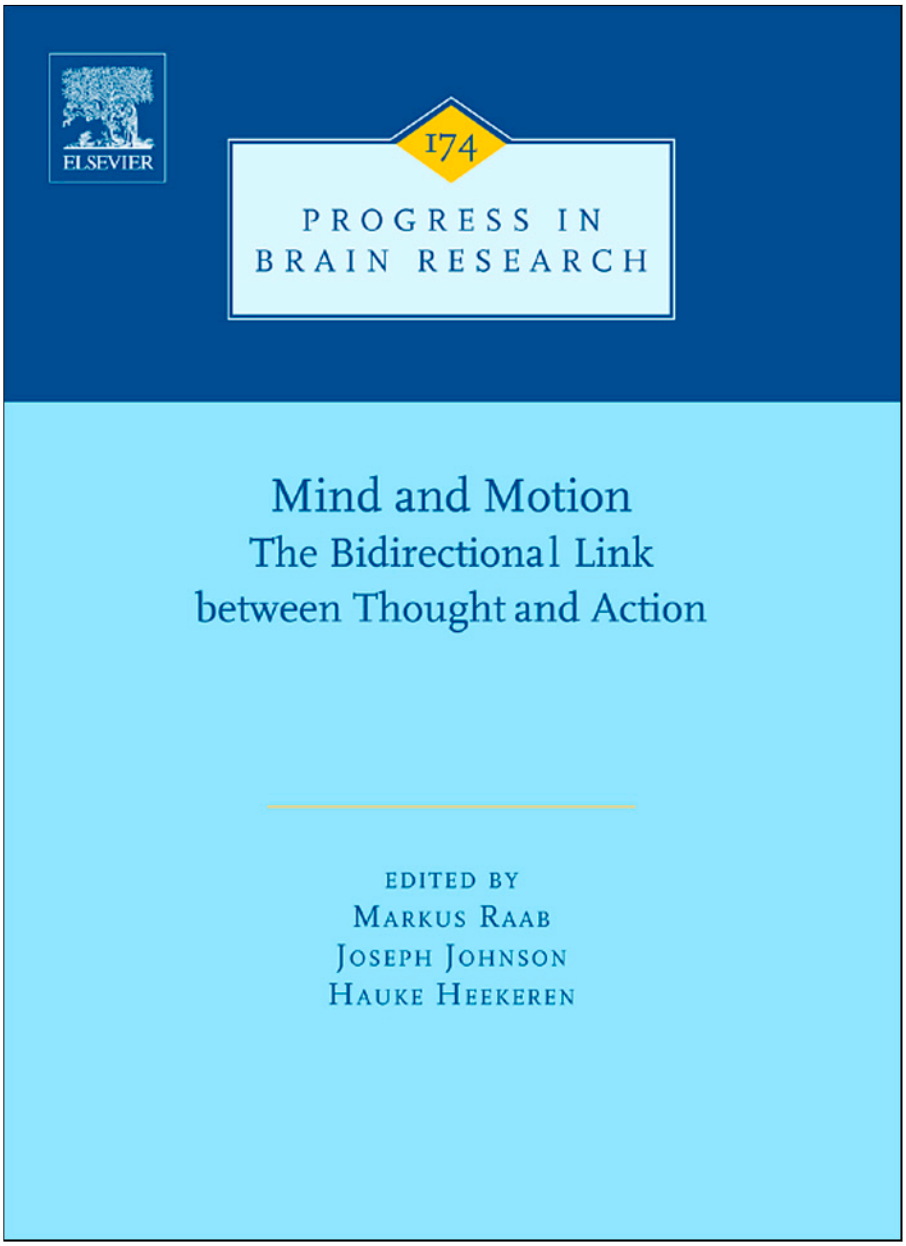

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CHAPTER 22

Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention, and action

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Abstract: One of the most elusive mysteries in psychology is perception–action coupling and the extent vision for perception is distinct from vision for action. In this chapter, I explore research on the control of the gaze during well-known sport tasks (vision for action) and the bidirectional link between perceptual and cognitive processes and optimal/nonoptimal motor performance. Considerable evidence now exists showing that specific gaze characteristics underlie higher levels of sport performance. The quiet eye has emerged as a characteristic of higher levels of performance and is the final fixation or tracking gaze that occurs prior to the final movement. Cognitive and ecological accounts of the quiet eye are presented and current controversies and future directions explored.

Keywords: quiet eye; decision making; attention; perception

Introduction

All actions have the three qualities that make up the themes of this workshop (entitled *Mind and motion: the bidirectional link between thought and action*; 29–31 May 2008; Bielefeld, Germany) — the individual must first be able to perceive what needs to be done and represent it within neural, perceptual, and/or cognitive structures (group 1); they must be able to select the best course of action from the many options that may be present efficiently (group 2); and they must be able to implement a cognitively planned course of action so that an intended outcome occurs (group 3). My goal in this chapter is to summarize my research in terms of the last theme — how is a cognitively intended course of action physically implemented. To answer this question I review the eye movements and gaze research in which my students, colleagues, and I have coupled perception and action in experiments using well-known sport and other motor tasks. Following this, I explain how the results we have obtained, in particular around the quiet eye, have led to successful training interventions. Finally, I cover the theoretical bases for the research and the two competing explanations currently in the literature, ending in the final section with a discussion on some current controversies and future directions.

My own work has concentrated on using eye movements, and more specifically measures of gaze, as a way of looking into the mind of motor performers. What is it that they see that contributes,

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either positively or negatively, to their motor success or failure? By concentrating on performance in well-known sport tasks it is possible to access the minds of individuals who have trained at least 10,000 hours in specific tasks and reached the highest levels of achievement as confirmed by independent statistics, or alternatively, have trained for 10,000 hours and not reached those heights (Ericsson, 1996; Helsen et al., 1998). Why is it that some athletes achieve the ultimate in performance statistics while many others, who are as gifted physically and have trained as hard, do not achieve these levels? Wrapped up within elite and near-elite athletes are living examples of intended actions going well and not so well.

In a typical research study carried out in my laboratory, elite and near-elite athletes perform experimental tasks in conditions that are very similar to those found within their sport. Their gaze is recorded by a mobile eye tracker, which is integrated with a motion analysis system that records their movements at the same time. The athletes perform until an equal number of successful and nonsuccessful trials are achieved under various experimental conditions in which we may vary task complexity, competitive pressure, athlete anxiety, and/or physiological arousal. Our goal is to determine the types of gaze behaviors that underlie both successful and nonsuccessful performances. From these gaze behaviors we then attempt to explain the perceptual and cognitive processes that define optimal and nonoptimal motor performance.

Linking gaze to attention and other cognitive processes has only been possible with important changes in the literature linking gaze and attention. For many years, it was difficult to link shifts in gaze with shifts in attention (e.g., Posner, 1980) but more recent studies show that under certain conditions a shift in the gaze is invariably preceded by a shift in attention (Shepherd et al., 1986; Kowler et al., 1995; Deubel and Schneider, 1996; Corbetta, 1998; Henderson, 2003). There is now strong evidence that when a saccade is made to a new location there is a corresponding shift in attention in the direction of the saccade. This means that when athletes shift their gaze to a new location, they also shift their attention to that location at least for a brief period. However, it is important to stress that once the gaze and attention have arrived at a new location, the duration of the gaze may not always be an indicator of attention. Athletes may still covertly divert their attention elsewhere even as fixation remains on a location.

In a typical study all the gazes are coded and analyzed coupled with the distinct motor phases that make up the movement. Over many studies, one gaze has emerged as being a characteristic of elite performance in a wide range of targeting tasks. For a given motor task, the quiet eye is defined as the final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace within 3° of visual angle for a minimum of 100 ms. The onset of the quiet eye occurs prior to the final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms, therefore the quiet eye can carry through and beyond the final movement of the task. The quiet eye of elite performers is significantly longer than that of near-elite, or lower-skilled performers, meaning those who consistently achieve high levels of performance have learned to fixate or track critical objects or locations for longer durations irrespective of the conditions encountered. The quiet eye onset of elite performers is invariably earlier; elite performers have found a way to see critical information earlier than near-elite and lower-skilled performers and to process this information longer prior to making the final movement. Finally, the quiet eye of elite performers is of an optimal duration, being neither too long nor too short, but ideal given the constraints of the task being performed. What is striking about the quiet eye is the robustness of the finding that has been found in targeting tasks (Vickers, 1992, 1996; Janelle et al., 2000; Williams et al., 2002; Vickers, 2004; Oudejans et al., 2005; Oliveira, 2007; Vickers and Williams, 2007), interceptive timing tasks (Adolphe et al., 1997; Vickers and Adolphe, 1997; Rodrigues et al., 2002; McPherson and Vickers, 2004; Panchuk and Vickers, 2006), as well as tactical tasks (Martell and Vickers, 2004; Vickers, 2006, 2007). The quiet eye has also been identified as a gaze affected by high levels of performance pressure and anxiety (Vickers and Williams, 2007; Behan and Wilson, 2008). In

Fig. 1. A frame of vision-in-action data showing the quiet eye gaze of the player on the front hoop as indicated by the black cursor.

addition, a recent meta-analysis by Mann et al. (2007) has identified the quiet eye as one of only three predictors of perceptual-motor expertise (along with fixation location and a low frequency of fixation). Figure 1 presents a typical frame of the vision-in-action data showing the quiet-eye location of an elite basketball player. Each frame of vision-in-action data is comprised of four parts: an eye image, a gaze image that below is shown on the right with the gaze indicated by the black gaze cursor on the hoop, a motor image shown below on the left, and a time code that records time synchronized in all three images.

Quiet-eye training

In addition to carrying out research to determine the characteristics of the quiet eye in various motor tasks, research has also determined the effectiveness of quiet-eye training to improve sports performance. In order for a perceptual and attention training program to be successful in any domain, four conditions must be met (Gopher, 1993; Williams and Grant, 1999). First, it must be shown that control over the gaze and attention leads to higher levels of motor performance. Second, individuals must be identified who have difficulty controlling their gaze and attention in a task and classified according to the depth and quality of training needed. Third, there must be evidence that these individuals have the ability to improve their gaze and attention with proper training. Finally, it must be shown that the training of a more optimal control of the gaze and attention contributes to improvements in motor performance in both the research and competitive setting. The first two conditions have been met by the many studies cited above showing that elite sports performers possess unique gaze and quiet-eye characteristics compared to those who are nonelite or near-elite. The third and fourth requirements have been met in sport studies where improvements in gaze and motor performance have been found under both experimental and field conditions (Adolphe et al., 1997; Harle and Vickers, 2001; Oudejans et al., 2005; Vickers, 2007).

Quiet-eye training involves using both video modeling and video feedback of the gaze coupled with the motor behaviour followed by training in drills that help athletes develop the same quiet-eye focus as found in elite performers. Seven steps are involved.

1. It is first critical to carry out research in the task and identify the quiet-eye characteristics of elite performers during successful trials. Elite athletes are tested and their quiet-eye location, onset, offset, and duration identified during successful and unsuccessful trials identified. Once this information is obtained then task-specific norms and standards for quiet-eye training can be applied.
2. The athlete is tested *in situ* using a mobile eye tracker and motion analysis system while performing the task in conditions similar to those found in competition. The duration of the quiet-eye location, onset, offset, and duration is determined during successful and unsuccessful shots.
3. Using an elite prototype (derived from step 1), the athlete is taught the gaze characteristics identified in the literature and reflected through the elite prototype in terms of a low frequency of gaze, the final fixation allocated to a specific location, and an early onset and duration of the quiet eye coupled with the final movement. The athlete is taught to reduce the frequency of fixation or tracking gaze to fewer locations with the final fixation, or quiet eye, being located on a critical location.
4. The athlete is then shown his/her own coupled gaze and motor data and given feedback about their quiet eye. An important part of this step is to ask the athlete questions about how their gaze and attention differs from, or is similar to, that of the elite prototype using frame-by-frame video comparison. The key is to probe cognitively how much the athlete understands about the control of their attention as they perform. Most athletes are adept at identifying the differences between their gaze and that of expert performers; many are surprised at how erratic their gaze and attention is compared to that of elite performers.
5. The athlete is asked to select an aspect of their quiet eye they want to change during subsequent attempts. During this decision-training phase it is important to encourage the athlete to concentrate only on adopting one or more of the quiet-eye attributes (location, onset, offset, duration) with limited or no coaching of changes in their technique. Preliminary studies have shown that when the gaze control improves athletes change their technique to accommodate the more effective control of their gaze and attention (Harle and Vickers, 2001; Oudejans et al., 2005).
6. The athlete should then practice drills designed to promote the desired quiet-eye focus. The goal is to have the athlete practice in drills designed to promote the attention, quiet eye, and other gaze characteristics of elite performers. A variety of drills should be designed using a number of decision-training tools that have strong support in the motor learning literature including variable and random practice, bandwidth feedback, questioning, and an external focus of attention rather than an internal focus. Using this approach, unusually high increases in performance have been found in a number of sport areas (Adolphe et al., 1997; Vickers et al., 1999; Harle and Vickers, 2001; Vickers, 2003; Vickers et al., 2004; Oudejans et al., 2005; Raab et al., 2005; Vickers, 2007).
7. The athletes' performance in competition should be assessed and follow-up quiet-eye tests carried out as is needed to improve the athlete's performance permanently.

We used this training process with elite and near-elite varsity basketball players (Harle and Vickers, 2001). We found a significant increase in quiet-eye duration and free-throw accuracy in the experimental setting in year 1 and in the second year, the team improved their free-throw shooting accuracy in games over a full season from 54 to 76% (an increase of 22%, which was significantly higher than two control teams who did not receive similar training). Oudejans et al. (2005) investigated the effects of "visual control training" on basketball jump shooting by expert male players. The goal of the training was to improve the athletes' pickup of information during the final period before ball release. Two methods were used over a training period of 8 weeks. The players wore liquid-crystal goggles that occluded the hoop so they could only see the hoop during the final 350 ms. The goggles forced the players to attend maximally to the hoop during the short amount of time it was visible. In addition, the players were required to shoot from behind a screen set up at the free-throw line and placed at a height that blocked their view of the hoop. The players increased the duration of time the goggles were open from a mean of 353 ms before training to 386 ms following training. Field-shooting accuracy improved in games from a mean of 46% before training to 61% following training, for a mean increase of 15%. The control group, who did not receive similar training, did not improve but maintained the same shooting percentage of 42%. The amount of improvement in these studies is considerable and shows that athletes who are trained to control their gaze, attention and decision making while performing in drills that simulate events within the game are much greater than when physical and/or psychological training are used alone.

Theoretical accounts of the quiet eye

Although the quiet eye has been found to underlie higher levels of skill and performance in a wide variety of sport tasks, two different theoretical accounts have been put forward to explain why this gaze is important in motor performance. Below these two theoretical perspectives are reviewed, with the first from cognitive psychology/neuroscience and the second from an ecological psychology/dynamic systems perspective.

Cognitive psychology/neuroscience

Because the quiet-eye onset occurs prior to the final movement in a task and is of longer duration when performance is higher, the quiet-eye period represents the period of time when the neural networks are organized to control the movement (Vickers, 1996; Williams et al., 2002; Behans and Wilson, 2008). The quiet-eye period represents the time needed to process cognitively the information that is being fixated or tracked and to focus attention on the demands of the task. In this view the neural networks underlying higher levels of performance must be ‘‘fed’’ very precise external visual information in order for the complex neural systems underlying control of the limbs to be assembled and activated. When the location, onset, offset, and duration of the quiet eye are all optimal then the resultant performance is superior; when any one of these dimensions is nonoptimal then performance is inferior.

Results in support of this view were found by Williams et al. (2002) who recorded the gaze of highly skilled and novice billiard players as they performed shots of varying complexity. In two experiments, they manipulated the quiet-eye duration during easy, intermediate, and difficult shots. Since more complex motor responses require longer pre-programming times (e.g., Henry, 1953) it was expected that if the quiet-eye duration was related to cognitive programming the more complex shots would require a longer quiet-eye period. The results showed that the quiet-eye period was significantly longer for the highly skilled players than for the novices in all levels of shots, and it was also longer on hits compared with misses. When the preparation time was reduced by 25% and 50% of what each player normally used, shorter quiet-eye periods were a characteristic of poorer performance, irrespective of skill level. Williams et al. (2002) interpreted the quiet-eye duration as the critical period when cognitive processing was carried out.

It is clear from this and other studies that the neural, perceptual, and cognitive systems need an optimal amount of time to process critical visual information prior to an action being carried out. Posner and Raichle (1994) have identified three attention neural networks that may be central to this process. The posterior orienting network is responsible for controlling the gaze and attention in space. This network, which is located in the parietal region, directs the gaze to specific locations of importance in a task. It is also responsible for preventing the disengagement of the gaze to other locations. Free-throw shooters, golfers, rifle shooters, and cricket players may use the posterior network to align their gaze to specific locations in space and maintain the gaze at a single location. The anterior executive network is responsible for bringing into consciousness critical aspects of what is being fixated. This network interprets what is being viewed and imposes a higher-order understanding on the task based on past experience and knowledge. Skilled players bring a richer knowledge base and more refined rules than less-skilled performers, who are often unsure of what they need to see as they perform. Finally, the vigilance network is responsible for coordinating the posterior and anterior networks and preventing unwanted or distracting information from gaining access to the other networks during periods of sustained focus. The vigilance network is responsible for the sustained concentration seen in elite players, especially during pressure-filled games of long duration.

More recently, neurophysiological studies in monkeys have suggested that the brain regions that are involved in selecting and planning a certain action have an important role in forming decisions that lead to that action. Heekeren et al. (2003) asked human observers to make direction-of-motion judgments about dynamic random-dot-motion stimuli and indicate their judgments with an eye movement to one of two visual targets. The authors localized regions that are part of the oculomotor network. Importantly, during the period of decision formation between the onset of visual motion and the cue to respond, the percent change in the blood-oxygen-level-dependent (BOLD) signal in the oculomotor network was highly correlated with the strength of the motion signal in the stimuli. These data are thus consistent with the single-unit studies in monkeys that identified similar regions in the process of forming a perceptual decision.

The results are also similar to those of Heinen et al. (2006) who had participants play ‘‘ocular baseball’’ while undergoing functional magnetic resonance imaging (fMRI). In this game, the subjects had to decide whether or not the trajectory of a dot moving across a computer screen was likely to cross into a visible ‘‘strike’’ zone. If the participants decided that the dot was likely to enter the strike zone, they had to make an eye movement; in the other case, their eyes had to remain fixed on a point in the centre of the screen. The results showed that when a decision was associated with a specific movement, the formation of the decision and the preparation of the behavioral response had a common neural substrate. Put more generally, the findings support the view that the human oculomotor system also has an important role in perceptual decision making.

In addition to the quiet eye being identified as an indicator of optimal focus and attention during low-pressure situations, the influence of anxiety and physiological arousal on the quiet-eye period has been examined (Vickers and Williams, 2007; Behan and Wilson, 2008). Behan and Wilson, in a simulated archery task, found that under conditions of elevated cognitive anxiety, optimal visual orientation, as indexed by quiet-eye duration, was altered. Participants generally showed reductions in the duration of quiet eye, as they took more fixations around the vicinity of the target than they did in the low-pressure condition. These results show that the quiet-eye period is sensitive to increases in anxiety and may be a useful index of the efficiency of visual orientation in aiming tasks. Vickers and Williams (2007) found that elite biathletes who increased their quiet-eye duration during high-pressure competition, as opposed to low-pressure practice, were able to overcome the normally debilitating effects of the high physiological workload, high competitive pressure, and anxiety.

These results raise the question of why a long-duration quiet eye should improve motor performance under conditions of high pressure and/or very high physiological arousal? A possible reason may lie in the work of Setchenov (1903/1935), a Russian physiologist who showed that when individuals were fatigued to exhaustion they could do more physiological work when a ‘‘diverting’’ activity was used to direct their attention to an external target. Assmussen and Mazin (1978a, b) subsequently found the phenomenon applied in a wide variety of tasks (both mental and physical) and that the amount of work that could be performed was greater with eyes open compared to eyes closed. Even when complete exhaustion was reached, opening the eyes led to a 15–30%

increase in the amount of exercise that could be performed. They reasoned that the input of afferent information acted to redirect attention away from the physiological demands of the task resulting in an ability to perform at a higher level. The Setchenov phenomenon is, therefore, not related to an internal focus of attention, but instead to an external focus of attention mediated by vision. These results further suggest that the ability to overcome the normally debilitating effects of maximum exercise can be aided through the use of an appropriate external focus of attention, as highlighted by the changes in the quiet eye found in the Behans and Wilson (2008) and Vickers and Williams (2007) studies.

Ecological psychology and dynamic systems

Alternate theoretical explanations for the quiet eye have also been proposed from an ecological psychology and dynamic systems perspective. Researchers from these approaches state that people perceive environments directly unaided by inference, memories, or other neural representations as suggested by cognitive psychologists (Gibson, 1979/1986; Michaels and Carello, 1981). Skilled movement depends on the establishment of direct optical relationships that develop without any apparent need for the processing stages that define cognitive psychology. Over time, and with experience and training, some of these relationships become invariant, which Michaels and Carello (1981) describe as ''those high-order patterns of stimulation that underlie perceptual constancies, or more generally, the persistent properties of the environment that an animal is said to know. Invariant structures in light and sound not only specify objects, places and events in the environment, but also the activities of the organism… Thus invariants are, by virtue of the laws that support them, information about the environment and the animal's relation to it'' (p. 40).

Researchers from an ecological or dynamic systems approach have argued that the quiet-eye period facilitates the orientation of the body in space and allows for the execution of movements that are more attuned to the affordances and other constraints that are present (Oudejans et al., 2002, 2005; Oliveira et al., 2007). Since the quiet eye has invariant characteristics of location, onset, offset, and duration relative to the final movement in a specific task, it optimizes optic flow and permits a better orientation of the performer relative to critical environmental constraints. For example, Oudejans et al. (2005) explains that the quiet eye is a factor in basketball shooting because it permits ''a continuous updating of the relation between shooter and rim, up until ball release, as this relation at ball release provides the best determination of force, direction, and velocity needed to make a successful shot.'' This updating is not carried out by an internal feedback system but through the generation of dynamical relationships between the position of the gaze in space and gaze relative to the target that are subconscious and require no cognitive processing.

Controversies and future directions

It is clear that cognitive, neuroscience, and ecological theories provide distinct, and in some ways competing, ways of understanding the role of a quiet eye in visuomotor coordination. To be successful, a theoretical framework must account for how human are able to perform both rapid dynamic tasks (such as ice hockey or soccer goaltending, cricket batting) as well as those that are slower (as found when walking, or shooting a free throw). Slow and fast movements are normally defined by the duration of their movement times since this dictates the extent to which feedback and additional cognitive processing can be used to modify or change the movement. Generally, cognitive theories are good at explaining how actions with movement times in excess of 200 ms are controlled, while ecological and dynamic systems accounts are best at accounting for rapid movements under 200 ms. Each theory is characterized by a number of emerging dichotomies, the main ones being focal and ambient vision; top-down and bottom-up processing; ventral and dorsal processing; and closed- and open-loop motor control. The focal, top-down, ventral, closed system is tailored for situations where movement times are more than 200 ms and there is adequate time for cognitive processing to occur, while the ambient, bottom-up, dorsal, and open-loop control systems are specialized for tasks performed when movement times are less than 200 ms therefore affected by time constraints. In all motor tasks the two systems work together and permit the great range of actions that humans perform. There is considerable empirical evidence showing that a long-duration quiet eye is a characteristic of higher levels of motor performance is tasks where movement times are both below and above the 200 ms threshold. Elite athletes find a way to get the information they need earlier and they process this information longer irrespective of task constraints than do nonelite athletes.

However, ecological psychologists have argued that it is the final information within the quiet-eye period that is most important and not the earlier information that is fixated (Oudejans et al., 2005; Oliveira et al., 2007). Cognitive psychologists argue just the opposite. Personally I do not know 100%, but to date, the weight of evidence is in support of early rather than late quiet-eye information. I believe the final answer will depend on how gaze data are ultimately coded and analyzed in perception–action studies. Currently this is being done in two ways, with each approach consistent with either a cognitive or ecological/dynamic systems view. Cognitive psychologists code gaze data using precedents arising from the eye-movements literature (Bridgeman et al., 1975; Optican, 1985; Carl and Gellman, 1987; Carpenter, 1988; Coren et al., 2004). Cognitive psychologists identify at least three types of gaze behaviors in the data stream — fixations, pursuit tracking, and saccades. Each gaze is defined according to rules that have been established over decades of eye-tracking research. Briefly, a fixation occurs when the gaze is held on an object or location within 3° of visual angle for 100 ms or longer (Optican, 1985; Carl and Gellman, 1987; Carpenter, 1988). The 100-ms threshold is the minimum amount of time needed to recognize or become aware of stimuli. Additional time is required to make a movement, with about 180 ms needed to actually see an object and initiate a simple movement, such as pressing a key. Pursuit tracking occurs when the gaze follows a moving object, such as a ball or a person. The 100-ms threshold is used for pursuit tracking for the same reason it is used for fixations; it is only when the gaze is stabilized on the moving object or person that the individual is able to process the information provided by that object or person. During both fixations and pursuit tracking information can be processed. Saccades occur when the eyes move quickly from one fixated or tracked location to another. Saccades are rapid eye movements that bring the point of maximal visual acuity onto to the fovea so that it can be seen with clarity. We average about three saccades each second when viewing a normal scene, and these range in duration from 60 to 100 ms. In order to see and comprehend a scene, we must move our eyes rapidly from one fixated location or object to another using saccades. During saccades, information is suppressed (Bridgeman et al., 1975). Information gained during fixation or tracking is maintained across saccades so that a stable, coherent scene is viewed (Irwin, 1996). We do not perceive the blur as our eyes move, neither are we able to see a new object that appears during a saccade. However, we do possess an object-file transsaccadic memory (Irwin, 1996) that allows us to perceive scenes that are cohesive and meaningful.

In contrast, ecological psychologists hold true to the teachings of Gibson (1979/1986) and treat every gaze as being equal to all others. Ecological psychologists do not use any of the definitions for the gaze arising from the eye-movements literature, but instead assume that each gaze detects critical affordances, invariants, or elements of optic flow in the dynamic environment. They are not concerned about whether visual information is processed by the brain, only that it is detected by the visual system. Since most eye trackers have rates of 30 or 60 Hz, then ecologists recognize that visual information detected in as little as 16.67 ms may be valuable in terms of affecting a movement (Oliveira, 2007). While the coding rules used by cognitive psychologists have a long history in eye tracking and are good at explaining contributions made by the focal system, these rules often do not recognize potential contributions made by the ambient system. Indeed, gaze data that do not meet the rules for fixations, pursuit tracking, or saccades are usually identified as "other" and are not reported in a major way. Conversely, the coding grids used by ecological psychologists do not recognize that humans possess both a focal and an ambient system, and that humans use eye movements during which information is both processed (fixations, saccades) and suppressed (saccades). One way to resolve this issue is to code and analyze the same data set using both methods. We are in the process of doing this within my laboratory in a study using both cognitive and ecological coding approaches.

As is evident, there are many issues still to be resolved in terms of understanding the contributions of the gaze to performance in motor skills. Regardless of the theoretical perspective taken, there is considerable research evidence showing that the quiet-eye period is a perception–action variable that defines higher levels of skill and performance. Gaze-training studies show that training the gaze improves performance and early evidence indicates that research insights into how the gaze functions in various motor tasks have a profound effect on the training of athletes and education of coaches. Despite considerable advances by a growing number of research teams around the world, there is still more research that needs to be done before we have a complete understanding of this intriguing phenomenon. In many ways the goal of gaze and quiet-eye research is similar to that carried out in the past that looked at the merits of open- versus closed-loop control, or dorsal versus ventral processing. The goal is to understand how humans perform so well under impossible time constraints. In many respects the questions and challenges are still the same; the theatre of investigation has just changed to investigating the role of the gaze in action.

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