A Narrative Literature Review About the Role of Microsaccades in Sports



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# A narrative literature review about the role of microsaccades in sports


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## Abstract

In many daily and sport situations, people have to simultaneously perceive and process multiple objects and scenes in a short amount of time. A wrong decision lead to disadvantage for a team or for a single athlete, and during daily live (i.e. driving, surgery) it could have more dangerous consequences. Considering the results of different studies, the ability to distribute visual attention depends by different level of expertise and environment-related constraint. This article is a narrative review of the current scientific evidence in the field of eye movements in sports, focusing on the role of microsaccades in sporting task situations. Over the past ten years, microsaccade studies have become one of the most increasing areas of research in visual, oculomotor and even in sport science area. Here we review the latest findings and discuss the relationships between microsaccades and attention, perception and action in sports.


**Keywords:** fixational eye movements; peripheral visual field; visual acuity; perception-action coupling

## Introduction

Several researches have investigated how athletes use their visual search strategy in different sporting situations. As predicted, results have shown that experts are better in perceiving and responding to sport-relevant cues, as demonstrated by higher response accuracy and faster response times during perceptual-cognitive tasks (Mann et al., 2007). One of the first study on gaze behavior in sports was published in 1976 by Bard & Fleury, who presented to their participants a series of videos in which players had to make decisions about game situations (Bard & Fleury, 1976). Few years later, Abernethy & Russel (1987) recorded the eye movements of expert and novice badminton players whilst they watched a film based-task, investigating the ability of the players to pick up advanced information from the opponent's arm and racket movements. In a recent review, Kredel et al., (2017) have collected sixty studies on natural gaze behavior in sports, revealing that over the last 40 years, the use of eye-tracking devices has considerably increased. Specifically, they have highlighted a large variance of methods used, analyses performed, and measures derived within the field. The authors suggested that sports-related eye-tracking research are subdivided in two main categories: the first one is oriented toward experiments done in the field, following an ecological approach. The second one is done in a laboratory setting, in favor of high measurement accuracy. The main findings of these articles are that expert performers generally utilize different perceptual behaviors than their less skilled counterparts, with fewer fixations of longer duration. However, these different perceptual behaviors are dependent upon the type of sport, research paradigm and stimulus presented to the subjects (Mann et al., 2007). It seems that, to fully understand the athletes' perceptual behaviors, researchers should investigate each sport individually, considering also the research setting and action requirements for the task. The same consideration could be done on the type of eye movements (or gaze strategy) that athletes utilize in a situation over another, like a soccer goalkeeper that have to predict the direction of the ball kicked at different distances. As retinal image size increases, more peripheral retina is stimulated, which raises the probability of triggering a saccade reducing the mean fixation duration. This finding suggests that the implicit relationship between fixation duration and information processing are not determined a-priori as initially presumed, and questions the validity of relying too rigidly on a strict cognitive assessment of search behavior (Williams et al., 2004).

In a real-live situation, vision is characterized by alternating sequences of rapid gaze shifts (saccades) and fixations. Even when we attempt to fix our gaze, small ocular motions, the so called fixational eye movements, undetectable to the naked eye, shift our eye position, meaning that our eyes are never still, even during fixation (Martinez-Conde et al., 2004). Three types of fixational eye movements exist: (i) ***drift***, eye movements characterized by low motion, (ii) ***tremor***, with a high-frequency oscillatory component, and (iii) ***microsaccade***, a ballistic high-velocity (<100°/sec), small-amplitude movement (<1°). Drifts occur simultaneously with tremors and are slow motion of the eye that occur during the periods between microsaccades. It seems that drifts have a compensatory role in preserving accurate visual fixation in the absence of microsaccades (Martinez-Conde et al., 2004). The contribution of tremor to the maintenance of vision is unclear, and is generally thought to be independent in the two eyes. This imposes a physical limit on the ability of the visual system to match corresponding points in the retinas during stereovision (Martinez-Conde et al., 2004). While saccades alternate with fixations, microsaccades occur within fixation. Microsaccades and saccades have different features in common; both of them originate from the superior colliculus, showed the same amplitude versus peak velocity relationship, and are made by both eyes simultaneously (Hafed et al., 2009).

Few studies have conducted gaze analysis on fixational eye movements in sports, and of these, only the microsaccades have been investigated (Piras et al., 2015, 2019, 2020, 2021). This is probably due to the difficulties in measuring such small eye signals during dynamic tasks, considering that sport-relevant stimuli consist of either live situations or dynamic videos, with greater body movements in comparison to participants in standard psychophysical settings. Many sports are not suitable to record such eye measurements, and even in situations when players are able to wear eye-tracking glasses, such devices are not best-suited for measuring fixational eye movements (Alexander et al., 2019). Moreover, the application of video eye trackers to the study of drift and tremor is difficult for a number of reasons, such as the color of the iris, the specific calibration methods used, lack of proper head immobilization and/or slippage of the head mounted eye tracker. All of these issues contribute to reduce the accuracy of measurements (Ko et al., 2016).

The purposes of our literature review are: (i) to discuss the most recent advances in microsaccade research inside the sports science field; (ii) to analyze how microsaccades could help in improving the athlete performance; and (iii) to recognize current trends in the field, their expected contributions in the near future and the most important gaps to address.

## Neural mechanism involved in microsaccade production

The neuronal mechanisms for generating microsaccades have been studied in extensive detail, and include circuits disseminated across numerous cortical and subcortical brain regions. The superior colliculus (SC), a retinotopically organized structure, known to be important for selecting and initiating voluntary eye movements, is also part of the neural mechanism that controls microsaccades and other orienting behaviors. Neurons across the entire SC are involved in the process of selecting targets for eye movements, and neurons in the rostral SC are important for the selection of targets near the fovea, even if this involves breaking visual fixation to move the eyes (Nummela & Krauzlis, 2011).

Recent neurophysiological evidence showed that microsaccades are generated by the same motor control mechanism as saccades (Hafed et al., 2009; Krauzlis et al., 2017). There are different properties that microsaccades and saccades shared, for example they are generally binocular; follow the same main sequence, the relationship describing how the peak velocity increases as increase the amplitude of the movement. Visual perception thresholds are elevated during saccades and microsaccades (saccadic/microsaccadic suppression), in which their rates can be reduced intentionally and during specific tasks. Voluntary saccades can be as small as fixational microsaccades and both have been linked to shifts in the covert attention (Martinez-Conde et al., 2009). Therefore, we can confirm that saccades and microsaccades are governed by the same brain structures. Omnipause neurons and burst neurons in the brainstem pause and fire during both saccades and microsaccades, meanwhile, the identical regions of the cerebellum involved in fine-tuning of the saccades horizontal amplitude are also implicated in the microsaccade adjustments (Krauzlis et al., 2017).

The SC neurons can also clarify an interesting link between microsaccades and the covert attention shift. During fixation, the shifting of the visual attention to peripheral target causes an increase in microsaccades toward the direction of the cue location, explained by changes in SC population activity. The stimulation of the peripheral retina evoked by the target creates an imbalance that trigger a saccade but not strong enough to induce a saccade toward the peripheral cue, hence the small saccade (Krauzlis et al., 2017). According to this hypothesis, when SC activity at the cued location is suppressed, early microsaccades directed towards the cue are almost completely eliminated (Hafed et al., 2013).

Saccadic eye movements are obtained due to changes in the referent eye position that predetermine the final fovea position relative to which the world image is going to be considered after the eye movements. This means that the size of referent eye rotation, defined before the saccade, is the eye rotation necessary to bring the image of the cue to the fovea. Therefore, whether or not the cue is moving is determined depending on the distance of the cue from the fovea. Thus, we have to leave the traditional theory that visual constancy is produced by compensating the shifts in the retinal images with a copy of motor commands to extra ocular muscles (Feldman & Zhang, 2020). Instead, the system identifies the positions of cues in the real world in the spatial frame of reference in which eye movements emerge and retinal images of objects are considered.

## Role of microsaccades in foveal and peripheral vision

Visual acuity is not uniform across the visual field. It deteriorates with increasing distance from the foveola, the center of the fovea that contains only cone cells with more densely packed receptors, than other retinal regions (Curcio et al., 1990). The foveola has the highest visual acuity in the eye (Intoy & Rucci, 2020). This anatomical substrate offers clear evolutionary advantages, since it enables monitoring of a large extent of visual space, implying a perception-action coupling: eye movements are required to sequentially inspect areas of interest with the high-acuity foveola. Once a salient stimulus is captured by the foveola, microsaccades are used to assist in analyzing the visual image in important and interesting ways. On the contrary, moving from the fovea to the periphery, the number of cones decreases, and the information are perceived more blurred (up to 90% at 40° of eccentricity) (Curcio et al., 1990). Despite this low visual acuity, the high quantity of rod cells in the peripheral retina implicate a high motion sensitivity (Raffi & Piras, 2019).

Sport actions comprise rapidly changing environments where players' ability to perceive their surroundings and make the most beneficial decisions could be the difference between winners and losers. Consequently, understanding the specific perceptual requirements and behaviors adopted by athletes in these scenarios is essential for coaches and sport scientists who are trying to enhance the development and performance of players. Moreover, athletes have to deal with various situations during a match, which are faced differently. Expert players have demonstrated different visual search behaviors under changing task constraints (Williams et al., 2004). What emerges from the studies is that the visual search strategy in sports seems to be driven by the constraints of the task. When the ball is far away, experts have time to undertake a complete analysis of the scene and appear to rely on information extraction via the fovea. In contrast, when the ball is closer and the time constraints are more severe, experts rely on peripheral retina to monitor opponents and teammates' movements, reducing the costs associated with eye movements. During small-sided games, played on reduced pitch areas and involving a smaller number of players, situations encountered during actual team sports (e.g. 1vs1; 3vs3; 2vs1, etc.), it is possible to have an involvement of both foveal and peripheral vision; the experts use the fovea to extract relevant information, whereas, as the opponent approaches they may rely more on peripheral vision to pick up the relative movement pattern. The emergent search pattern in these situations would appear to be at least partly constrained by the number of players involved in the action and the relative distance between teammates, the ball, and the opponents (Piras et al., 2021; Williams et al., 2004; Williams & Davids, 1998).

Recent researches have related in microsaccade the role of counteracting adaptation and visual fading during fixation. Martinez-Conde et al. (2006) found increased microsaccade rates before a peripheral target appeared and decreased rate before the target faded, concluding that microsaccades enhance vision during fixation. McCamy et al (2012) revealed that larger and multiple microsaccades were more efficacious than smaller or single microsaccades in restoring vision during both foveal and peripheral vision. Specifically, larger microsaccades may be more efficacious due to their increased ability to bring the neuronal receptive fields (RFs) to uncorrelated stimulus regions. The RFs of the visual neurons are spatial regions within which sensory stimuli can elicit a neural response. Our visual cortex has a retinotopic organization, meaning that close neurons have RFs that encode similar spatial locations (Hubel & Wiesel, 1965). Moreover, visual RFs have the capacity to shift toward a future location before a saccade, an event defined *RF remapping*. It has been found that during steady fixation, participants anticipated the execution of a saccade in the corresponding direction, remapping their receptive fields toward the target. This phenomenon is called *presaccadic enhancement*, a kind of attentional effect in which RFs that are sufficiently close to the saccade target can enhance the responses to stimuli presented near the target (Neupane et al., 2020). This type of *convergent remapping* (a shift of the RFs toward the saccade target) can therefore be explained as a side effect of covert attention directed toward the saccade target. Previous work has shown that attentional modulation can shift the positions of RFs in others brain areas (V4 and MT), without any eye movements (Connor et al., 1996; Womelsdorf et al., 2006). These results suggest that attention shifts can lead to a complex pattern of RF effects, maybe involving the microsaccades. Moreover, since the shift of the RFs are initiated prior to the saccade onset, it seems natural that visual RF remapping is observed before every saccade (Zhang et al., 2022). Researchers have also proposed many other microsaccade functions, such as the control of fixation position, performance in high acuity visual tasks and visual scanning of small regions (Rolfs, 2009).

The sport environment is a good model to investigate the foveal and peripheral role on microsaccade generation, given that, at recent, such role is largely unknown. Although differences in fixation locations through expertise have been reported in the majority of studies (Mann et al., 2007), few researches have investigated differences between the utilization of the fovea in comparison to the periphery during sport situation. Since the different functional organization of foveal and peripheral visual field (Raffi & Piras, 2019), the cue's proximity could impact on the utilization of the foveal or the peripheral vision to pick-up relevant information necessary to produce predictive judgments early in time, just before the initiation of the motor response (Williams, 2009). Different studies have found that stimulating the fovea and/or the peripheral retina allows the successful prediction of a sporting action through microsaccades and saccades (Piras et al., 2015, 2019, 2021). Specifically, during the visual perception of extrafoveal cues, before the eyes start to move, peripheral vision is enhanced, and sensory orientation is reorganized by the saccade target location (Piras, Raffi, et al., 2016). These fluctuations occur rapidly, with an impact on the visual perception, as humans perform saccades every few hundred milliseconds (Klein & Ettinger, 2019). It has been hypothesized that foveal involvement may bring to more saccades generation; meanwhile, the absence/reduction of saccades in favor of fixations would rather support the players' ability to use peripheral vision to detect change events (Piras et al., 2021). Piras et al. (2021) have investigated the visual search strategy of soccer goalkeepers engaged in penalties kicked from different distances (11m vs. 6m). Their hypothesis was that experts adopted a different visual search strategy dependent on situational constraints, with more microsaccades and less saccades during near in comparison to far action

*** Figure 1 near here ***

Results showed that expert goalkeepers used a visual search strategy with more fixations, and consequently, greater saccade rates during penalties kicked from 11m (far) with respect to penalties kicked from 6m (near), where they exhibited fewer fixations with higher microsaccade rates (0.59±0.18 N/sec vs. 0.63 ± 0.19 N/sec; see Fig.1). Authors discussed results in term of opponent's and ball distance, meaning that as long as the kicker's distance is large and thus time pressure is low, gaze can be frequently shifted between interest areas (kicker's body and the ball) because the cost of saccades is low. Meanwhile, closer images need both foveal and peripheral vision to be processed because the kicker is close and time pressure is high. This means that the cost of saccades is high, and the fovea is not the only important part of the retina to acquire visual information. It is necessary to monitor different cues also with the peripheral vision, probably using microsaccades or small saccades. Thus, microsaccades may suggest attention to peripheral target due to pick up relevant information; hence, a very precise fixation may not be necessary.

## Covert and overt attention in sports

Visual attention plays a central role in sports. Team sport players are submitted to different simultaneous activities, from one side the teammates' movements, from the other the opponents' movements and the ball used to play the game. Player at high level has the ability to shift the attention quickly, knowing the positions of the opponents as well as to predict how such positions will change over time. A particular skill that only expert athletes show in a match (i.e. basket and soccer) is the "no look" pass. The no look is a classic example on how experts can shift the attention without making eye movements (or at least undetectable at naked eye), passing the ball to an empty location knowing that the teammate will be there to catch the ball. This particular skill is comprised within the category of covert attention, when attention is shifted in the absence of gaze movement, different from the overt attention, when the gaze is directed toward an object of interest (Posner, 1980).

The allocation of covert and overt attention can be detected through microsaccades and saccades (Belopolsky & Theeuwes, 2009; Hafed & Clark, 2002). The coupling between attention and eye movements have assisted in clarifying the microsaccade characteristics, showing that this tiny eye movements could indicate the place where our mind is unconsciously focusing, although our gaze is directed elsewhere (Piras et al., 2015). Previous studies have revealed a relationship between microsaccades and visual perception in natural scenes (Otero-Millan et al., 2008). It seems that the spatial location of attention could influences the rate and/or the direction of microsaccades during fixation, and it has been found that microsaccades provide a mechanism for precisely relocating gaze in high-acuity tasks, supporting the proposal that microsaccades are exploratory movements, similar to larger saccades (Ko et al., 2010). A research performed in table tennis players demonstrated that the opponent's overt attention is directed mostly to hand, racket, and ball area especially when the racket touch the ball (Abernethy & Russell, 1987; Singer et al., 1998). Piras et al. (2015) recorded eye movements from novice and expert table tennis players who had to predict the outcome of an opponent's ball throw while they were forced to maintain their eyes on the center of the opponent's chest. The hypothesis was to verify if experts were able to use microsaccades to shift the attention covertly toward the areas with information necessary to predict the direction of the ball. Results showed that experts were able to predict the outcome of the throw, producing more microsaccades directed toward the interest areas with richest information, essential to predict the outcome of the action. Experts fixated longer on task-relevant areas ''anchoring'' or "pivoting" the fovea in the middle of different key locations, taking advantages of the peripheral retinal functions to pick up relevant information. The effective use of these strategies, in which the gaze is centrally located between different interest areas – hands/racket/ball – in table tennis (Abernethy & Russell, 1987; Piras, Lanzoni, et al., 2016; Singer et al., 1998) or – kicking-leg/non-kicking leg/ball in soccer (Piras & Vickers, 2011), enables optimal use of both the foveal and the peripheral vision. Piras et al. (2015) argued that when participants were forced to maintain fixation in the middle of the opponent's chest, they are fostered to shift the attention covertly in order to predict the development of the action, making longer and wider microsaccades with respect to novices. Microsaccade directions are biased towards covert attention shift, then peripheral retinal stimulation could alone make microsaccade dynamics, even without a foveal stimulation (Otero-Millan et al., 2019). Athletes who play ball games are repeatedly exposed to motion stimuli during their training, increasing their ability to quickly shift attention from one relevant cue to another, leading to an improvement in their perception of moving objects (Memmert & Furley, 2007). These experiments indicate that the direction of microsaccades can be influenced by attentional cues in sport specific tasks. Microsaccade studies reveal links between visuomotor performance and covert attention shifts. The potential impact of these findings could be that detailed assessment of visual performance may help to acknowledge potential elite skills and that vision training offers a means to further improve performance.

The extent to which foveal versus peripheral visual information contribute to microsaccade generation remains unclear. Microsaccade directions are influenced by the covert attention shift, meaning that peripheral visual stimulation could be enough to produce regular microsaccade dynamics, even without foveal stimulation. It has also been found that microsaccade production is reduced in the absence of foveal stimulation, supporting the idea that they require the presence of a "target to anchor to" (Otero-Millan et al., 2008). Moreover, is emerged that the size of the fixation cue is important for microsaccade production, with bigger cue resulting in larger and less frequent microsaccades (McCamy et al., 2013). Considering the importance of the covert attention in the contrast sensitivity and in the perception of important cues, it seems appropriate to train athletes in improving this capacity. Basic vision science tells us that peripheral vision is not only important for maintain posture (Raffi & Piras, 2019) but can help athletes in saccades planning, tracking multiple objects at once, perceive the surrounding, and perform some object-recognition tasks. In some settings, a player might need to monitor multiple locations, each of which require information available with both central and peripheral vision, as for example in soccer, in which the player in possession of the ball had to utilize peripheral vision to monitor opponents and teammates. In this situation, players adopt a visual pivot strategy, fixating their gaze to a location that minimizes the time required to move their eyes, reducing the saccades cost, and using a wide focus of attention to get the most reliable cues to make the action.

## Quiet eye and microsaccades

In the last thirty years, most of the studies on gaze behavior in sports have investigated the expert-novice paradigm using the vision-in-action system (Vickers, 2007). In 1992, Vickers found that during successful actions experts golfers fixated, for a long time, at a specific location (in this regard the back of the ball) prior to and following the final movement initiation (ball-bat contact). This gaze strategy was termed Quiet Eye (QE), hereinafter defined as "*the final fixation of at least 100 ms within 1–3° of visual angle prior to the final movement initiation*" (Vickers, 1992, 1996). Experts show longer QE duration compared with novices, and longer duration is also linked to successful actions (Piras & Vickers, 2011; Timmis et al., 2018). Therefore, with the use of video-based eye-tracking systems, these findings have been replicated across several types of aiming and interceptive sports (for a review see Gonzalez et al., 2017). Gonzalez et al. (2017) have discussed the functional mechanism underlying QE, speculating on the neural networks in which QE may be involved and on the relationship between attention and eye movements. The allocation of attention to a fixation point results in a "suppression" (reduction in saccade amplitude and velocity) of the oculomotor system (Goldberg et al., 1986), indicating that active fixation on a specific cue make attention allocated to that position and not to peripheral locations (Gonzalez et al., 2017). It supports the QE definition; the suppression of eye movements outside of 1-3° of visual angle increases the ability to fixate on relevant cues and in a more efficient extraction of information (Vickers, 1996). Considering that microsaccades are small (≤1°) involuntary rapid eye movements (≤100 °/sec) that occur 1–2 times/sec during fixations, and looking at the QE definition, it is important to highlight that the eyes are rarely "quiet", and that this tiny eye movements may arise inside the QE. Therefore, Piras et al. (2020) investigated the subtle eye movements and underlying mechanisms immediately prior to and during QE, focusing on the role of microsaccades and saccades during the approaching of the foot-ball contact while goalkeepers attempted to predict the direction of the soccer penalty kicks. Authors hypothesized that expert goalkeepers, during the QE, identify the useful cues necessary to predict the direction of the ball shifting covertly their attention through the utilization of the microsaccades. Results demonstrated that the microsaccade rates decreased 1 second before the experts' final movement time initiation, with a concomitant increase of small saccades of about 3° of visual angle. As suggested by Gonzalez et al. (2017), in the definition of QE the term fixation inside 3° of visual angle could include different types of eye movements, such as small saccades, microsaccades, and smooth pursuit, without fitting inside the normal definitions of fixation. Otero-Millan et al. (2008) have found that saccades greater than 1° of visual angle and made during prolonged free-viewing fixations may be considered as involuntary and could be considered as microsaccades. This is because the microsaccades amplitude described in the literature has changed over time. The original descriptions reported microsaccades with amplitudes frequently smaller than 0.3° of visual angle, which are indeed miniature saccades (Steinman et al., 1973). Nevertheless, mainly due to the extensive use of video-based eye trackers, subsequent studies often apply a more liberal criterion and include much larger saccades with amplitudes of up to about 1°, sometimes referring to them as 'fixational saccades' (Krauzlis et al., 2017). Moreover, it has been found that microsaccades can be suppressed during visual tasks that need higher attention, with associated saccadic intrusions (Gowen et al., 2007). Piras et al. (2020) demonstrated that the direction of microsaccades could reveal the experts' intention, showing a main vector directed to the right when goalkeepers moved to the right, and to the left when goalkeepers moved to the left. This finding may suggest that microsaccades are not casual but may indicate where our mind is instinctively directing.

It is known that when all eye movements are suppressed (i.e. under retinal stabilization conditions), visual perception rapidly fades to a homogeneous field (Ditchburn & Ginsborg, 1952). Microsaccades counteract fading and are most effective in high frequency and large amplitude, with their increased ability to bring the neuronal receptive fields to regions not correlated with the target stimulus (McCamy et al., 2012). This could be related with QE duration and relevant for performance. Microsaccades with low frequency and small amplitude may suggest enhanced attention to a small target area, in contrast, microsaccades with high frequency and large amplitude may suggest the involvement of the peripheral portion of the retina, thus a very accurate fixation may not be required. Thus, these tiny eye movements within QE may offer an important understanding regarding the link between the oculomotor control, visual perception and the allocation of attention in sports. All these parameters could be comprised in the QE description, which indicates the suppression of large eye movements within 1–3° of visual angle, with the improved capacity to fixate on relevant cues, avoiding the irrelevant ones.

## Pupil size and microsaccades

Particular attention should be paid to pupil size. Pupil dilation and microsaccade production are modulated by stimulus presentation and are generated by the intermediate layers of the SC. As described before, the SC is involved in voluntary-saccade target selection which projects directly to the brainstem reticular formation to provide the required input to initiate the eye movements as small as 0.2 to 0.3 degrees (Hafed et al., 2009) and coordinates pupil dilation as one of the component of the orienting reflex, increasing visual sensitivity (Wang et al., 2012).

It is well known that pupil dilation happens during mental activity, used as a tool to investigate human cognitive processing (Beatty, 1982). In golf, pupil size has been considered an index of the allocation of cognitive control, in which experts made high and consistent pupil dilation during putting tasks (Campbell et al., 2019). Meanwhile, in equestrian performers, pupillometry has been used to recognize skill-based differences of attentional effort while viewing a video-based of jumping sequence (Moran et al., 2016). Wang et al. (2012) demonstrated the central role of the SC on pupil dilation and microsaccade generation through recording on single neurons. The SC is importantly involved in both multisensory integration and initiation of the orienting response, indeed, pupil dilation, microsaccades and saccades can be evoked and modulated following the appearance of relevant stimuli (Corneil & Munoz, 2014). Piras et al. (2021) demonstrated a multisensory integration between stimulus-response and pupil size. The pupils of expert athletes dilate prior to saccade initiation, increasing visual sensitivity to optimize perceptual processes immediately after redirection of the eyes.

Present literature reveals little information about the relationship between microsaccade frequency and the average change in pupil diameter. It seems that both microsaccade rate and the pupil size point specifically to those fixations that include visual detection and decision – likely they are both expressions of the same neurological substrate triggered by the decisional process (Privitera et al., 2014). Moreover, combining and comparing pupil diameter with microsaccades could be more efficacious in measuring attention and decision-making. More precisely, in the context of decision-making microsaccade rate is highest during fixations on a specific cue, with an involvment of the Locus

Coeruleus (LC) which is linked to pupil dilation (Joshi & Gold, 2020). Indeed, the SC is known to be involved in microsaccade generation, and is in turn linked to LC (LC projects directly to the SC), demonstrating correlation between pupil size and LC activation during distinctive decision-making tasks.

## Future directions and recommendations

The links between microsaccades and performance need to be deeply investigated. Future research should be directed to analyze experts' gaze behavior during both intercepting and aiming tasks, and with respect to the motor phases, because it would provide important information about the time course of microsaccade/saccade orientation in relation to the action. Microsaccade characteristics should be linked to image informativeness, which combines top-down scenarios, in which the athletes decide what kind of action do. For example, a pass, a kick, a free-throw, or during shooting, with bottom-up situations where athletes are exposed to motion stimuli like goalkeepers during penalty kick, tennis player receiving a ball, or a middle blocker that try to block a volleyball attack. It should be determined whether these microsaccade dynamics are task- or expert-related and whether more types of microsaccades may come into play. Thus, caution should be taken when relying on microsaccades generated during prolonged fixations - *fixational microsaccades* - with respect to microsaccades generated during free-viewing – *exploratory microsaccades*. Exploratory and fixational microsaccades can unlikely be discerned in experiments in which stimuli are observed while maintaining accurate fixation on an interest area.

Moreover, it would also be useful to better understand the subtle eye movements and underlying mechanisms immediately prior to athletes' final movement initiation through the use of the deceptive gaze behaviors. A deceptive strategy and a blind-pass strategy (also called no-look pass) are performed when a player looks in one direction and make the pass to opposite direction (covert attention).

In conclusion, microsaccades seem to be i) crucial for anticipate the opponent's direction, ii) modulated by visual attention and iii) functionally related to saccadic intrusions. These fixational eye movements could improve the perception of the game, could help athletes during the period that precedes the final movement initiation, could be involved in shifting from overt to covert attention necessary to identify the useful cues with both foveal and peripheral vision.

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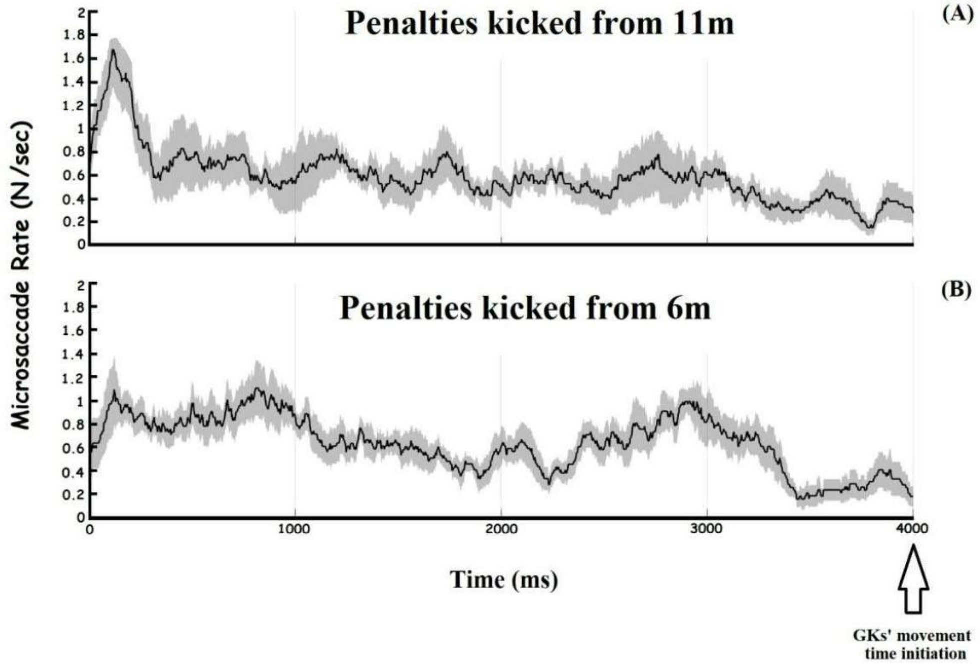
## Figure captions

**Figure 1** — Time course of microsaccade rates during penalties kicked from 11 (**A**) and 6 m (**B**), calculated from the GK's final movement initiation to backward for 4,000 ms (adapted from Piras et al., 2021). Rates were computed for each GK using a moving time window of 200 ms and then averaged over all athletes. Solid black lines represent the mean rate; meanwhile, the shaded gray areas represent the SE of the mean. GK = goalkeeper.

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