the effects of pressure on the visuomotor planning and control of the skill and the utility of gaze-based training and quiet eye interventions as a way to reduce anxiety. Going forward, it will be important to expand gaze and quiet eye research and training into areas such as surgery, emergency medicine, the military, law enforcement, the arts, business, and social behavior. There is also a need for the creation of quiet eye training protocols that have been proven to be effective in actual sport competitions, surgery on live patients, law enforcement, and everyday events where the ability to perform at a high level is critical. There is also considerable interest in determining whether some are born with a quiet eye. Is the quiet eye genetic or is it acquired only as a result of extensive practice? Quiet eye training for children may be beneficial, especially those with learning or movement difficulties. More research on individual differences is also needed. It would be especially interesting to determine differences between experts, as the expertise literature suggests some find pathways that are more advanced than others. It may be that these pathways originate in elusive spatial gaze characteristics that we are now beginning to measure and understand.

> Talent hits a target no one else can hit; Genius hits a target no one else can see.
> Arthur Shopenhauer (1788–1860)

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