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Understanding the underlying mechanisms of Quiet Eye: The role of microsaccades, small saccades and pupil-size before final movement initiation in a soccer penalty kick

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**Understanding the underlying mechanisms of Quiet Eye: the role of microsaccades, small saccades and pupil-size before final movement initiation in a soccer penalty kick**

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Manuscripts

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3 1 **Title: Understanding the underlying mechanisms of Quiet Eye: the role of microsaccades, small**  
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5 2 **saccades and pupil-size before final movement initiation in a soccer penalty kick**  
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7

8 3 **Abstract**  
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11 4 Experts keep a steady final fixation at a specific location just before final movement initiation, the  
12  
13 5 so-called “quiet eye” (QE). However, the eyes are rarely “quiet”, and small eye movements occur  
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15 6 during visual fixation. The current research investigated the subtle eye movements and underlying  
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17 7 mechanisms immediately prior to and during QE. The gaze behaviour of 8 intermediate-level  
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19 8 goalkeepers was recorded as they moved (either left or right) in an attempt to predict the future  
20  
21 9 direction of the ball during a soccer penalty kick. Goalkeepers showed more predicted, with longer  
22  
23 10 final movement time, than missed penalties. The temporal sequence of microsaccade rates dropped  
24  
25 11 about 1000 ms just before goalkeepers’ final movement initiation. Saccade rates increased, reaching  
26  
27 12 the peak at about 500 ms just before final movement initiation, in concomitant with microsaccades  
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29 13 reduction. Microsaccades anticipate the goalkeepers’ direction, oriented to the right when goalkeepers  
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31 14 moved to the right, and conversely to the left when they moved to the left. Microsaccades may be  
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33 15 modulated by attention and appear functionally related to saccadic intrusions. Pupil-size increased  
34  
35 16 proportionally with the approaching of the action, reaching a plateau at final movement initiation. In  
36  
37 17 conclusion, microsaccades could improve the perception of the game, helping athletes during the  
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39 18 period that precedes the critical movement initiation, shifting from covert to overt attention, necessary  
40  
41 19 to identify the useful cue to guide the output from the motor system.  
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49 20 **Keywords:** vision, motor control, attention, perception-action, eye tracking, pupillometry  
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## 25 **Introduction**

26 In recent years, attention has been dedicated to examining the distinct gaze patterns that differentiate  
27 expert and novice players while performing different actions, recognising that experts kept a steady  
28 fixation at a specific location just before the critical movement initiation (Vickers, 1992). This steady  
29 fixation was identified in basketball players and termed “quiet eye” (QE; Vickers, 1996). The QE  
30 corresponds to the final fixation of at least 100 ms within 1-3° of visual angle prior to the final  
31 movement initiation. Experts exhibited longer quiet eye durations compared with non-experts, and  
32 longer durations are characteristic of successful rather than unsuccessful actions (Piras & Vickers,  
33 2011; Timmis, Piras, & van Paridon, 2018).

34 In a recent review, Gonzalez et al (2017) examined the functional mechanism underlying QE,  
35 discussing the neural networks that may be involved, and in particular the relationship between  
36 attention and eye movements. Attention allocated to a fixation point results in a “suppression” of the  
37 oculomotor system (Goldberg et al., 1986), and supports the QE definition (Vickers, 1996); the  
38 “suppression” of large eye movements outside of 3° of visual angle enhances the ability to fixate on  
39 relevant cues and through discarding irrelevant stimuli, results in a more efficient extraction of  
40 information (Gonzalez et al., 2017).

41 The direction of attention is influenced by stimulus presentation. Overt attention occurs when gaze is  
42 directed toward an object of interest; whereas the reallocation of attention in the absence of gaze  
43 fixation is termed covert attention (Posner, 1980). Several studies have found that the allocation of  
44 covert and overt attention can be detected through microsaccades and saccades (Belopolsky &  
45 Theeuwes, 2009; Hafed & Clark, 2002). Saccades are voluntary, rapid eye movements used to re-  
46 orientate the gaze. Human saccadic eye movements vary in size from a few minutes of arc to 100°,  
47 most naturally occurring, human saccades are 15° or less in magnitude, with peak velocities ranging  
48 from 3 to 600 °/seconds (Liversedge et al., 2012). Microsaccades are much smaller ( $\leq 1^\circ$ ) involuntary  
49 rapid eye movements ( $\leq 100^\circ/\text{sec}$ ) that occur 1–2 times/sec during fixations (for a review see

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3 50 Martinez-Conde et al., 2013). When considering the QE definition, it is important to highlight that  
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5 51 the eyes are rarely “quiet”, and that small eye movements occur during visual fixation, the so-called  
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7 52 fixational eye movements. Microsaccades (a categorisation of fixational eye movements) help to  
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10 53 perform high-acuity tasks. These subtle eye movements restore the fixated image which would  
11  
12 54 otherwise fade from view due to neural adaptation (McCamy et al., 2012). Indeed, research has  
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14 55 demonstrated that when all eye movements are eliminated (i.e., under retinal stabilization conditions),  
15  
16 56 visual perception rapidly fades to a homogeneous field (Ditchburn & Ginsborg, 1952; Riggs &  
17  
18 57 Ratliff, 1952). Microsaccades counteract fading, and are most effective when they exhibit a high  
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20 58 frequency and large amplitude, due to their increased ability to bring the neuronal receptive fields to  
21  
22 59 regions not correlated with the target stimulus (McCamy et al., 2012). This could be linked with QE  
23  
24 60 duration and important for performance. Microsaccades with low frequency and small amplitude may  
25  
26 61 suggest enhanced attention to a small target area only and no or very little peripheral visual  
27  
28 62 information pickup. In contrast, high frequency and large amplitude may suggest that peripheral  
29  
30 63 visual fading is avoided, thus a very accurate fixation may not be required (Piras et al., 2015, 2019).  
31  
32 64 To date only two studies have investigated the role of fixational eye movements in sport (Piras, Raffi,  
33  
34 65 Lanzoni, Persiani, & Squatrito, 2015; Piras, Raffi, Perazzolo, Malagoli Lanzoni, & Squatrito, 2019),  
35  
36 66 showing that microsaccades could be influenced by attentional cues, revealing links between  
37  
38 67 visuomotor performance and covert attention shifts, needed for the prediction of the action  
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40 68 development. Therefore, microsaccades may be modulated by attention and appear functionally  
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42 69 related to saccadic intrusions, which are also influenced by the shift of attention (Gowen et al., 2007).  
43  
44 70 Thus, these subtle eye movements within QE may provide an important understanding regarding the  
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46 71 link between the oculomotor control, visual perception and attention allocation in athletes.  
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54 72 With the same cortical areas involved in both the allocation of spatial attention and the control of eye  
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56 73 movements (Moore & Fallah, 2001) and during fixation, the allocation of attention produces a  
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58 74 saccadic “suppression” in terms of amplitude and peak velocity (Gonzalez et al., 2017). These results  
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3 75 strongly support the idea that the allocation of attention leads to an activation of oculomotor circuits,  
4  
5 76 in spite of eye immobility (Sheliga et al., 1995). All these mechanisms could be included to the QE  
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7 77 definition, which indicates the suppression of large eye movements within 1–3° of visual angle, with  
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10 78 the improved capacity to fixate on relevant cues, and the ability to avoid irrelevant stimuli for a more  
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12 79 efficient extraction of information (Piras & Vickers, 2011). Moreover, it could also be important to  
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14 80 analyse the pupil diameter during the task, because larger pupil diameter reflects increased attentional  
15  
16 81 resource allocation (Moran et al., 2016). Pupil dilation could be the best predictor of the attentional  
17  
18 82 effort, as it reflects the current rate at which mental energy is used (Kahneman, 2011). In accordance  
19  
20 83 with this, a recent study (Alnæs et al., 2014) has revealed that pupil diameter foresees brain activity  
21  
22 84 in the locus coeruleus, that is the main centre of the brain's noradrenergic system, and it is assumed  
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24 85 to modulate the processes of the brain's attentional systems. Task-evoked pupil dilations are  
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26 86 extensively conveyed in the literature (Beatty, 1982; Karatekin, Couperus, & Marcus, 2004) and the  
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28 87 degree of the pupillary dilation appears to be also a function of the cognitive workload required to  
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31 88 perform the task (Porter, Troscianko, & Gilchrist, 2007).

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36 89 With the assumed relationship among microsaccades, visual perception, and direction of attention,  
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38 90 the current research investigated the role of small saccades, microsaccades and pupil-size when a  
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40 91 goalkeeper was tasked with predicting the direction of a soccer penalty kick. Our research specifically  
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42 92 analysed the time period immediately prior to and during QE period of the soccer penalty kick.  
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44 93 Previous research has demonstrated that during a soccer penalty kick, expert goalkeepers tended to  
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46 94 spend more time fixating on the opponent's kicking leg, non-kicking leg and ball regions, particularly  
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48 95 as the moment of foot-ball contact approached (Kim & Lee, 2006; Piras & Vickers, 2011;  
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50 96 Savelsbergh, Williams, Van der Kamp, & Ward, 2002). Piras and Vickers (2011) found that the QE  
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52 97 was located between the ball and the kicking action, area subsequently called "visual pivot", that was  
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54 98 fixated as the final kicking action occurred. Therefore, we can hypothesize from these elements that  
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56 99 athletes, just before final movement initiation, maintain a steady fixation on the visual pivot to predict  
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3 100 the outcome of a sporting action, shifting their attention, with microsaccades or small saccades,  
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5 101 toward the side where they think that the opponent could kick the ball. Accordingly, the accuracy of  
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8 102 prediction depends on the ability to shift visual attention from one location to another by identifying  
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10 103 the useful cue in the visual field, using both foveal and para-foveal vision.

## 13 104 **Methods**

### 16 105 **Participants**

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19 106 Eight (n = 8) intermediate-level male goalkeepers with a mean age of 23.5 (SD = 5.2) years and one  
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21 107 (n = 1) right footed male kicker of 28 years volunteered for the experiment. Based on the effect size  
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23 108 evident in Piras and Vickers' study (2011), G\*power, version 3.1.9.2 (Franz Faul,  
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25  
26 109 Christian-Albrechts-Universität Kiel, Kiel, Germany), predicted that a total sample size of 7 would  
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28 110 give sufficient power (0.80) to detect a significant difference at alpha level of 0.05. One additional  
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30 111 participant was included to ensure availability of data in case of missing or corrupt data. At the time  
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33 112 of the study, the goalkeepers had been playing soccer for 14.7 years, and trained on average 3.5 times,  
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35 113 7 hours per week, with a competitive match at the end of the week. All had normal vision, and after  
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37 114 receiving oral and written information concerning the study protocol, all participants gave their  
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40 115 written informed consent to participate in the study. The study was approved by the Bioethics  
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42 116 Committee of the University of Bologna.

### 45 117 **Stimuli and procedure**

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48 118 A right footed male kicker was filmed, from the participants' (goalkeepers') perspective, with a  
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50 119 digital video camera (Casio® 300 frames/s, with a max resolution 1280 × 960 pixels) positioned in  
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52 120 the middle of a standard, full sized (7.32 m wide and 2.44 m height) soccer goal, with the ball (size  
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55 121 5) positioned 11 m from the centre of the goal. The kicker was required to start his run-up at least 4  
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57 122 m behind the ball using the same approaching angle for all penalty kicks. Ten penalty kicks were  
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3 123 filmed and subsequently subdivided in five directed to the right and five to the left (goalkeepers'  
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5 124 perspective). These videos were used in the experiment.

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8 125 The experiments were performed in the dark. Stimuli were back-projected (Epson EB-W12, 720 ×  
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10 126 486 resolution; frame rate 60 Hz) onto the translucent screen positioned 300 cm away. The screen  
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13 127 covered  $135 \times 107^\circ$  of visual field and was placed 170 cm from the goalkeepers' eyes, who stood in  
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15 128 front of the screen ready to catch the ball as they were in the soccer pitch (Figure 1).

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18 129 \*\*\*\*\*Figure 1 near here\*\*\*\*\*  
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21 130 The video was presented from when the kicker started approaching the ball up to the ball passing to  
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23 131 the right or to the left of the goalkeepers' point of view. In soccer, goalkeeper movements typically  
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25 132 occurred through side-steps. Therefore, goalkeepers were instructed to predict the ball direction by  
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27 133 moving laterally (left or right) in an attempt to correctly predict the ball direction and catch the ball  
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29 134 as they would on a soccer pitch, but without diving. Goalkeepers were given a familiarisation period  
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31 135 with the experiment, where they were presented, randomly, with penalties (not the same videos of the  
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33 136 experiment) kicked to the right and to the left. In total, each participant faced 30 penalties. Penalties  
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35 137 were subdivided into three blocks, with the same ten videoclips in each block interspersed by 5  
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37 138 minutes of rest. Each clip had a mean duration of 6 seconds. The 10 penalties were presented in a  
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39 139 random sequence, and the randomization was kept in the same order for each participant. Overall, a  
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41 140 total number of 240 clips were analysed.

#### 42 141 **Eyes and body movement recording**

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45 142 Horizontal and vertical eye movements were recorded binocularly by a video-based eye tracking  
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47 143 system (EyeLink® II, SR Research) consisting of two miniature cameras mounted on a leather-  
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49 144 padded headband. Pupil tracking was performed at 500 samples/s, with a gaze resolution  $<0.005^\circ$  and  
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51 145 noise limited to  $<0.01^\circ$ .

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3 146 The eye tracker was calibrated at the beginning of the experiment and after every 10 videos. Then,  
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5 147 data validation and drift correction were performed by applying a corrective offset to the raw eye  
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8 148 position data after every clip. Calibration and validation of the system was repeated every time  
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10 149 possible measurement error occurred due to participants' movements. The accuracy of the eye  
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12 150 positions was checked after every trial, and if necessary, a drift correction was performed. Practice,  
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15 151 calibration, validation and data collection took about 30 minutes per participant.

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18 152 In order to collect right and left body movement, two inertial sensors (Cometa Systems, Italy) were  
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20 153 positioned on the goalkeepers' anterior superior iliac spine, one to the right and one to the left. Inertial  
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22 154 sensors were synchronised with the EyeLink system in order to have corresponding goalkeepers' eyes  
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25 155 and body movement data.

## 26 27 28 156 **Data analysis**

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31 157 The number of video frames used for analysis was initially selected. Due to the QE definition  
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33 158 (Vickers, 1996), which is the final fixation before the goalkeeper's final movement initiation, data  
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35 159 was analysed from 4000 ms prior to the instance where goalkeepers started their final movement;  
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37 160 analysis showed an average response time of 4677 ms in all clips.

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40 161 Analyses then considered response accuracy (correct or incorrectly predicted) and the final movement  
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43 162 time, that is the time in ms from the trial start to goalkeepers' final movement to predict the ball.  
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45 163 Goalkeepers were required to react between <150-400> ms after foot-ball contact, otherwise trials  
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47 164 were excluded from analysis, due to early or delayed movement necessary to catch the ball (Morya  
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50 165 et al., 2003).

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52 166 Both variables, response accuracy and movement time initiation, were analysed separately, in which  
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55 167 a repeated measures ANOVA were performed with trial blocks (1-3) and response accuracy (correct  
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57 168 or incorrect prediction) as the within-subjects factors.

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3 169 Fixation was defined when the gaze was stable inside  $1^\circ$  of visual angle for a minimum of 100 ms  
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5 170 (Piras & Vickers, 2011). Microsaccades were defined as eye movements smaller than  $1^\circ$  in amplitude,  
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7  
8 171 with a peak velocity smaller than  $100^\circ/\text{sec}$ , and that followed the same peak velocity versus amplitude  
9  
10 172 curve as large saccades (Zuber et al., 1968). Microsaccades and saccades were identified using the  
11  
12 173 algorithms of Otero-Millan et al. (2014). In the current study, microsaccades were only considered if  
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15 174 they occurred simultaneously in both eyes during at least 3 data samples (6 ms). Data was excluded  
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17 175 200 ms before and after each blink as well as when the pupil was still partially occluded (Otero-  
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19 176 Millan et al., 2008). Microsaccade and saccade amplitudes, durations, and peak velocities were first  
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21 177 calculated for each goalkeeper in each condition (left and right goalkeepers' direction, correct or  
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23 incorrect prediction) separately. Then, the values of all subjects in each condition were averaged.  
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26 179 Microsaccade rates were calculated considering the duration of each clip (4000 ms).  
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29 180 A 2 x 2 repeated measures ANOVA was performed separately to analyse microsaccade rate, and  
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31 181 microsaccade and saccade amplitude, duration, and peak velocity. Goalkeepers' movement direction  
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34 182 (right, left) and response accuracy (correct or incorrect prediction) were the within-subjects factors.  
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37 183 Two-dimensional distribution of all microsaccade and saccade orientation were calculated with  
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39 184 respect to goalkeepers' movement directions (right, left). The Watson-Williams test for homogeneity  
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41 185 of means (Oriana® 4.0) was performed in which the null hypothesis was that the orientations of  
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43  
44 186 microsaccades and saccades between goalkeepers' movement direction (left versus right) have similar  
45  
46 187 continuous distribution at the 5% level of significance. Furthermore, analysis considered response  
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48 188 accuracy (correct or incorrect prediction) as a dependent variable to reveal any relationships between  
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51 189 response accuracy and saccade and microsaccade orientation.  
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54 190 The raw data from the pupil diameters were normalised with z-scores procedure, by expressing every  
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56 191 sample as a standard deviation score from the mean calculated within each clip. This procedure  
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58 192 allowed data to be comparable across condition (Jainta et al., 2011). Left and right pupil size  
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60 193 diameters were correlated with the duration of the corresponding clip, from the trial start to

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3 194 goalkeepers' final movement to predict the ball. Then, each correlation was analysed with a  $3 \times 2$   
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5 195 repeated measures ANOVA where trial blocks (1-3) and response accuracy (correct or incorrect  
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7  
8 196 prediction) were the within-subjects factors.

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11 197 Effect sizes were calculated as the mean difference standardised by the between-subject standard  
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13 198 deviation and interpreted according to the following thresholds: trivial,  $<0.20$ ; small,  $\geq 0.20 < 0.50$ ;  
14  
15 199 moderate,  $\geq 0.50 < 0.80$ ; large,  $\geq 0.80$  (Cohen, 1988). Partial eta squared ( $\eta_p^2$ ) was used during multiple  
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17 200 comparisons. Statistical significance was set at  $p < 0.05$ . Post hoc test was corrected with Bonferroni  
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20 201 procedure.

## 21 22 23 202 **Results**

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26 203 After pre-processing data, in which responses shorter than 150 ms and longer than 400 ms (early or  
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28 204 delayed responses) were discarded (see Methods for description), 216 clips were retained for analysis  
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31 205 (of a total of 240; 24 clips were excluded).

### 32 33 206 ***Response accuracy and final movement time***

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36 207 Analysis of variance showed a significant main effect for response accuracy ( $F_{1,7} = 48.0$ ,  $p = 0.030$ ,  
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38  $\eta_p^2 = 0.51$ ), with more penalty kicks correctly (60%) than incorrectly predicted (40%) across all  
39 208 blocks. For final movement time analysis, ANOVA showed a significant main effect for response  
40  
41 209 accuracy ( $F_{1,7} = 9.77$ ,  $p = 0.017$ ,  $\eta_p^2 = 0.58$ ), in which goalkeepers showed a slower movement time  
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43 210 during correctly than incorrectly predicted penalty kicks (4721ms vs. 4634 ms), and it was exhibited  
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45 211 in all blocks.

### 46 47 48 212 49 50 51 213 ***Saccade and microsaccade characteristics***

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53  
54 214 Microsaccade and saccade rates have been calculated considering the total time in each trial (4000  
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56 215 ms). The temporal sequence of microsaccade rates was mostly constant for all time analysed,  
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58 216 lowering about 1000 ms just before goalkeepers' final movement started (Figure 2). Meanwhile,

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3 217 saccade rates increased, reaching the peak at about 500 ms just before the final movement initiated,  
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5 218 in concomitant with microsaccades reduction (Figure 2).

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8 219 \*\*\*\*\*Figure 2 near here\*\*\*\*\*

10  
11 220 There was significant difference in microsaccades duration between correctly vs. incorrectly  
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13 221 predicted penalty kicks, in which correct prediction showed longer microsaccades than incorrect  
14  
15 222 prediction (37.4 vs 33.3 ms;  $F_{1,204} = 4.94$ ,  $p = 0.027$ ,  $\eta_p^2 = 0.024$ ). No significant differences were  
16  
17 223 observed for amplitude (mean  $0.62 \pm 0.08$  and  $0.63 \pm 0.07^\circ$  of visual angle) and peak velocity (mean  
18  
19 224  $42.35 \pm 2.10$  and  $43.01 \pm 4.22$  °/second) between correctly and incorrectly predicted penalties.

22  
23 225 There was no significant difference between correctly and incorrectly predicted penalties for saccades  
24  
25 226 duration (mean  $114.91 \pm 15.79$  and  $106.72 \pm 10.72$  seconds), amplitude (mean  $3.50 \pm 0.29$  and  
26  
27 227  $3.67 \pm 0.46^\circ$  of visual angle) and peak velocity (mean  $112.68 \pm 3.69$  and  $121.59 \pm 8.07$  °/second).

### 30 31 228 *Saccade and microsaccade orientation*

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33  
34 229 Microsaccades orientation showed significant differences between right and left goalkeepers'  
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36 230 movement [t-test (7) = 2.62;  $p = 0.034$ ;  $d = 0.63$ ], and given that goalkeepers' gaze behaviour was  
37  
38 231 analysed before their final movement initiation (so the ball was still on the penalty spot), we can  
39  
40 232 suppose that microsaccades anticipate the goalkeepers' direction, showing a main vector directed to  
41  
42 233 the right when goalkeepers moved to the right, and conversely to the left when moving to the left  
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44 234 (Figure 3). Saccades orientation instead showed a main vector directed to the left for both left and  
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46 235 right goalkeepers' movement direction ( $p = 0.45$ ; Figure 3 lower panel).

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51 236 \*\*\*\*\*Figure 3 near here\*\*\*\*\*

### 52 53 54 237 *Pupil size changes*

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57 238 There was a significant positive correlation between pupil size and the progression of the action ( $r =$   
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59 239  $0.86$ ), meaning that, the pupil increases as the goalkeepers' perception of the penalty taker intention  
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3 240 develops (Figure 4). In fact, pupil size reaches the greatest value just before the goalkeepers started  
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5 241 their final movement, and was significantly higher for correctly than incorrectly predicted penalties  
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8 242 ( $F_{1,7} = 12.81, p = 0.009, \eta_p^2 = 0.65$ ).

9  
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11 243 \*\*\*\*\*Figure 4 near here\*\*\*\*\*

## 12 13 14 244 **Discussion**

15  
16 245 The purpose of this study was to deepen our knowledge about what happens before the critical  
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18 246 movement initiation and during the QE period, investigating the role of microsaccades, small  
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20 247 saccades, and pupil diameter during the approaching of the foot-ball contact. The analysis was  
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22 248 focused on the gaze behaviour of intermediate level soccer goalkeepers trying to predict penalty kicks  
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24 249 directed to the left and to the right of their goal. Given the relationships between microsaccades,  
25  
26 250 visual perception, and with the allocation of attention when the eyes are fixating, the current study  
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28 251 hypothesises that athletes, during the period that precedes the final movement initiation and during  
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30 252 QE, shift their attention with microsaccades or small saccades, identifying the useful cue with both  
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32 253 foveal and parafoveal vision.

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35 254 Correct prediction occurred in 60% of trials, with a slower movement time, with respect to 40% of  
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37 255 incorrectly predicted penalty kicks. Bar-Eli and Azar (2009) have documented that elite goalkeepers  
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39 256 who play at the international level stop a mean of 30% of penalty kicks, then, our results approached  
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41 257 this level.

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43 258 Analysis of microsaccade rates demonstrated a drop about 1000 ms just before goalkeepers' final  
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45 259 movement started. Meanwhile, saccade rates increased, reaching the peak at about 500 ms just before  
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47 260 the final movement initiated, concomitant with microsaccades reduction. Microsaccades can be  
48  
49 261 suppressed during fine visual tasks, suggesting they may be modulated by attention and appear  
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51 262 functionally related to saccadic intrusions, which are also influenced by the shift of attention (Gowen  
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53 263 et al., 2007; Piras, Raffi, et al., 2016). Microsaccade generation is modulated by stimulus presentation

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3 264 (Hafed & Clark, 2002; Piras, Raffi, Lanzoni, Persiani, & Squatrito, 2015), with a short inhibition after  
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5 265 stimulus appearance, followed with an increased rate of microsaccade occurrence, or as in this  
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8 266 situation, small saccade manifestation. In the current study the mean saccadic amplitude was about  
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10 267 3° of visual angle, microsaccadic amplitude was about 0.6° of visual angle. Some of the saccades  
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12 268 greater than 1° produced during prolonged fixation, and possibly during free-viewing, may be  
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14 269 involuntary and could be therefore categorized as microsaccades (Otero-Millan et al., 2008). As  
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17 270 highlighted by Gonzalez et al. (2017), in the definition of QE, the term fixation at 1-3° of visual angle,  
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19 271 could incorporate different types of eye movements, such as saccades, microsaccades, and smooth  
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21 272 pursuit, that may be used as a functional mechanism to predict an action, without fitting inside the  
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24 273 normal definitions of fixation. Moreover, a high frequency of microsaccades may facilitate larger  
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26 274 saccadic intrusions that may fall inside of the QE threshold. Moderate head motion requires the  
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28 275 involvement of oculomotor compensatory mechanisms, such as the vestibulo-ocular response,  
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31 276 optokinetic reflexes, smooth pursuit or saccades. This could suggest that other gaze behaviours may  
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33 277 be considered in the measured QE period, particularly at the larger 3° threshold (Gonzalez et al.,  
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35 278 2017). The eye tracker used in the current study, with high-resolution (under 0.1° of spatial resolution  
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38 279 and sampling at 500 Hz), was suitable to identify differences in oculomotor control, and the amount  
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40 280 and/or type (pursuit, saccades, microsaccades) of eye movements related to attention/inhibition  
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42 281 mechanisms (Gonzalez et al., 2017). In recent years there has been renewed interest in the role of  
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44 282 microsaccades and other small saccades during fixation, including their role in perceptual tasks and  
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47 283 their links to attention (Kowler, 2011). Recent works suggest that microsaccades may be suitable in  
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49 284 tasks where gaze is centrally located between different interest areas (Piras et al., 2015; Piras et al.,  
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51 285 2019), as for example inside of 3° of visual angle.  
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55 286 Significant differences were found in microsaccade orientations, in which microsaccades anticipate  
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57 287 the goalkeepers' direction, showing a main vector directed to the right when goalkeepers moved to  
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60 288 the right, and conversely to the left when moving to the left. These results suggest that microsaccades

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3 289 are not casual, rather they could indicate where our attention is unconsciously focusing (Figure 3,  
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6 290 upper panel). A clear polarization of microsaccade orientation means that a specific location has been  
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8 291 focused, most likely under the control of covert attention shift. However, saccades reached their peak  
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10 292 500 ms before the goalkeepers' final movement initiation, showing a mean direction to the lower left  
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12 293 of the goalkeepers' visual field, irrespective of subsequent movement direction. We can suppose that  
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14 294 this saccade orientation may be conditioned by the penalty taker's body movement, as he approached  
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17 295 the ball from the right to the left of the goalkeepers' point of view.  
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21 296 Particular attention should be directed toward pupil dilation, given that no research has investigated  
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23 297 its role during the prediction of a sport action. To our knowledge, the only two studies that have  
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25 298 analysed pupillometry during a sport action were that of Campbell et al (2019) where golfers showed  
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28 299 high and consistent pupil dilations during the putting tasks, and that of Moran et al. (Moran et al.,  
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30 300 2016) who found that pupillometry can be used to identify skill-based differences in attentional effort  
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32 301 during QE in equestrian performers viewing a video-based show-jumping sequence. In the current  
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34 302 study, we demonstrated that multisensory integration between stimulus-response influenced these  
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37 303 ocular movements. Larger pupil dilation and microsaccade inhibition, as well as saccade response,  
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39 304 were observed when a complex visual stimulus was projected to our participants and aligned in space  
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42 305 and time with their motor response. The pupil dilates prior to saccade initiation, and this increase in  
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44 306 pupil size could increase visual sensitivity to optimize perceptual processes immediately after  
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46 307 redirection of the eyes (Wang, Blohm, Huang, Boehnke, & Munoz, 2017). Pupil dilation,  
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48 308 microsaccades and saccades occurrence are additional components of orienting (Corneil & Munoz,  
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51 309 2014; Wang & Munoz, 2015), and both can be evoked and modulated following the appearance of  
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53 310 relevant stimuli (Wang & Munoz, 2014). Moreover, there is a connection between pupil dimension,  
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55 311 microsaccades and saccades. Wang et al. (2012) found the central role of the superior colliculus on  
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58 312 pupil dilation and microsaccade generation through recording on single neurons. Because the superior  
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60 313 colliculus is importantly involved in both multisensory integration and initiation of the orienting

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3 314 response (Boehnke & Munoz, 2008; Corneil & Munoz, 2014), our results implicate the superior  
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5 315 colliculus in coordinating such behaviour. In the current study, the presentation of a salient stimulus  
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8 316 has produced a series of coordinated eye movements, between saccades, microsaccades and pupil  
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10 317 dilatation, with the intention to orient the body towards the predictive timing task.

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14 318 Of note, despite not being reported in the results section, analysis of the final fixation confirmed  
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16 319 previous results (Kim & Lee, 2006; Piras & Vickers, 2011; Savelsbergh et al., 2002), showing that a  
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18 320 longer fixation duration was located on the visual pivot, a location between the ball and the kicking  
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21 321 action just before the final movement initiation. To avoid repetition, these results have not been  
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23 322 reported, and instead we focused on saccades and microsaccades produced before final movement  
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25 323 initiation. The potential role of visual pivot, and its contribution to goalkeepers making successful  
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28 324 saves in a soccer penalty kick, was identified and described in a number of studies (Piras, Lanzoni,  
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30 325 Raffi, Persiani, & Squatrito, 2016; Piras, Raffi, Lanzoni, Persiani, & Squatrito, 2015; Piras et al.,  
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32 326 2019; Piras, Lobiatti, & Squatrito, 2014; Piras & Vickers, 2011; Ripoll, Kerlirzin, Stein, & Reine,  
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34 327 1995; Williams & Elliott, 1999), and reviewed extensively by Vater et al., (2019). The effective use  
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37 328 of such “gaze pivot”, with the gaze centrally positioned between different areas, allows the use of  
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39 329 both foveal and parafoveal vision, shifting the attention (overt to covert) to acquire information from  
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41 330 interest areas in which informational content is high (Piras et al., 2019). Finally, the functionality of  
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44 331 the visual pivot would then be to maintain the gaze on a location close to relevant cues and initiate  
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46 332 (micro-) saccades to these cues (Vater et al., 2019).

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50 333 How visual information is presented, and the response required to this information (i.e., representative  
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52 334 design c.f. Araújo et al., 2007), can influence individuals’ visual search strategies. If eye movement  
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54 335 behaviours and required responses in an experimental setting differ from what participants would  
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57 336 experience in a real competitive environment, external validity is reduced, and generalisability of  
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59 337 findings are limited (Araújo et al., 2007; Dhami et al., 2004; Dicks et al., 2010). However, whilst  
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3 338 representative designs are theoretically desirable, the challenges of achieving truly representative  
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5 339 studies necessitate that hybrid designs may have to be used as an alternative (Dhmi et al., 2004;  
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8 340 Dicks et al., 2010). Hybrid designs may incorporate aspects of systematic design (e.g., increased  
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10 341 experimental control over conditions, control or removal of variables that are irrelevant, or that may  
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12 342 mask effects) (Dicks et al., 2010; Pluijms et al., 2013), whilst attempting to be as representative as  
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14 343 possible. In the current study, a hybrid design was used where goalkeepers were required to move in  
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17 344 response to a 'life-size' projection of a soccer penalty kick taker. This design was necessitated by the  
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19 345 requirements of the eye tracker (binocular with at least 250 Hz of sample/s) and to our knowledge, in  
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21 346 commerce there is no device with these characteristics that can be used in a more dynamic situation  
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24 347 (Dhmi et al., 2004; Pluijms et al., 2013).  
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28 348 Future research should be directed to analyse goalkeepers' gaze behaviour with respect to penalty  
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30 349 taker movement phases to have information about time course of microsaccade/saccade orientation  
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32 350 in relation to penalty taker's run up/kicking action (Piras et al., 2015). Moreover, could be interesting  
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34 351 to better understanding the subtle eye movements and underlying mechanisms immediately prior to  
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36 352 the critical movement initiation of athletes during aiming tasks (e.g., penalty taker in soccer; attacker  
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39 353 in volleyball) through the use of deceptive gaze behaviours to cover their intentions. A deceptive  
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41 354 strategy and a blind-pass strategy (also known as no-look pass) are performed when a player looks in  
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44 355 one direction but shoot or pass the ball to another direction. This is a typical sport action in which  
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46 356 gaze direction and attention are separated (Piras et al., 2019). Despite the extensive use of deceptive  
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48 357 gaze and no-look pass in sports, little empirical evidence exists to support the utility of such  
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51 358 behaviours (Wood et al., 2017). Therefore, future research could address more specifically the  
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53 359 microsaccade occurrence and features during these strategies.  
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56 360 In conclusion, the results of the present experiment suggest that microsaccades are important to  
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58 361 anticipate the goalkeepers' direction, modulated by visual attention and functionally related to  
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60 362 saccadic intrusions. These microsaccades could improve the perception of the game, helping athletes

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3 363 during the period that precedes the critical movement initiation, shifting from covert to overt  
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5 364 attention, necessary to identify the useful cue with both foveal and parafoveal vision.  
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8 365 **Disclosure statement**

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11 366 No potential conflict of interest was reported by the authors.  
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### 18 531 **Figure captions**

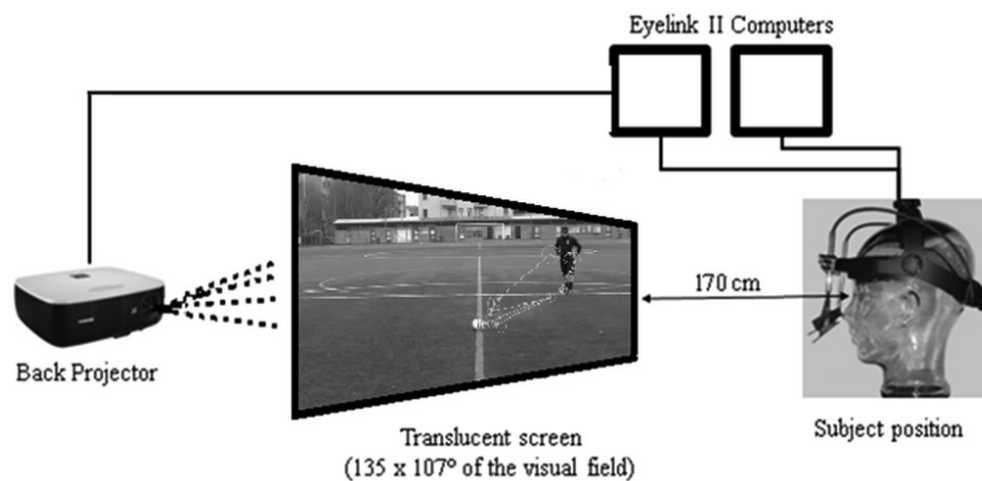
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21 532 **Figure 1.** Experimental setup showing subject wearing the eye tracker, standing in front of the  
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24 533 translucent wide screen, in which the videos were back projected.  
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27 534 **Figure 2.** Time course of microsaccades and saccades rate calculated from the final movement  
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30 535 initiation to backwards for 4000 ms. Rates were computed for each goalkeeper using a moving time  
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32 536 window of 200 ms and then averaged over all participants. Solid lines represent the mean rate of  
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34 537 microsaccades (upper plot) and saccades (lower plot), with the shaded area around each curve that  
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36 538 represents the standard error of the mean.  
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40 539 **Figure 3.** Panels represent the mean vector direction of microsaccade (upper) and saccades (lower)  
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43 540 across condition (left; right goalkeepers' movement). Each angular sector is 22.50° in width. Radial  
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45 541 thick lines are the mean vectors, curved lines external to the diagrams indicate the standard deviation,  
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47 542 with the 95% of confidence interval ( $p < 0.05$ ).  
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51 543 **Figure 4.** Plot show the increases of left (grey line) and right (black line) pupil size (z-score) of all  
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53 544 participants, correlated with the time of the trial, reaching a plateau at the goalkeepers' final  
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55 545 movement initiation.  
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23 Figure 1. Experimental setup showing subject wearing the eye tracker, standing in front of the translucent  
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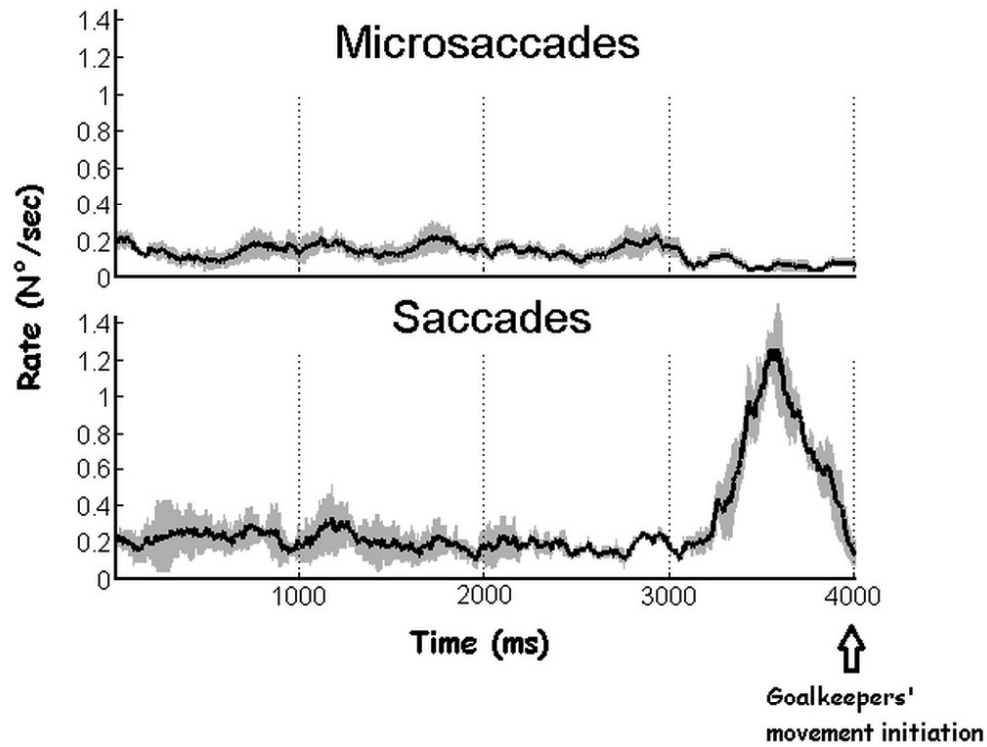


Figure 2. Time course of microsaccades and saccades rate calculated from the final movement initiation to backwards for 4000 milliseconds. Rates were computed for each goalkeeper using a moving time window of 200 ms and then averaged over all participants. Solid lines represent the mean rate of microsaccades (upper plot) and saccades (lower plot), with the shaded area around each curve that represents the standard error of the mean.

43x34mm (600 x 600 DPI)

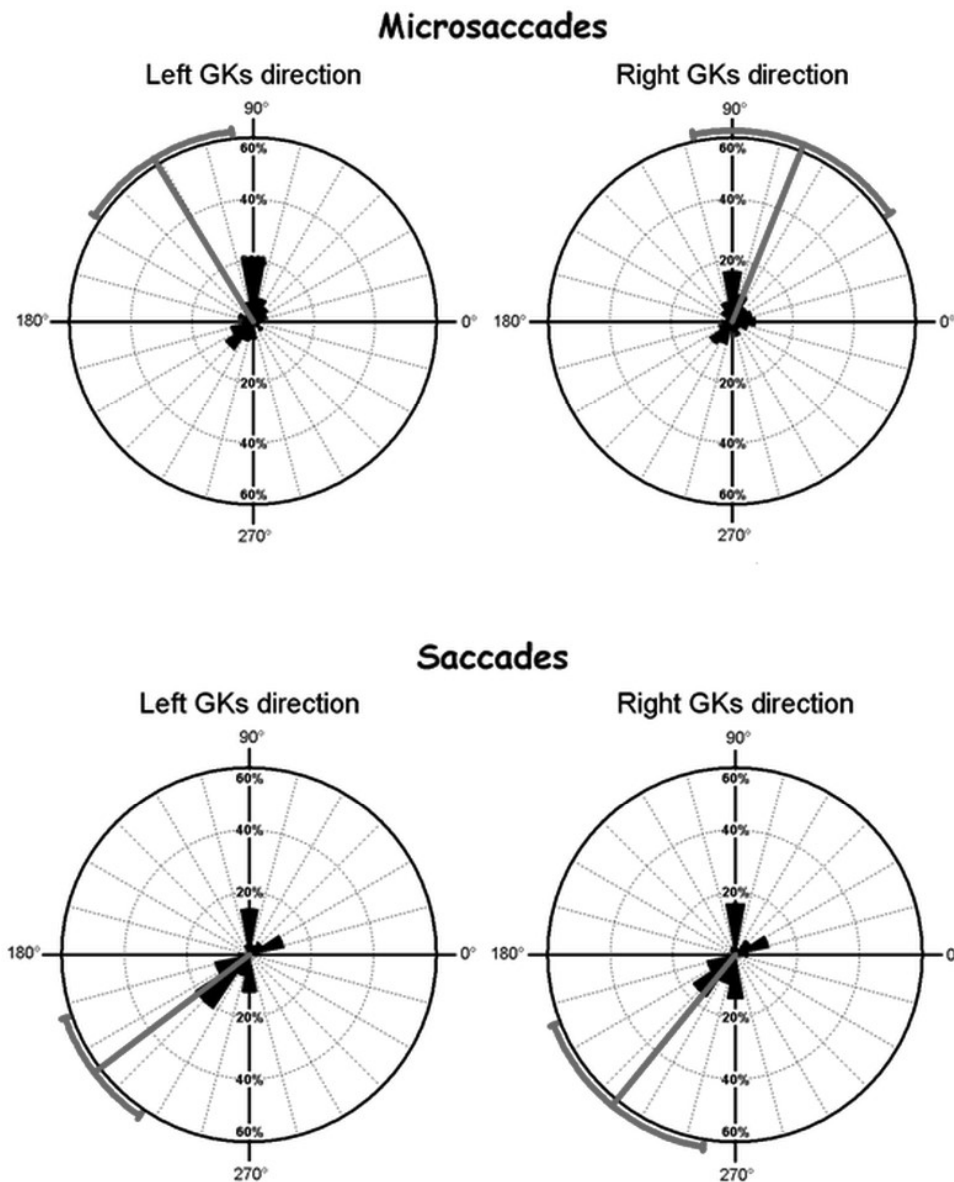


Figure 3. Panels represent the mean vector direction of microsaccade (upper) and saccades (lower) across condition (left; right goalkeepers' movement). Each angular sector is 22.50° in width. Radial thick lines are the mean vectors, curved lines external to the diagrams indicate the standard deviation, with the 95% of confidence interval ( $p < 0.05$ ).

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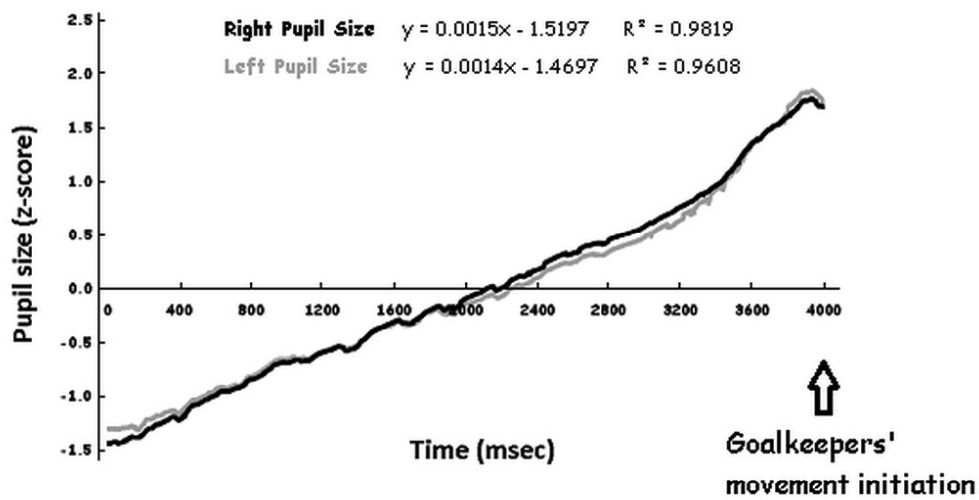


Figure 4. Plot show the increases of left (grey line) and right (black line) pupil size (z-score) of all participants, correlated with the time of the trial, reaching a plateau at the goalkeepers' final movement initiation.

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