THE ROLE OF EYE MOVEMENTS IN SPORTS AND ACTIVE LIVING

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THE ROLE OF EYE MOVEMENTS IN SPORTS AND ACTIVE LIVING

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EDITORIAL
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Editorial: The Role of Eye Movements in Sports and Active Living

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Editorial on the Research Topic

The Role of Eye Movements in Sports and Active Living

Eye movements are essential to collect accurate visual information from relevant scene locations, allowing optimal control of human movements in sports and active living. This Research Topic of the Frontiers in Sports and Active Living examines the role of the visual system in picking up the information necessary to guide action. It shows how essential gaze behavior is to timely collect accurate visual information from relevant scene locations and optimize control of human movements. Over the last four decades, substantial progress in research on eye movements and its application to sport and active living has been achieved through the use of more natural, ecologically valid research environments (in laboratory and *in situ* data collection situations), availability of newer technologies with higher measurement accuracy, increased experimental control, and novel approaches and analyses (Kowler, 2011; Discombe and Cotterill, 2015; Kredel et al., 2017; Moran et al., 2018).

Sport contexts are usually complex, often requiring fast actions, and eye movements are used to acquire adequate visual information. Particularly, gaze behavior of athletes reflects perception-based decision making and execution of motor responses involved in dynamic sports settings. Literature reveals strong evidence that skilled athletes show more efficient patterns of visual search than their less-skilled counterparts (e.g., Williams et al., 2005; Vickers, 2016). However, beyond describing relatively simple visual scanning paths during sports skills, many new theoretical questions relating to visual attention mechanisms, the relevance of visual information to action control and learning, gaze behavior training, as well as effects of new research methods have been investigated in the recent years. In short, researchers seem interested in answering not only *where* athletes and humans in general look, but *why* they do so when performing complex tasks (Kowler, 2011; Vater et al., 2020).

Articles in the present Research Topic highlight the growth of interest and the mentioned changes in this area. A rich combination of themes related to sport skills is presented by seven articles dedicated to perception and action characteristics of those skills. First, a perspective article by Klostermann et al. opens the debate on gaze behavior in sports. They analyzed the functionality of foveal and peripheral vision through three types of gaze behavior. The manuscript expands from the uniquely foveal tradition ("foveal spot"), which would optimize information acquisition from periphery ("gaze anchor" and "visual pivot") in a complementary rather than a mutually exclusive manner.

Following on from this conceptual discussion, six articles investigated the following sport modalities: soccer, baseball, kendo, darts, and volleyball. Two studies focused on effects of environmental stimuli on gaze dynamics and motor performance. Paterson et al. analyze whether a task-irrelevant contextual information (i.e., moving advertisement behind the goal area) would distract players while performing a soccer penalty kick. They confirm that kickers' attention was disrupted during their goalkeeper-dependent strategy, highlighting systematic, direction-specific effects of advertisement motion on aiming task. Kishita, Uedo, Kashino et al. examine effects of varying speeds of a task-relevant stimulus (the ball) on visuomotor strategies used in baseball batting; authors stress that eye-head coordination depends on ball speed, but regardless of it, predictive saccade and quick head movement were temporally linked to bat-ball contact and hip motion. Next, two studies explore different gaze strategies. In another article, Kishita, Uedo, Kashino et al. focused on eye and head coordination patterns used by elite baseball players during batting in-game situations. They highlight that top batters delay initial saccades to obtain slightly more time acquiring visual information, as well as they may use head (instead of eyes) direction to encode bat-ball impact location. Kato explores how expert kendo fighters use a particular gaze strategy (referred above as "visual pivot") during *in situ* sparring practice in offensive, defensive, and real match situations. He emphasizes that kendo experts keep gaze calmly stable on opponents' face but use peripheral vision strategy to obtain information from their body movements. Finally, two sport articles refer to distinct aspects involved in visual anticipation and gaze training. First, Lüders et al. examine effects of knowledge of an opponent's action preference on anticipation performance and gaze behavior during defense of volleyball attacks. They highlight influence of contextual information on anticipation, while systematic changes in the number of fixations and the duration of final fixation unobserved in defenders when they had preference information. Second, Neugebauer et al. examine characteristics of focus of attention during a quiet duration training for darts throwing. Even with similar throwing accuracy, authors show that visually instructed groups increased quiet eye duration whereas the kinesthetic group decreased it, suggesting perceptual and motor learning processes are dyssynchronous.

This Research Topic concludes with three articles bringing interesting applications of eye movements research to the context of public health and active living. Properly timed gaze behavior is critical to control the movements during active living; eye movements support adaptive motor control. First, a review article by Stuart et al. covers measurements of eye-movements in patients with mild traumatic brain injury, showing that there are no diagnostic criteria available for this injury. Next, Vargas et al. analyze body sway of sleep-deprived participants, highlighting that saccadic eye movements improve postural control even in sleep-deprived situation but are insufficient to avoid its deterioration due to sleep deprivation.

Finally, a brief report article by Baker et al. examine how individuals with Parkinson's disease perform walking turns with visual cues to promote anticipatory eye movements and, possibly, reduce the risk of falls. They emphasize that visual cue training is capable of changing from no anticipatory eye or segment movement to a pattern similar to that of neurotypical young adults, with craniocaudal rotation sequences during walking turns.

The multiplicity of contents presented in this Research Topic is illustrative of the growing interest in gaze behavior in sports and related activities and should stimulate new and innovative studies. As eye-tracking technologies and other motion measuring systems improve and become more popular in this field, many inspiring ideas and challenges are available for those interested in investigating the role of eye movements in sport and active living.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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PERSPECTIVE
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Perception and Action in Sports. On the Functionality of Foveal and Peripheral Vision

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An optimal coupling between perception and action is crucial for successful performance in sports. In basketball, for example, a stable fixation onto the basket helps to gain precise visual information of the target to successfully throw a basketball into the basket. In basketball-defense situations, however, opposing players cutting to the basket can be detected by using peripheral vision as less precise information are sufficient to mark this player. Those examples elucidate that to solve a given task foveal and peripheral vision can be used to acquire the necessary information. Following this reasoning, the current state of our framework will be presented that allows one to predict the functionality of one or the other or both depending on the current situation and task demands. In more detail, for tasks that require high motor precision like in far-aiming tasks, empirical evidence suggests that stable foveal fixations facilitate inhibitory processes of alternative action parameterization over movement planning and control. However, more complex situations (i.e., with more than one relevant information source), require peripheral vision to process relevant information by positioning gaze at a functional location which might actually be in free space between the relevant information sources. Based on these elaborations, we will discuss complementarities, the role of visual attention as well as practical implications.

Keywords: gaze behavior, expert performance, gaze anchor, visual pivot, foveal spot, quiet eye

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In sports, athletes have to solve various tasks that require different solutions. To make this clear, imagine, you would be standing on a basketball court at the free-throw line with the task to *shoot* the ball into the basket. After two shot attempts, however, it is likely that you must immediately return to your own basket to *defend* the opponents' offensive actions. Obviously, the first and second task demand different motor actions. But, do they also require different gaze behaviors? Ask yourself: When solving these two tasks, where would you look and attend at? In the shooting task, you might look at the basket, the rim, or maybe at your hands while performing the shooting action. And in the defensive situation, you could focus the ball carrier, one of your teammates or maybe the opponent you are responsible for. Are these behaviors substantially different and what might be underlying functions? Exactly these questions which touch upon eye-movement associated behavioral costs have been addressed by our research group (for on overview on the current state of the art, e.g., Williams and Jackson, 2019). In this Perspective Paper, we will summarize current (own) research, underlying mechanisms and theoretical frameworks of cost-reducing eye movements. Different to earlier publications (e.g., Vater et al., 2019b), a recently developed framework proposing the functionality of foveal *and* peripheral vision in sports will be presented which states the complementarity of these two behavior. Beforehand, a glimpse of the physiological basis of the human eye and gaze behavior will be provided.

STRUCTURE AND MOVEMENTS OF THE HUMAN EYE

Because of the retinal structure (i.e., distribution of photoreceptor cells), visual information can be received via foveal and peripheral vision. Foveal vision refers to the small area-rule of thumb: size of your thumbnail hold at sleeve length-at which visual information can be gathered with very high visual acuity. However, since the number of cones decreases with increasing eccentricity-i.e., the angular distance from the fovea-all visual information outside of this foveal area (up to 5° of visual angle) are being perceived as increasingly blurred (up to 90% at 40° eccentricity). Despite this low visual acuity in peripheral vision, the high amount of rod cells on this retinal area leads to a high motion sensitivity (Strasburger et al., 2011).

In order to process information with high visual acuity, humans use body-, head-, and eye-movements to reposition the fovea at specific regions of interest. The latter is further divided into saccades, smooth-pursuit eye movements, vergence, and vestibular eye movements. Humans mostly apply saccades which are rapid eye movements with velocities as high as 500° per s (Rayner, 1998). During saccades sensitivity to visual information is reduced, a phenomenon which is also known as saccadic suppression (Binda and Morrone, 2018). In contrast, during smooth-pursuit eye movements visual-information sensitivity is comparable to fixations-i.e., the period of time the eyes are relatively still-but they only occur when the eyes are following an object (Spering et al., 2011). Thus, the repositioning of the fovea is quite costly because of the information loss. To avoid these costs, it makes sense to assume, that, particularly in sports, which requires to act in a complex environment with severe timing and precision demands, eye movements become attuned to the tasks to be solved (a current overview on perceptual-cognitive skills in sports can be found, e.g., in Brams et al., 2019). We will now elaborate this line of thought by addressing the functionality of an optimal timing of eye movements as well the use of peripheral vision.

THE USE OF FOVEAL VISION

When reviewing the literature about the optimal timing of saccades (e.g., dynamic saccade analyses) only little is known. For example, in their extensive meta-analysis, Gegenfurtner et al. (2011) reported <10 studies, which analyzed saccades. It was found that experts initiate their saccades later (i.e., they have shorter durations to fixate task-relevant areas) and show longer saccadic amplitudes. However, the actual timing of eye movements, e.g., in relation to motor actions, particularly is reflected in the gaze phenomenon called Quiet Eye (QE), which is defined as the final fixation of a task-relevant object in space *before* movement initiation (Vickers, 2007). High-skilled athletes have been found to deploy longer QE durations than low-skilled athletes (e.g., Vickers, 1996) and successful attempts have been associated with longer QE durations than unsuccessful attempts (e.g., Klostermann et al., 2013). Usually, these differences in QE duration result from earlier QE onsets (for an overview, Vickers, 2007).

The QE has been assumed to optimize cognitive processes like information processing (e.g., Williams et al., 2002), movement parameterization (e.g., Vickers, 1996), and attentional control (e.g., Vine et al., 2014) (for an overview on potential mechanism, Gonzalez et al., 2015). Recently, Klostermann et al. (2014) proposed an advancement of the existing models to account for the improbable fundamental assumption of increased cognitive demands in highly skilled athletes (see also "efficiency paradox," Mann et al., 2016). Drawing on an inhibition mechanism as introduced by Neumann (1996) and Cisek and Kalaska (2010), it is suggested that the QE subserves a shielding mechanism that promotes the parameterization of the optimal task solution. Recent work has been supporting this mechanism, as for example in a study that revealed relations between QE duration and response-selection demands in a far-aiming task. The higher the number of optional targets the earlier the QE onset and the longer the QE duration (Klostermann, 2019).

Regarding high motor performance, the empirical evidence emphasizes the functionality of an optimized coupling between perception and action which allows to perceive sufficient visual information for inhibition processes in subsequent actions. However, gaze behavior in high-skilled athletes further suggests that not only visual information from the fovea (as for example the QE phenomenon) is of relevance. But, visual information from the periphery seems crucial as, for example, shown by Hausegger et al. (2019) for defensive behavior in martial arts.

THE USE OF PERIPHERAL VISION

Experimentally, we investigated possible functionalities of peripheral vision by making use of a multiple-object-tracking (MOT) task (Pylyshyn and Storm, 1988). In a series of studies (Vater et al., 2016, 2017a), an experimental paradigm was introduced, which allowed us to study peripheral-perception performance in dual task situations (i.e., a primary monitoring task and a secondary detection task). In detail, participants are required to track four targets among six distractors, which all move on linear paths in a virtual box that spans an area of 40° × 40° of visual angle. Crucially, participants track those four targets by means of a virtual centroid and detect target changes with peripheral vision (Vater et al., 2016, 2017a). The advantage of this paradigm is that it can be applied to sport-specific settings (e.g., the monitoring of multiple players) without constraining the natural gaze behavior (for the technological implementation, e.g., Kredel et al., 2015; Vater et al., 2017b).

Our findings showed that when required to track information from multiple locations, peripheral vision outperforms saccades, in particular, when simultaneously solving further tasks like motion-change detection (Vater et al., 2017a). However, peripheral-perception performance is limited by crowding, i.e., the close proximity between objects at (far) eccentricities, which requires increased spatial acuity and evokes re-positioning of

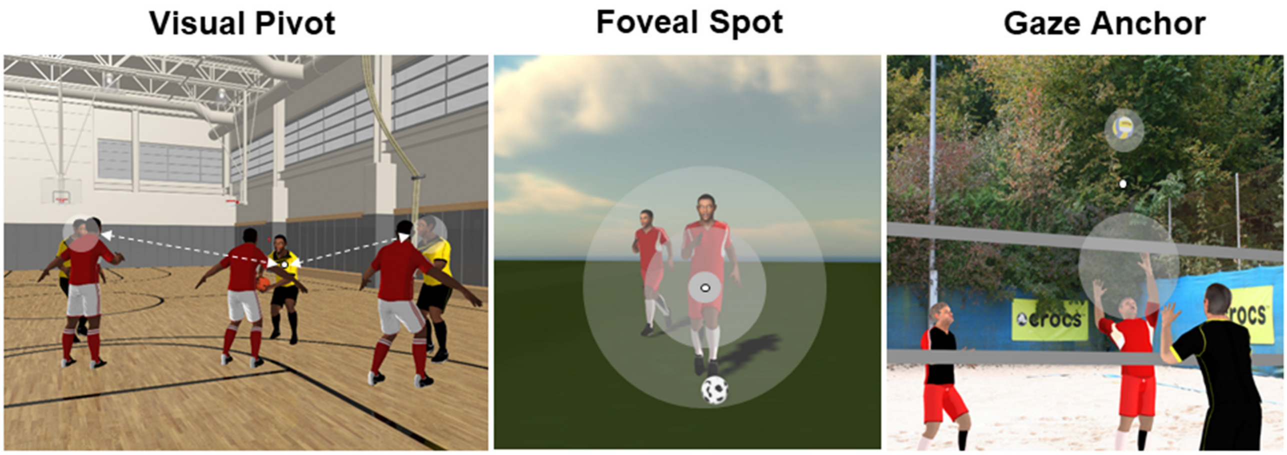

FIGURE 1 | Three types of gaze behavior for the use of foveal and peripheral vision in sports (modified from Vater et al., 2019b). It should be noted that the small white spot illustrates the current gaze point and the grayish circled areas indicate potential attention locations as a function of respective relevant cues. Finally, in case of a foveal spot the breadth of attention can be modified as a function of the task demands.

the gaze and a shift of the virtual centroid in the respective direction. Moreover, in case of (unpredicted) event changes (like a collision between objects), saccades need to be initiated to visually confirm the anticipation of the outcome of this event (e.g., Vater et al., 2017c).

Consequently, the empirical evidence points at the functional role of peripheral vision in sports requiring the monitoring and detection of peripheral events, particularly in time-demanding and complex situations often found in combat and team sports. However, due to biological constraints-both foveal (eccentricity) and peripheral (acuity)-and task constraints optimized gaze behavior seems necessary to make use of foveal and peripheral vision in sports.

OPTIMAL GAZE BEHAVIOR IN SPORTS

The hypothesis of an optimized gaze behavior was addressed by Vater et al. (2019b) who reviewed the use of peripheral vision in sports (for general eye-tracking applications in sports, e.g., Kredel et al., 2017). Based on the findings from 29 studies covering different types of sports and tasks, levels of expertise and methods applied, they suggested three different, task-dependent functionalities of peripheral vision as indicated by different gaze behaviors.

If the task requires and the situation allows one to focus on one specific aspect-as for example the basketball free throw with high precision and low time demands-gaze is stabilized on one specific cue-like the rim of the basket-to get accurate visual information. If, however, the task still requires to process visual information with high spatial acuity but more than one cue prevails crucial information-like in 2 vs. 1 soccer situation when focusing the ball carrier-the attentional width can be increased if needed. This gaze behavior was labeled *foveal spot* (**Figure 1**, middle).

In a number of studies (e.g., Vansteenkiste et al., 2014), it was found that athletes locate their gaze in free space. For example, in beach-volleyball defense (Hossner et al., manuscript in preparation) instead of tracking the opponent and/or the ball, athletes locate their gaze at a position where the ball will be hit. It was assumed, that in these situations high spatial acuity is not required (otherwise gaze would be positioned to make use of foveal vision) and athletes use a *gaze anchor* (**Figure 1**, right) which allows one to monitor the movement of objects with peripheral vision (see also Vater et al., 2016). In contrast to the foveal spot, covert attention can be distributed to multiple objects. This, however, requires an optimal positioning of the gaze as it was shown by Hausegger et al. (2019) who found that the height of the gaze anchor on the opponent's body axis varies as a function of the attacking style in martial arts. Specifically, if attacks could be performed with arms and legs (Qwan Ki Do), athletes positioned the gaze anchor higher at the opponent's body compared to situations where mainly the legs are used to attack (Tae Kwan Do).

Finally, a *visual pivot* is used in situations that demand the processing of accurate visual information from a number of spatially distributed cues that cannot be covered by (para-)foveal vision (alone) and requires to reposition the fovea (**Figure 1**, left). As for the gaze anchor, it is hypothesized that the visual pivot is optimally located in-between the relevant information sources to allow for frequent fixation transitions by minimal saccadic costs. The visual pivot can be located in free space but also on information-rich cues, like the opponent's hip in soccer-defense situations (e.g., Vater et al., 2019a).

As emphasized by Vater et al. (2019b), crucially, one given situation does not evoke one of these gaze behavior only. As the situation evolves, different gaze behavior might interact, as for example in a basketball-offense situation in which the ball carrier, first might *anchor* his *gaze* centrally between his teammates to evaluate who might receive a pass. In the next moment, however, he might decide to shoot and to *foveally spot* the rim of the basket. Though, whether, indeed, the gaze positioned at the rim of the basket is used as foveal spot or as *pivot point* to still fixate the teammate which runs into an optimal playing position is difficult to determine by gaze data alone, because the gaze location might not indicate information processing.

COMPLEMENTARITY AND FUTURE RESEARCH

As emphasized above, due to the complex interactions as they occur in sports with highly dynamic situational conditions and (motor) tasks with different demands, foveal and peripheral vision are necessary to be successful. Consequently, the mechanisms introduced are not mutually exclusive but, rather, complementary. We suggest that constraints inherent in the task require to balance an optimal positioning of the gaze with an optimally early onset of this fixation before movement initiation. The former depends on potential costs that occur when repositioning the fovea using a saccade (i.e., duration of information suppression) or when finding an optimal distance between adjacent objects to be monitored (i.e., perceptual impairment due to peripheral crowding) (see also **Figure 1**). The latter is necessary to facilitate (movement) parameterization via inhibition processes, thus, is highly dependent on the demands associated with the task. Consequently, an optimal gaze-anchoring location might not only be useful for processing peripheral information (i.e., perception) but also for the usage of this information for the following parameterization (i.e., motor control). Moreover, the positioning and the relative onset of this gaze-anchoring should be highly dependent on the associated cost-benefit equation. To the best of our knowledge, this hypothesis has not been addressed yet and will be pursued in future research projects in our laboratory.

Directly related to these questions, fundamental questions on the role of vision and attention in complex movement behavior should be made clear. As explained earlier, visual capabilities largely influence our gaze behavior and the use of foveal and peripheral vision. The interaction with attentional capabilities, however, and particularly research *directly* combining attention and vision measures in sport has been addressed only rudimentarily. Piras et al. (2017) suggested to study microsaccades as they might signal the direction of covert attention, thus, disentangling the current location of gaze from the location of attention (i.e., the microsaccade direction). But, this approach challenges eye-tracking technology, particularly when investigating complex movement behavior. Therefore, experimental approaches should be favored as proposed by Vater et al. (2019b) who suggested the systematic manipulation of peripheral information together with the prediction of gaze location. For example, based on previous research, it can be predicted that the ball carrier in soccer is the most likely gaze location. If one is able to react to a peripheral player's action without looking away from the ball carrier, this could be seen as an indicator of peripheral vision usage.

Finally, sport scientists should aim to transfer the obtained knowledge back into sports practice to improve the athletes' skills. The so-called perceptual training draws on the expert-performance approach (e.g., Ericsson and Smith, 1991) which requires to extract expert-like behavior, to empirically test its functionality, and to develop respective training programs which train these skills in less-skilled athletes (e.g., Vickers, 2007). Although a fair number of studies examined the effectiveness of these training programs, more often than not, research failed to show significant transfer effects (for an overview, e.g., Broadbent et al., 2019). In addition to issues with ecological validity (e.g., Hadlow et al., 2018), the training method is still debated. For example, research suggests that so-called gaze training by means of attentional cueing does not foster the learning of anticipation skills in beach-volleyball when compared to active control groups (e.g., Klostermann et al., 2015). Therefore, in the next years, increased efforts should be devoted to the theory-practice transfer answering questions like the trainability of expert-like gaze behavior in sports.

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Moving Advertisements Systematically Affect Gaze Behavior and Performance in the Soccer Penalty Kick

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The aim of the current study was to investigate whether a moving advertisement positioned behind the goal area would influence the visual attention of participants performing a soccer penalty kick, and, whether this would an effect on subsequent motor performance. It was hypothesized that if the (moving) advertisement would function as a distractor, then this would result in non-specific disruptions in penalty performance measures, especially affecting aiming location and precision. Alternatively, it was reasoned that, in line with the Dunker illusion, the moving advertisement would systematically affect perception of target location, resulting in changes in penalty performance and aiming that are specific for the direction of motion of the advertisement. To test these hypotheses, we investigated the gaze behavior and kicking performance of intermediate skilled soccer players taking penalty kicks in three differing advertisement conditions, namely no advertisement, a stationary advertisement, and a moving advertisement. The latter condition consisted of an advertisement moving from left to right and an advertisement moving from right to left. Results showed that a moving advertisement placed behind the goal area indeed caught the visual attention of soccer penalty kickers using a goalkeeper-dependent kicking strategy. Participants kicking performance tended to be less variable within the no advertisement condition compared to the moving advertisement condition. In addition, systematic, direction-specific effects on aiming were found when comparing conditions in which the advertisement moved in opposite directions. This pattern of findings indicate that the accuracy of the penalty kick is impacted by task-irrelevant contextual information.

Keywords: penalty kick, far aiming, visual search, visual attention, duncker illusion

INTRODUCTION

In soccer, penalty kicks are decisive events that can decide the outcome of a match. The average number of goals scored by both teams is typically low during regulation time in soccer matches (i.e., 2.5; Bar-Eli et al., 2007), and as a consequence, the scoring opportunity that is provided by a penalty kick can decide the outcome of a match. In addition, during a decisive penalty shoot-out, the importance to the outcome of the match is even more obvious.

In the penalty kick, the ball is placed 11 m from the goal area, which measures 24 ft (7.32 m) wide by 8 ft (2.44 m) high, giving the kicker a target area of 18 m^2 to aim at. Further to this, a kick is struck with a typical speed of 22–27 m/s, with the ball reaching the goal line in approximately 600 ms (Wood et al., 2015; van der Kamp et al., 2018). Due to constraints on the time that the goalkeeper requires to cover the entire goal area, the overwhelming advantage is in favor of the kicker (Wood and Wilson, 2010; Noël and Van der Kamp, 2012). It is therefore surprising that a large percentage of penalty kicks are not converted, with ∼20–25% of the shots being missed or saved (Mcgarry and Franks, 2000; Jordet et al., 2007).

With this in mind, researchers have shown a significant interest in uncovering factors that effect accuracy and success in the penalty kick. Specifically, recent advances in mobile gaze registration systems have led to an increase in empirical studies that have attempted to explore gaze behavior and visual attention within the performance of the penalty kick (e.g., Wilson et al., 2009; Wood and Wilson, 2010, 2011; Piras and Vickers, 2011; Van der Kamp, 2011; Noël and Van der Kamp, 2012). Evidently, and similar to other far aiming tasks (e.g., Helsen et al., 2000; Rodrigues et al., 2002; Vickers and Williams, 2007; Land, 2009), these studies have demonstrated a functional coupling of gaze behavior and kicking, with the information made available from gaze fixations being pertinent in decision making, as well as maintaining effective performance (Behan and Wilson, 2008). That is, within the soccer penalty situation, the kicker has to deal with both a proximal and a distal target, i.e., the foot has to hit the ball (proximal target) as accurately as possible with an sufficient amount of force, and secondly, the kick has to accelerate the ball toward a target location within the goal that is outside of the goalkeeper's reach (distal target).

The kicker generally adopts one of two penalty kick strategies, which include to either attempt to anticipate the direction of the goalkeeper dive during the run-up to the ball and kick to the opposite side of the goal at the last moment (i.e., the keeper-dependent strategy); or, to use a more controlled approach and decide the direction of the kick without taking the goalkeeper's actions into account during the run-up phase of the kick (i.e., keeper-independent strategy) (Van der Kamp, 2006, see also Kuhn, 1988). The two penalty kick strategies have been shown to invoke distinct patterns of gaze, which are directly associated with the success of penalty kicks. For example, Noël and Van der Kamp (2012) showed that the distinct pattern of gaze in the case of the keeper independent strategy allowed for more optimal control of the kicking movements as compared to the gaze pattern elicited by the keeper dependent strategy. Gaze behavior within the goalkeeper independent strategy was associated with prolonged focus on the inside areas of the goal (distal target), shorter times fixating the goalkeeper, and longer fixation times toward the ball (proximal target), all of which resulted in kicks that were less centralized and gave the goalkeeper less opportunity to save the ball (Noël and Van der Kamp, 2012; see also Wilson et al., 2009; Van der Kamp, 2011; Wood et al., 2015; Kurz et al., 2018).

In the competitive environment, there are a number of distractors that can potentially influence typical gaze patterns of kickers. Such shifting in attention to task irrelevant cues has the potential to disrupt motor performance (Beilock and Carr, 2001; Wood and Wilson, 2010; Morris, 2012; Lidor et al., 2013). One of the more modern potential distractions to visual attention in soccer stadiums includes billboards that are used to advertise during competitive matches. These boards can typically be seen on the entire perimeter of the field, including being placed directly behind the goal area. These modern LED (light emitting diode) display boards allow for multiple advertisements to be scrolled across their screens for the duration of a match. Advertisements appear and re-appear in differing formats and typically also include images that move from left to right, or right to left in direction. It is clear that a moving advertisement behind the goal has the potential to catch visual attention during a penalty task and thus to disrupt the typical gaze patterns of the kicker, with potential performance implications.

These performance implications can be two-fold. First, the attentional shift could have a non-specific effect on performance, in which the mere presence of the advertisement and/or the motion of the advertisement would result in a generic disruption of kicking performance measures including increased inaccuracy and/or precision in aiming. In other words, the (moving) advertisement may function as a distractor (e.g., Beilock and Carr, 2001). On the other hand, the attentional shift could have a specific effect on performance, that is, influencing kicking accuracy in a systematic manner depending on the direction of the moving advertisement. This would be analogous to the Duncker illusion (Duncker, 1929). Duncker (1929) demonstrated that background motion can induce an illusory perception of motion of a stationary foreground object. This illusory perceived motion of the object is in the direction opposite to that of the background motion (Zivotofsky, 2004). Most critically, it has been shown that such background motion can have similar effects on action, particularly within aiming tasks. Brouwer et al. (2003; see also Soechting et al., 2001) reported that background motion from left to right and right to left resulted in systematic aiming errors to the left and right of the target, respectively. This is in line with later findings that far aiming tasks are impacted by allocentric or contextual information (Van der Kamp and Masters, 2008; Van der Kamp et al., 2009; Shim et al., 2014).

The present study examines the effects of a stationary and moving advertisement behind the goal area on penalty kick performance. To this end, we investigated the gaze behavior and kicking performance of intermediate skilled soccer players taking penalty kicks in three differing advertisement conditions, namely no advertisement, a stationary advertisement, and a moving advertisement. The later condition consisted of an advertisement moving from left to right and an advertisement moving from right to left. Participants were enticed to use a keeper-dependent strategy and give themselves the best opportunity to score a goal by taking the goalkeepers dive into consideration when deciding in which direction to kick the ball[1]. We were interested to see whether the moving advertisement did in fact catch the kicker's attention and affect gaze behavior, and if so, whether this would

[1]The choice to encourage the participants to use of a keeper-dependent strategy was to ensure that during every penalty kick, participants would maximize (visual) attention toward the goalkeeper and goal while running up to and kicking the ball. That is, with a keeper-independent strategy, kickers typically focus earlier and longer exclusively to the ball (and perhaps even more so within the repetitive circumstance of an experiment).

disrupt subsequent penalty kick performance. We hypothesized that if the advertisement would serve as a distractor, then the disruption, if any, would be non-specific that is, it would result in an overall decrease in kicking performance measures (e.g., aiming location and/or precision). Alternatively, if the moving background would have specific effects, then systematic changes in kicking performance measures (e.g., aiming location) would be dependent on the direction of motion of the advertisement.

MATERIALS AND METHODS

Participants

Sixteen intermediately skilled soccer players volunteered to participate in the study (mean age = 26.3, SD = 2.8 years, one female). Fifteen of the participants were right-footed with one of the participants being left-footed. All 16 players played in the national amateur leagues of the Royal Dutch Football Association (KNVB). The experiment was approved by the local ethics committee and all participants signed a written informed consent form before the start of the experiment.

Material and Equipment

Eight different video clips were created showing a goalkeeper diving either to the left or right side, under three differing advertisement conditions. These video clips were recorded using a digital video camera (Kodak Playfull ZE2) from the perspective of a penalty kick taker. The advertising was projected onto a white wall ("goal area") using a projector (Dell 1510X) with the goalkeeper standing in the middle of the goal area. The goalkeeper was instructed by the researcher to dive the left or the right side of the goal, under the following advertisement conditions: No advertising present/control (C), stationary advertisement (S), and moving advertisement (M), which (continuously) moved from either the left to the right (MLR), or from right to the left (MRL). The advertisement was a digital picture of 0.9 m in height, and 2.44 m in length made out of salient colors i.e., yellow and orange. The bottom of the advertisement was placed approximately 0.9 m from the ground when projected onto the screen (see **Figure 1**). This resulted in a total of eight clips, each 3.2 s in length. Windows Media Player editing software was used in order to synchronize the time between the start of the clip and goalkeeper movement across all eight clips. Accordingly, the clips showed the goalkeeper starting his movement at 1.8 s after the start of the clip. This allowed us to coordinate the goalkeeper movement to the participants' run-up phase (**Figure 1**).

The experiment took place in an indoor sporting facility. The penalties were performed in accordance with official FIFA law, using a standard sized goal area (7.32 × 2.44 m), with the distance to the goal being 11 m from the penalty spot. A "FIFA-Approved" size 5 football with standard inflation was used. A white PVC canvas was attached to the goal (post and crossbar) (see **Figure 2**).

The video clips were projected onto the PVC canvas using a projector (Dell 1510X) that was located 40 cm to the side of the penalty mark. A digital video camera (Kodak Playfull ZE2) was positioned 1 m behind and 1 m to the side of the penalty mark in order to record the goal area. An Opto-switch (E3S-R 30E4 Omron) and light beam, positioned at knee height, were positioned 2.2 m behind the penalty mark. When participants walked through the switch, the beam was interrupted, and the clips were initiated (see **Figure 2**) and after 1.8 s, the goalkeeper initiated the dive. Based on pilot work, this was timed just before or at the moment of the participants' support foot landing next to the ball, but with trial-to-trial variability, depending on the participants' current run-up speed. A white background was projected onto the wall between the penalty kick trials.

Gaze behaviors were recorded using an Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye-Tracker. The device measures eye-line of gaze at 25 Hz with respect to eye and scene cameras that are mounted on a pair of glasses, worn by the participant. The system records onto a modified DVCR, which was worn in a pouch around the waist of the participant. The DVCR is plugged into a laptop (Dell Inspiron 6400) with Eyevision recording software installed. A circular cursor, representing 1° of visual angle indicates the location of gaze on a video image of the scene (i.e., the system has an accuracy of ± 1° of visual angle and a precision of ±0.5°) was then recorded for offline analysis. The system was calibrated before each participant began the experiment by having participants look at nine specific target areas located on the PVC canvas representing the goal area. Participants stood on the penalty spot and were instructed to fixate on each of the pre-determined calibration points, one after the other. On completion of the calibration, participants were asked to view specific areas within the performance environment in order to verify the accuracy of the calibration. After each block of 12 penalties, the accuracy of calibration was checked with a recalibration only being performed in the case of line of gaze inaccuracy. A firewire cable was used to connect the DVCR to the laptop during calibration. Once calibration was complete, the firewire was removed, allowing the participant and eye tracker to be fully mobile. Data was saved onto the DVCR recorder and downloaded after the experiment in order to conduct offline analysis.

Procedure and Design

After being fitted with the Mobile Eye and completing the calibration, participants were instructed to warm-up by performing 10 penalty shots at the blank PVC canvas, i.e., with no video clip being projected onto the canvas. During the 10 penalty warm up shots, the participants were required to aim for one of two target areas within the goal area i.e., left target and right target area. The two circular target area locations were 22 cm in diameter (similar to the diameter of the ball) and were black in color. The center of each target area was 0.8 m from the ground and 0.9 m from the goal post (see **Figure 1**).

After the warm-up was complete, the participants began the experiment with the following instructions. Participants were required to start their run-up at minimum distance of 3.5 m from behind the ball and were asked to take the penalty as they would in competition (using their preferred foot). Participants were told that when they interrupted the light beam, a video clip with a goalkeeper would project onto the goal area in front of them. The goalkeeper would dive to either the left, or right side of the goal after a short amount of time after appearing in the goal area.

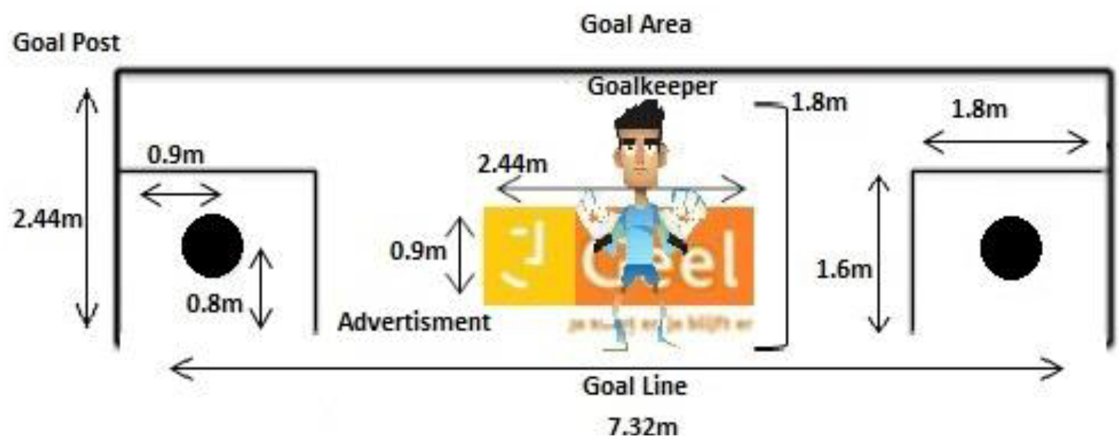

FIGURE 1 | Frontal view of the experimental design, showing a standard size goal area with the two circular target area locations, the goalkeeper and the advertisement.

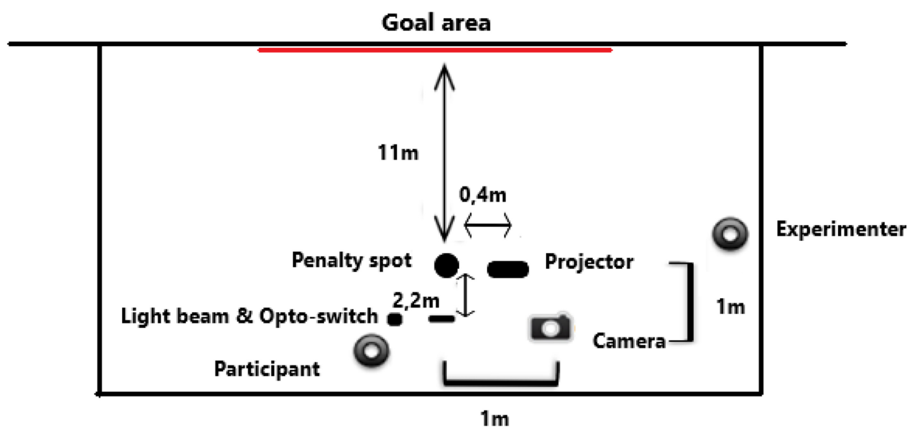

FIGURE 2 | Birds-eye view of the experimental setup. The video clips were projected onto the goal area PVC canvas using a projector to the side of the penalty mark. The digital video camera was positioned to the side of the penalty mark, and the Opto-switch was positioned behind the penalty mark.

Participants were required to shoot the ball to the opposite side of the goal the goalkeeper was diving to. In order to be successful, the participants had to place the ball to the opposite side of the goalkeeper dive, toward the side of the goal area, as they would in competition, to give themselves the best chance of scoring a goal. The two circular target areas remained visible throughout the trial. The participants received no information about the advertisement that was projected onto the goal area within the differing advertisement conditions.

For each participant, the experiment started with the initial interruption of the light beam, which initiated the first video clip. In each of the advertisement conditions, the goalkeeper could dive to either to the left or right side of the goal area, with clips diving to the left or the right being completely randomized. A repeated measures design with differing conditions of 12 penalty kicks were used. The blocks were counterbalanced with the total of 48 penalty kicks (i.e., 12 each in the control, stationary, moving from left to right, and moving from right to left), lasting ∼20 min per participant.

Data Analysis

In a first round of analysis, we compared gaze and performance across the three advertisement conditions, namely C-, S-, and M-conditions to assess non-specific effects of the (moving) advertisement. In a second round, we focussed on systematic, direction-specific effects of the moving advertisement by comparing gaze and performance between the two moving MLR- and MRL-conditions. Finally, we also assessed non-specific and specific effects for only the trials that the participants looked to the moving advertisement between the MLR- and MRL-conditions.

Gaze Behavior

WIN-analyse software was used for a frame-by-frame analysis of the point of gaze (POG) recordings during the penalty trials, from the moment the participant initiated the run-up, until contact with the ball was made (total viewing time). Each frame was analyzed with each gaze fixation being divided into one of the following six areas of interest: Goalkeeper, ball, left target, right target, advertisement and "other." The "other" area was every frame in which a participant did not look at either of the initial five areas of interest. After all trials were analyzed, gaze directed at each of the areas of interest was expressed as a percentage of total viewing time of the penalty kicks (see Van der Kamp, 2011). We also determined the percentage of trials during which participants were actually directing gaze toward the (moving) advertisement.

Penalty Performance Measures

Video recordings were used to categorize each penalty kick as either a kick directed to the right or left of the goal, with an inter-reliability ($r = 0.88$, $p < 0.05$) and intra-reliability ($r = 0.92$, $p < 0.05$) of the observers, independent of the direction of the goalkeeper's dive. The penalty kicks were further categorized as either a score (i.e., a shot to the opposite side of the goalkeeper's dive, between the posts and crossbar), a save (i.e., a shot in the same direction of the goalkeeper dive, between the posts and the crossbar), or a miss (a shot that completely missed the goal area).

Subsequently, screenshots were created for each penalty kick at the moment of ball contact with the canvas (i.e., crossed the goal line) and with Kinovea Motion Analysis software, with the absolute distance in cm of the ball landing location from the center of the goal being determined to indicate the accuracy of aiming of the kick (i.e., absolute error). In addition, we took the standard deviation of the absolute distance in cm to determine the precision in aiming between conditions (i.e., variable error). Penalty kicks that completely missed the goal area were also included in the analysis with kicks outside of the video frame being assigned the maximal distance from the center of the goal to the edge of the video frame (i.e., 705 cm). Related to specific, directional effects on performance measures, we determined the signed distance in cm of the ball landing location from the goal center (i.e., constant error), with a negative value being allocated for locations to the left of the center of the goal, and a positive value being allocated for locations to the right of the center of the goal. The absolute and variable distance measures served as an indicator of distraction (i.e., aiming accuracy and precision), while the signed distance measure allowed the assessment of systematic, directional effects on penalty kick performance between the two moving MLR- and MRL-conditions.

Statistics

The percentage viewing time to each of the areas of interest were analyzed with separate ANOVAs with repeated measures for the factor condition (i.e., C-, S-, M-conditions). It must be taken into account that the areas of interest are interdependent. When viewing time of one of the areas of interest increases, the sum of the viewing times of the other areas of interest must decrease, and vice versa. However, there does not exist a reciprocal relationship between two variables, and therefore we decided to report separate ANOVAs for the dependent variables (Kurz et al., 2018). A Huyn-Feldt correction to the degrees of freedom was applied in the case of any violations of sphericity and partial eta-squared (η_p^2) values were computed to determine the proportion of total variability attributable to each factor. *Post-hoc* pairwise comparisons were conducted using the Bonferroni correction procedure to identify where the specific differences occurred between the conditions. Subsequently, we used paired t-test to compare difference in percentage viewing time of each of the areas of interest for the MLR-condition and MRL-condition.

Similarly, for the penalty kick performance measures including the score, save and miss percentage, and the absolute and variable distance measure were submitted into separate one-way ANOVAs with repeated measures for the factor condition, while Friedman tests were selected for variables that violated the assumption of normality (i.e., C-, S-, M-conditions). Next, score, save and miss percentage, and the signed distance measure were submitted to a paired t-test to compare performance between MLR- and MRL-conditions. The final analyses involved the same series of paired t-tests, but only in the trials in which participants looked to the advertisement.

RESULTS

Initial analysis of the Mobile-Eye data revealed that of the 16 participants, we were unable to analyse the gaze behavior of four of the participants due to issues with their video clarity. Therefore, 12 participants (all male, and right footed) were used in the final data analysis, totalling a possible number of 576 penalty kicks to be analyzed. However, a total of 564 penalty kicks were analyzed due to problems with the digital camera not having recorded every possible kick for each of the participants. To test the assumption of data normality, the Shapiro-Wilks W-tests were conducted on all dependent variables. In the cases that the assumption of normality was violated, Friedman and Wilcoxon Signed-Rank tests substituted parametric ANOVA'S and t-tests, with Dunn-Bonferroni corrections used where appropriate.

Gaze Behavior

Figure 3 below shows the average percentage viewing time to the six areas of interest across the C-, S-, and M-conditions. In line with the instructions, the results provided a clear indication that the participants used a goalkeeper dependent strategy during the penalty kick experiment due to the high percentage of viewing time to the goalkeeper. They spent very limited time viewing the two target areas between conditions, with more, albeit brief, time spent looking to the ball and the advertisement.

The Friedman test with repeated measures results revealed a significant difference for the percentage viewing time to the goalkeeper between the three conditions [$x^2\,(3) = 10.18$, $p < 0.05$]. *Post-hoc* analysis indicated that participants viewed the goalkeeper for a significantly shorter period of time in the M-condition when compared to both the C- and S-conditions. The Friedman test also showed a significant difference in percentage viewing time to the ball [$x^2\,(2) = 10.18$, $p < 0.05$] with *post-hoc* analysis indicating that participants viewed the ball longer in the M-condition when compared to that of the C- and S-conditions. The percentage viewing time to other areas suggested that in the M-condition, participants viewed these locations for a longer period when compared to the other two conditions, however, the ANOVA only approached significance [$F_{(2, 22)} = 3.22$, $p =$

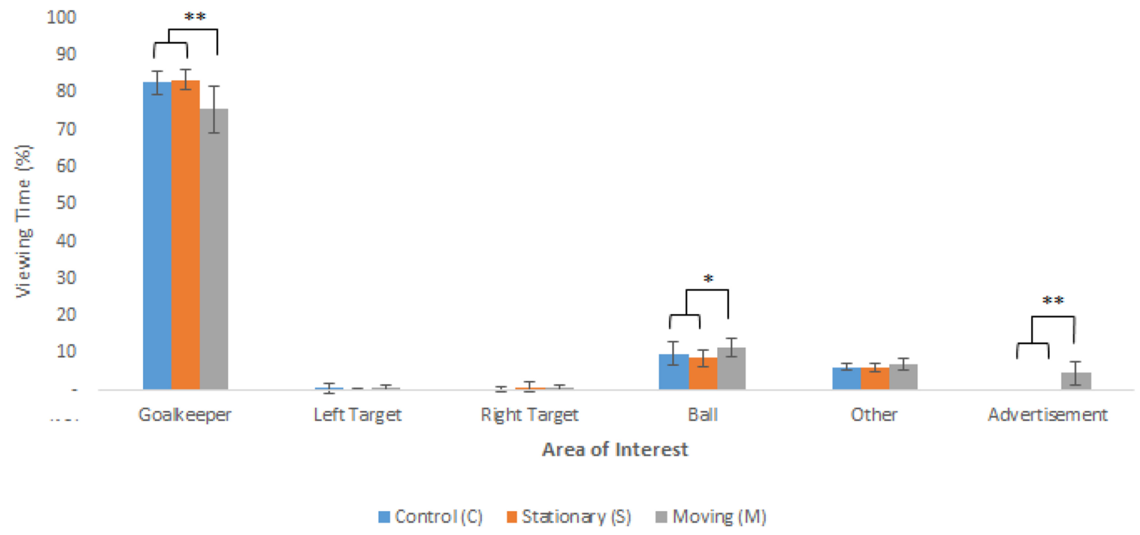

FIGURE 3 | Average percentage (+SD) viewing time to each of the areas of interest between the control (C), stationary (S), and moving (M) conditions. (NB. *$p < 0.05$, **$p < 0.001$).

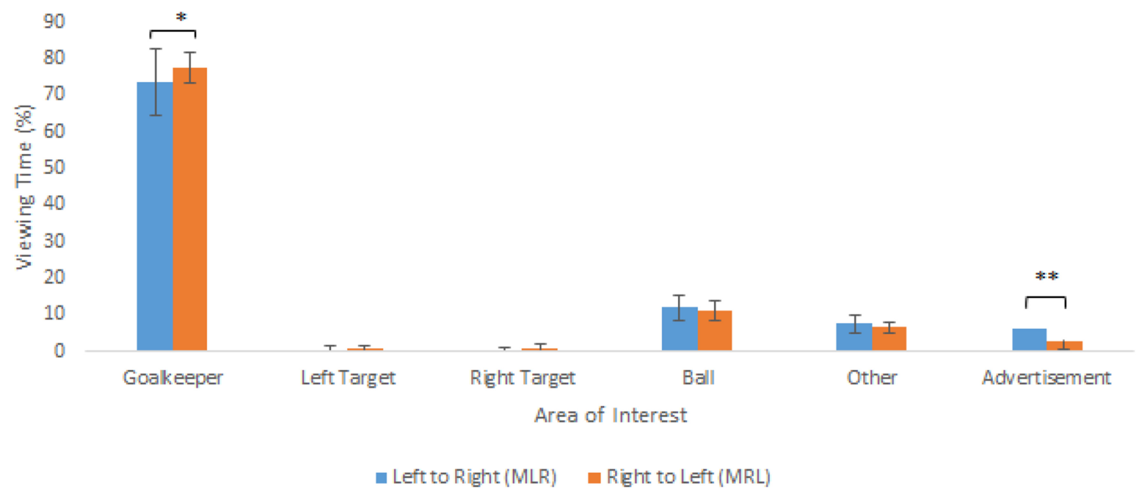

FIGURE 4 | Average percentage (+SD) viewing time to the six areas of interest between the moving left to right (MLR) and right to left (MRL) conditions. (NB. *$p = 0.05$, **$p < 0.01$).

0.06, $\eta p^2 = 0.23$]. Finally, the ANOVA for percentage viewing time to the advertisement revealed a significant main effect for condition [$F_{(2, 22)} = 26.97$, $p < 0.001$, $\eta p^2 = 0.71$], with *post-hoc* comparisons indicating significantly longer viewings to the advertisement in the M-condition when compared to both the C- and S-conditions.

Next, we examined gaze behavior differences within the moving advertisement condition by comparing MLR- and MRL-conditions (**Figure 4**). Paired sampled t-tests indicated that the percentage viewing time was significantly less for viewing the goalkeeper [$t_{(11)} = 2.19$, $p = 0.05$, $d = -0{,}63$] in the MLR-condition when compared to the MRL-condition. Further to this, a paired t-test indicated significantly more time spent on viewing of the advertisement within the MLR-condition than in the MRL-condition [$t_{(11)} = 3.92$, $p < 0.01$, $d = 1.13$]. For the other areas of interested no significant differences between MLR- and MRL-conditions were revealed.

Finally, analyses were performed to see if there were differences in the percentage of trials that participants looked at the advertisement between MLR- and MRL-conditions. The analysis indicated that, on average, participants looked at the advertisement in 38.4% of the trials within the M-condition compared to 61.6% of trials in which they did not look at the advertisement. Further analysis showed that the participants looked to the advertisement more often in the MLR-condition than in the MRL-condition [$t_{(11)} = 2.18$, $p = 0.05$, $d = 0.63$], with

TABLE 1 | Penalty kick performance measures (Mean ± SD) between the three penalty kick conditions.

	Control (C)	Stationary (S)	Moving (M)
Score (%)	74.9 ± 21.4	77.7 ± 16.3	78.6 ± 14.2
Miss (%)	8.2 ± 7.8	6.3 ± 6.3	7.4 ± 7.4
Save (%)	18.0 ± 19.8	16.0 ± 16.8	14.1 ± 14.1
Opp. side GK (%)	80.6 ± 20.6	82.6 ± 17.9	84.9 ± 14.2
Absolute distance (cm)	202.0 ± 30.0	205.5 ± 33.0	205.2 ± 43.2
Variable distance (cm)	67.6 ± 24.5*	88.1 ± 42.7	84.6 ± 12.5*

*$p < 0.05$.

TABLE 2 | Penalty kick performance measures (Mean ± SD) between moving advertisement conditions.

	Left to right (MLR)	Right to left (MRL)
Score (%)	77.7 ± 18.2	79.6 ± 15.4
Miss (%)	5.6 ± 8.9	9.2 ± 7.7
Save (%)	16.7 ± 18.4	11.3 ± 12.7
Opp. side GK (%)	83.3 ± 18.4	86.6 ± 14.6
Absolute distance (cm)	207.0 ± 50.7	203.3 ± 43.4
Variable distance (cm)	81.2 ± 18.5	88.0 ± 19.0
Directional distance (cm)	−51.5 ± 87.8	22.1 ± 55.3*

*$p < 0.05$.

TABLE 3 | Penalty kick performance measures (Mean ± SD) between moving conditions in trials to which participants looked to the advertisement only.

	Left to right (MLR)	Right to left (MRL)
Score (%)	72.9 ± 36.2	88.3 ± 16.1
Miss (%)	3.9 ± 10.2	5.3 ± 9.3
Save (%)	23.2 ± 32.5	6.4 ± 15.7
Opp. side GK (%)	76.8 ± 32.5	89.1 ± 20.2
Absolute distance (cm)	191.6 ± 87.1	161.9 ± 67.3
Variable distance (cm)	62.4 ± 38.7	42.5 ± 50.7
Directional distance (cm)	−63.3 ± 117.3	39.5 ± 101.5*

*$p < 0.05$.

the participants looking at the advertisement in 47.7% of trials in the MLR-condition and 28.6% of the trials in the MRL-condition.

Performance Measures

With the visual search analyses indicating that participants did in fact look to the moving advertisement, we proceeded to examine the key performance measures of the penalty kick. Average score, save and miss rate as a percentage of total penalty kicks, as well as absolute and variable distance measures can be seen in **Table 1**. At first glance, no clear differences came to the fore.

The separate Friedman tests found no significant difference between the number of successful penalty kicks [$x^2\,(2) = 0.17$, $p > 0.05$], the percentage of missed penalty kicks [$x^2\,(2) = 0.14$, $p > 0.05$], the percentage of kicks saved by the goalkeeper [$x^2\,(2) = 0.15$, $p > 0.05$], or the percentage of kicks to the opposite side of the goalkeeper [$x^2\,(2) = 0.14$, $p > 0.05$], between the C-, S-, and M-conditions. Similarly, Friedman tests also did not reveal significant differences for the absolute distance [$x^2\,(2) = 1.17$, $p > 0.05$], yet it did show a significant difference for variable distance [$x^2\,(2) = 7.17$, $p < 0.05$], with *post-hoc* analysis indicating kicks were more variable for the M-Condition when compared to the C-condition ($p > 0.05$).

Next, we examined differences within the moving condition by comparing MLR- and MRL- conditions (**Table 2**). A Wilcoxon Signed-Ranks test found no significant differences between the MLR- and MRL-conditions for score ($Z = -0.31$, $p > 0.05$), save ($Z = -1.26$, $p > 0.05$), miss [$t_{(11)} = -1.60$, $p > 0.05$], or kicks to the opposite side of the goalkeeper ($Z = -0.99$, $p > 0.05$) percentages. A paired sampled t-test also found no differences between the absolute [$t_{(11)} = 0.33$, $p > 0.05$, $d = 0.10$] and variable distance measures [$t_{(11)} = -0.83$, $p > 0.05$, $d = -0.24$]. However, an effect was found between the two moving advertisement conditions for the signed distance [$t_{(11)} = -2.49$, $p < 0.03$, $d = -0.71$], with the MLR-condition showing kicks that were placed to the left of the center of the goal (on average), while in the MRL-condition kicks were placed to the right of the center of the goal (on average).

Given the fact that the results of gaze behavior showed that participants did not shift visual attention in all trials within the moving advertisement conditions, we compared performance measures between MLR- and MRL-conditions for only those trials in which they looked at the advertisement. Participant 2 was left out of the analysis as the participant did not look at the advertisement in any of the penalty kick trials in the MLR condition. This left 11 participants in the analysis (**Table 3**). Wilcoxon Signed-Ranks tests did not reveal significant differences between the MLR- and MRL-conditions when looking to the advertisement for score ($Z = -0.84$, $p > 0.05$), save ($Z = -1.57$, $p > 0.05$,), miss [$t_{(11)} = -0.37$, $p > 0.05$], or kicks to the opposite side of the goalkeeper ($Z = -0.94$, $p > 0.05$) percentages. Paired t-test also did not reveal significant differences for the absolute [$t_{(10)} = 1.13$, $p > 0.05$, $d = 0.34$] and variable distance measures [$t_{(10)} = 1.15$, $p > 0.05$, $d = 0.35$]. However, a significant difference was found for the signed distance measure between the MLR- and MRL-conditions [$t_{(10)} = -2.69$, $p < 0.05$, $d = -0.81$]. Results indicate that in the MLR-condition, the kicks were to the left of the center of the goal (on average), while in the MRL-condition the kicks were placed to the right side of the center of the goal (on average).

DISCUSSION

With the introduction of LED billboards within competitive sport that allow moving advertisements to be displayed around soccer stadiums during game time, there is a need to understand its potential effects on visual attention. Specifically, these billboards are placed around the field, including the area behind the soccer goal area, with the potential to distract the visual attention of a player during a penalty kick, a critically decisive event within competitive soccer. It is important to understand this as previous research has demonstrated a functional coupling of gaze behavior and kicking, with the information made available from gaze fixations being pertinent in decision making, as well as maintaining effective performance (Behan and Wilson, 2008). Further to this, studies have shown the effect of distractions to visual attention, with shifts in attention to task irrelevant cues having the potential to disrupt motor performance within far-aiming tasks like the penalty kick (Beilock and Carr, 2001; Wood and Wilson, 2010; Morris, 2012; Lidor et al., 2013). We therefore investigated whether a moving advertisement positioned behind the goal area did in fact catch the visual attention of participants performing the penalty kick, and, whether this has any effects on subsequent motor performance. We hypothesized two possible effects of the moving advertisement. First, a moving background can function as a distractor, resulting in a non-specific disruption of penalty performance measures, especially in terms of aiming accuracy and precision. Alternatively, a moving background may affect the perception of target location, inducing systematic changes in penalty performance and aiming which would be specific for the direction of motion of the advertisement, analogous to the effects of the Dunker illusion observed for aiming task (e.g., Soechting et al., 2001).

It is worth noting from the initial perusal of the gaze behavior results that participants indeed used a goalkeeper dependent strategy during the experiment, with an average 78% of gaze spent looking at the goalkeeper, which was expected given the nature of the instructions to participants. The key significant finding in the gaze behavior data however was that the moving advertisement indeed caught the attention of participants compared to the no- and stationary advertisement conditions. Although gaze was affected by the motion of the background, no significant differences between the penalty performance outcome measures, namely success, miss and save rates, were found between the three conditions. Also, the participants did not significantly differ in the ability to decide and kick the ball to the opposite side of the goalkeeper dive, or differ in the accuracy of ball placement (i.e., absolute distance from the goal's center) between conditions. In fact, the only significant difference observed was with respect to the precision of ball placement (i.e., variable distance), suggesting less precise kicks in the moving advertisement condition compared to the no advertisement condition. This might suggest a small non-specific distractive effect; however, we note that the variable measure for the stationary condition was numerically (but not statistically) even higher, suggesting that the disruptive effect, if any, is not induced by the motion of the advertisement.

When comparing gaze behavior between the moving advertisement conditions, we found that participants' visual attention shifted in more trials to the advertisement when it moved from left to right compared to when moving right to left. Presumably, this also lead participants, on average, to spend more time viewing the advertisement when it moved from left to right. In relation to this finding, it has been found that when looking at pictures of natural scenes, neurologically intact individuals show a leftward bias in the direction of their first eye movement. The presence of this leftward bias within spatial attention is known as pseudoneglect (Nuthmann and Matthias, 2014; Hartmann et al., 2019; see Nicholls et al., 2010; Noël et al., 2015 for pseudoneglect in kicking tasks). This as well as the fact that the angle of the run up for the right footed players place the advertisement in the corner of the eye, could be the reason why the participants were more likely to look to the advertisement within the left to right condition. We did only include right-footed players within the present study. Future research should consider whether similar findings occur within left-footed players due to the differing constraints on the run-up for these players, and also because some authors have argued that pseudoneglect effects may be lateralized (McCourt and Garlinghouse, 2000).

Although visual attention differed, we found no measurable difference in the penalty performance outcome measures between the two moving advertisement conditions. Yet, when aiming is concerned, a significant effect on the ball landing location was found: kicks were aimed to the left of the center of the goal when the advertisement moved from the left to right, while kicks were placed to the right of the center of the goal when the advertisement moved in the opposite direction. This theoretically pertinent result is aligned with previous findings in pointing and hitting using the Duncker illusion (Soechting et al., 2001; Brouwer et al., 2003), in which the presence of background motion from left to right and right to left resulted in systematic aiming errors to the left and right of a target, respectively. Taking this as well as later findings that accuracy of far aiming tasks is impacted by allocentric or contextual information (Van der Kamp and Masters, 2008; Van der Kamp et al., 2009; Shim et al., 2014), our results suggest the exploitation of allocentric information sources in far-aiming task like the penalty kicks. Initially, this would seem in contradiction to the two visual systems model proposed by Milner and Goodale (2008), as the control of action typically exploits egocentric information. Yet, as Van der Kamp and Masters (2008), Van der Kamp et al. (2009), Shim et al. (2014) have suggested, aiming tasks such as the penalty kick may involve identifying landing location and this process may actually be more consciously controlled and thus involve the ventral stream, thereby exploiting allocentric information (see also Willingham, 1998). To what degree, the, presumably unintended, systematic effects on aiming accuracy can actually also bring about a degradation in performance outcome with a real goalkeeper trying to save the penalty kick must be addressed in future studies. That is, in the present study, the exact aiming location did not affect the performance outcome scores, but when using a real goalkeeper, differences in aiming can potentially bring the ball (just) within reach, affecting the opportunities for the goalkeeper to intercept the ball.

A few additional notes have to be made regarding the findings that relate to representativeness of the current experimental procedures. With our current design, the situation enforced a keeper-dependent strategy which has allowed us to maximize the penalty takers visual attention to the goalkeeper and the goal area. However, it is important seek to which degree these findings can be generalized to kickers who use a goalkeeper-independent strategy. Due to the differences in visual gaze patterns across the two penalty taking strategies, it is pertinent to understand the effects on visual attention and subsequent penalty performance within the goalkeeper-independent strategy as well. A likely difference is toward the timing of the effect. While with the current keeper-dependent strategy, a moving advertisement can affect aiming almost through the entire run-up and kick, it is likely that with a goalkeeper-independent strategy the effect is restricted to the preparation and early phase of the run-up, because within the keeper-independent strategy, kickers tend to focus their attention earlier and longer toward the ball. Also, the length of the run-up is a potential factor influencing the relative amount of time kickers spend looking at the goalkeeper, goal and ball, and thus, their susceptibility to a moving advertisement (Kurz et al., 2018). Another concern might be that in the competitive environment, kickers only have one attempt to complete a penalty kick and previous research has suggested that participants tend to adjust penalty strategies as the trials continue in order to be more successful (Wood and Wilson, 2010), and in the current study also may have adapted to the attention drawing effect of the moving advertisement, having less effect over time. It would be interesting to see the effects of a moving advertisement in a single attempt in future studies in order to better mimic the competitive situation. We do think, however, that with respect to the information available for aiming and the spatial constraints on action our design is reasonably representative relative to on-field or competitive situations. In fact, the major flaw in terms of representative design is in the absence of dynamic interactions between kicker and goalkeeper. This relates to kicker being instructed to use a keeper-dependent strategy (as discusses above) and the use of a goalkeeper projection, which -obviously- did not respond to the kickers' action. Importantly, therefore, future research must verify the observed effects of moving advertisement in on-field environments, for instance, by analyzing video-footage of competitions. A final but relevant concern would be the difference between the pressure perceived by the participants during the current study, vs. the pressure experienced in a competitive environment. Attentional control theory (ACT) propose that anxious individuals both orient more rapidly to salient or conspicuous stimuli, and disengage from them more slowly (Wilson et al., 2009). This is theoretically interesting as implications are that in higher anxiety competitive situations, a moving advertisement could affect attention even more that in the penalty kickers shown within this study. Future research, including notational analysis of video-footage, should take this into consideration.

In conclusion, a moving advertisement placed behind the goal area was found to catch the visual attention of soccer penalty kickers using a goalkeeper-dependent strategy, with no measurable distractive non-specific effects on penalty kick performance measures. However, importantly, systematic effects on aiming were found when comparing conditions in which the advertisement moved in opposite directions suggesting that the aiming accuracy of the penalty kick is impacted by task-irrelevant contextual information.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Scientific and Ethical Review Committee, Faculty Committees, Faculty of Behavioral and Movement Sciences. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Article was planned by GP, JK, and GS. Data was collected by GP. Data analyzed by GP and JK. Article write up by GP, assisted by JK, and final sign off by GS.

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REVIEW
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The Measurement of Eye Movements in Mild Traumatic Brain Injury: A Structured Review of an Emerging Area

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Mild traumatic brain injury (mTBI), or concussion, occurs following a direct or indirect force to the head that causes a change in brain function. Many neurological signs and symptoms of mTBI can be subtle and transient, and some can persist beyond the usual recovery timeframe, such as balance, cognitive or sensory disturbance that may pre-dispose to further injury in the future. There is currently no accepted definition or diagnostic criteria for mTBI and therefore no single assessment has been developed or accepted as being able to identify those with an mTBI. Eye-movement assessment may be useful, as specific eye-movements and their metrics can be attributed to specific brain regions or functions, and eye-movement involves a multitude of brain regions. Recently, research has focused on quantitative eye-movement assessments using eye-tracking technology for diagnosis and monitoring symptoms of an mTBI. However, the approaches taken to objectively measure eye-movements varies with respect to instrumentation, protocols and recognition of factors that may influence results, such as cognitive function or basic visual function. This review aimed to examine previous work that has measured eye-movements within those with mTBI to inform the development of robust or standardized testing protocols. Medline/PubMed, CINAHL, PsychInfo and Scopus databases were searched. Twenty-two articles met inclusion/exclusion criteria and were reviewed, which examined saccades, smooth pursuits, fixations and nystagmus in mTBI compared to controls. Current methodologies for data collection, analysis and interpretation from eye-tracking technology in individuals following an mTBI are discussed. In brief, a wide range of eye-movement instruments and outcome measures were reported, but validity and reliability of devices and metrics were insufficiently reported across studies. Interpretation of outcomes was complicated by poor study reporting of demographics, mTBI-related features (e.g., time since injury), and few studies considered the influence that cognitive or visual functions may have on eye-movements. The reviewed evidence suggests that eye-movements are impaired in mTBI, but future research is required to accurately and robustly establish findings. Standardization and reporting of eye-movement instruments, data collection procedures, processing algorithms and analysis methods are required. Recommendations also include comprehensive reporting of demographics, mTBI-related features, and confounding variables.

Keywords: mild traumatic brain injury, eye-tracking, eye movement, methods, vision

INTRODUCTION

Eye movements are the basis of how humans gather information about the environment, which is then used to allow the perception of vital information needed for safe navigation or task performance. Eye movements have been investigated via various methods since the 1700s (Porterfield, 1752), with progression from eye-tracking that used large-scale photographic technology to invasive high resolution scleral search coils, and finally to more modern non-invasive small-scale infrared camera systems (Land, 2006). There are many eye movements that can be captured with modern technologies, such as saccades (fast eye movements), fixations (pauses on areas of interest), smooth pursuits (fixations on moving objects), and nystagmus (repetitive non-voluntary resetting eye movements; Tatler and Wade, 2003; Duchowski, 2007; Holmqvist et al., 2011). A combination of these eye movements provide the mechanisms through which we are able to explore and sample our environment (McPeek et al., 2000; Deubel and Schneider, 2003; Tatler and Wade, 2003; Marigold and Patla, 2008; Tatler, 2009; Stuart et al., 2014a). In order to derive and classify the different types of eye movements, a range of spatial-temporal and kinematic outcome variables are typically used, such as latency, velocity, acceleration, number/frequency, timing and duration (Duchowski, 2007; Holmqvist et al., 2011; Stuart et al., 2019a). Advancements in eye-tracking technologies have enabled eye movements to be monitored with small-scale devices that can be used in a variety of environments, such as research laboratories, clinics, field-based and community facilities. Similarly, collection of eye movement data with eye-tracking devices has progressed from traditional static tasks (e.g., seated or standing) to more dynamic tasks (e.g., walking or navigation of the environment), which is an important step toward understanding the impact that deficits can have on real-world function. The development of simple, high resolution, quantitative eye-tracking technologies is allowing disease or injury-specific impairments to be uncovered.

Eye movements are increasingly being studied in mild traumatic brain injury (mTBI) (commonly referred to as concussion; Thiagarajan et al., 2011; Ventura et al., 2015; Hunt et al., 2016; Snegireva et al., 2018), as eye-tracking protocols can be used to detect subtle deficits in cognitive, motor and visual processes that may occur following a head injury (Liversedge and Findlay, 2000; Maruta et al., 2010a). Detection of mTBI and monitoring of recovery of subtle impairments is not always possible with conventional means, such as neuroimaging (Eierud et al., 2014) or clinical assessments (McCrea et al., 2015). A lack of accurate and robust diagnostics, biomarkers and outcome measures leads to mTBI going undetected (Jeter et al., 2013; Kim et al., 2018; Quinones-Ossa et al., 2019). Undetected mTBI can lead to impaired functional activities, self-medication and return to sport/work/play before recovery is complete, which may lead to increased future injury risk and other health burden (McPherson et al., 2019; Reneker et al., 2019). Interestingly, the incidence of self-reported visual impairments in those following a traumatic brain injury has been reported to be as high as 90% (Ciuffreda et al., 2007), but incidence reports vary with the lowest recorded at 22% (Lara et al., 2001; Cockerham et al., 2009). This is not surprising, as the processing of vision and control of eye-movements is known to involve a large proportion of the brains circuits and regions (Antoniades et al., 2013), as well as underlying neural pathways and structures (Mays et al., 1986; Noda, 1991; Catz and Thier, 2007; Shinoda et al., 2019). For example, visual signals from the retina are sent to the superior colliculus then initially processed by the lateral geniculate nucleus, pulvina and mediordorsal thalamus, where signals are then sent for top-down visual processing at the pre-frontal cortex, frontal eye-field, supplementary eye field and lateral intraparietal area; as well as basic visual processing at the visual cortex (V1/V2, V4), middle temporal area and inferotemporal cortex, with the striatum, substantia nigra pars reticulate, and brainstem involved in eye movement initiation and control (Baluch and Itti, 2011). Therefore, as a result of an mTBI eye movements may be impaired and eye-movement recordings could provide a simple, quick and non-invasive means to quantify impairments and recovery in mTBI (Snegireva et al., 2019). Furthermore, imaging evidence suggests that saccades, smooth pursuits and nystagmus eye movements activate largely similar neural structures (Konen et al., 2005; Dieterich et al., 2009), and therefore individual eye movement tests may be of value to mTBI diagnosis.

Eye-tracking technology has been used to further understand mTBI-related impairments in eye-movements (Akhand et al., 2019), demonstrating some efficacy for use in mTBI assessment and clinical diagnostics. However, until recently most eye movement research in mTBI involved simple, subjective, clinical, self-reported, or symptom-based tasks that could be performed in the field or within clinic with minimal training [e.g., the vestibular/ocular-motor screening (VOMS) Mucha et al., 2014]. Several previous reviews of studies that have used self-report/symptom-based outcomes have reported vision impairments in mTBI (Thiagarajan et al., 2011; Hunt et al., 2016; Whitney and Sparto, 2019). However, many mTBI subjective rating scales have not had rigorous validity or reliability testing (Alla et al., 2009), and scales may miss subtle symptoms due to reliance on clinician experience and self-report (Meier et al., 2015). Progression to the use of eye-tracking devices in research

KEY TERMS

Mild Traumatic Brain Injury: "mild Traumatic*" OR "mTBI" OR "concussion" TITLE-ABS-KEY

Eye Movement: ("vision" OR "visuomotor" OR "gaze" OR "visuospatial" OR "eye movement" OR "ocular motor" OR "ocular movement" OR "oculomotor" OR "sensorimotor" OR "visual movement" OR "visual behaviour" OR "visual behavior" OR "orientat*" OR "attention" OR "saccad*" OR "smooth*" OR "pursuit" OR "convergence" OR "vergence" OR "visual sampling" OR "visual search" OR "visual field" OR "visual exploration" OR "oculo motor" OR "ocularmotor") TITLE-ABS-KEY

Eye-tracking: ("eye track*" OR "eye-track*" OR "EOG" OR "electro-ocu*" OR "scleral search coil" OR "video-ocul*" OR "infra-red") TITLE-ABS-KEY

NOT ("sleep*" OR "monkey*" OR "rat*" OR "mouse" OR "mice" OR "animal") TITLE-ABS-KEY

('*' indicates a wildcard and 'TITLE-ABS-KEY' indicates a title, abstract and keyword

FIGURE 1 | Search strategy used to screen for relevant articles included in this review.

that are capable of capturing eye-movements at high speed and providing quantifiable outcomes has led to an array of testing protocols (Hunt et al., 2016; Snegireva et al., 2018), indicating a lack of standardization that limits outcome interpretation and generalizability. Several recent reviews provided overviews of reported impairment of eye-movement outcome measures in mTBI (Hunt et al., 2016; Snegireva et al., 2018), but provided limited details regarding the use of specific eye-tracking methodologies and how differences in methods or devices may impact findings. Researchers who want to conduct similar research are therefore left with the choice between numerous eye-tracking devices, outcomes and protocols that differ in many respects and complexities. In the process of developing robust protocols it is helpful to have evidence-based recommendations. We therefore examined previous work that assessed eye movements in mTBI and healthy control participants in order to provide some guidance regarding the selection of appropriate methodology.

We focused the review on the following: (1) eye-tracking instrumentation used to examine people following an mTBI compared to healthy controls; (2) commonly reported eye movement outcomes from eye-tracking studies; (3) mTBI specific influences on these eye movement outcomes; and (4) recommendations concerning future protocols.

METHODS

Search Strategy

The key terms were "mild Traumatic Brain Injury," "Eye movement," and "Eye-tracking." A list of synonyms was created for each key term (**Figure 1**). Key terms were matched and expanded with medical subject headings (MeSH) in each separate database where appropriate. Databases searched included Medline/Pubmed (from 1950), PsychInfo (from 1806), CINAHL (from 1937), and Scopus to July 2019. Studies were relevant if they used terminology that focused on eye movement tracking in those with mTBI and healthy control subjects in the title, abstract or keywords. Articles with titles related to "sleep," "monkeys," "rats," "mice," or "animal" models were excluded using separate key terms.

An initial title screen for relevant articles was performed by the reviewer (SS) once the searched database results had been combined. After the initial title screen, both the titles and abstracts of the selected articles were reviewed by three independent reviewers (SS, DM, LP). A review of the full text was required if it was not clear from the title or abstract whether the study met the review criteria.

Inclusion and Exclusion Criteria

Articles were included if they reported use of an eye-tracking measurement instrument to quantify eye movements (i.e., saccades, smooth pursuits, convergence, fixations etc.) in people with mTBI. Studies were included only if they tested a healthy control cohort or used a baseline pre-injury test as a control for comparison with mTBI cohorts so that injury-specific differences could be identified. If articles including another clinical cohort (i.e., whiplash, acquired brain injury, moderate to severe TBI; Samadani et al., 2015), or an additional visual assessment that was not quantified via eye-tracking (e.g., measurement of convergence), only the eye-tracking data from the mTBI and healthy control cohorts was reviewed. If clinical cohorts were combined [i.e., mTBI with traumatic whiplash (Herishanu, 1992) or mild-to-severe TBI (Vakil et al., 2019)] or studies used a control group that had experienced an mTBI and were classified as recovered compared to a symptomatic mTBI population (Heitger et al., 2009), then the data were not reviewed. Acute and chronic (including post-mTBI syndrome) mTBI cohorts were reviewed, but studies without a diagnosis of an mTBI [i.e., repetitive head injuries or those with a self-reported history of head injuries with no current symptoms or recent referral to study by a clinician (Rizzo et al., 2016)] were excluded. Rehabilitation studies that did not include a baseline examination, or did not include any cross-sectional comparison to healthy controls were not reviewed (Kaldoja et al., 2015; Johansson et al., 2017). Only articles written in English were considered for review and any abstracts, case studies, reviews, book chapters, commentaries, discussion papers, editorials or conference proceedings were excluded.

Data Extraction

Data were extracted by the reviewer (SS) and were synthesized into table format by the reviewer (SS) and a second reviewer (LP) confirmed the entered data (**Tables 1–3**). Data included demographic, eye movement measurement instruments, eye movement outcomes, study protocol and key findings.

RESULTS

The Evidence Base

The search strategy yielded 86 articles, excluding duplicates (Figure 2–adapted from Moher et al., 2009). There was an initial screening in 128 articles of interest of which 22 were identified for inclusion for review by consensus of the screening reviewers (SS, LP, DM). Of the title screened 50 were excluded for not meeting inclusion criteria of the review. The majority of screened studies were excluded because they were either not relevant or did not provide quantitative measurement of eye movements in mTBI (**Figure 2**).

Participants

The reviewed articles ($n = 22$) investigated healthy controls and mTBI with average age ranges between 13 and 39 years old (**Table 1**), with the majority of the studies including both males and females. Several studies did not provide specific demographic characteristics of participants, such as age (Maruta et al., 2010b; Johnson et al., 2015a; Webb et al., 2018), sex (Suh et al., 2006; Contreras et al., 2011; Cifu et al., 2015), time since injury (Johnson et al., 2015a,b; Maruta et al., 2017; Webb et al., 2018; Cochrane et al., 2019) etc. There were also various inclusion and exclusion criteria for participants within the reviewed studies, with little consensus and a lack of reporting in some studies. Seven of the studies examined subjects with chronic post-mTBI symptoms (time since injury ranged from 3 months to 5 years) and 13 studies examined subjects with acute/sub-acute mTBI (time since injury ranged from within 2–40 days post-injury, **Table 1**). The majority of the studies compared mTBI to healthy controls, but two studies (Maruta et al., 2018; Hecimovich et al., 2019) examined athletes during a pre-season baseline and then a follow-up post-injury. One study (Kelly et al., 2019) investigated mTBI subjects at an average of 22.2 days post-injury, but time since injury ranged from 1 to 328 days, so both acute and chronic mTBI subjects were included as one cohort. Similarly, two other studies grouped acute and chronic mTBI for all of their data analysis (Suh et al., 2006; Wetzel et al., 2018). Several studies also examined the same mTBI and control cohorts but produced one article on the baseline acute injury testing and another on the follow-up sub-acute periods (Johnson et al., 2015a,b; Balaban et al., 2016; Hoffer et al., 2017).

Instruments

Eye movements in the reviewed articles were measured using a variety of eye-tracking instruments, which largely depended on the desired eye-movement outcome or task being evaluated. For example, stationary eye-trackers were used for activities where restricted head movement was required, whereas mobile eye-trackers tended to be used for tasks that allowed head movement (i.e., walking or playing a computer game while standing balance was also examined; Murray et al., 2014, 2017; Stuart et al., 2019b). The 22 articles described an array of instrumentation including desk or computer-mounted infrared eye-trackers, rotary chairs within enclosed rooms, tethered head-mounted eye-trackers and fully mobile eye-trackers (**Table 2**). The sampling frequencies used to record eye movements varied considerably, despite many studies using similar devices (frequency range 60–1,000 Hz, **Table 2**). One study (Hecimovich et al., 2019) using the King-Devick eye-tracking system did not report the sampling frequency of the device.

Reliability and Validity

Of particular importance was that none of the reviewed studies reported the validity or reliability of the eye-tracking instrumentation used, and studies provided no detail regarding manufacturer specifications of the equipment (i.e., accuracy of tracking).

There was also very poor reporting of specific data processing or analysis methods used to derive the outcomes of interest within the reviewed studies. Only one study comprehensively provided their eye-tracking data processing method to derive eye movement outcomes, as the article developed and validated an eye-tracker algorithm to derive saccades while walking in mTBI and controls (Stuart et al., 2019b). Whereas another study reported that if there was <70% of eye-tracking data available then their instrumentation stated the trial was not valid and it was repeated until a valid trial was collected (Cochrane et al., 2019). One study also reported a comparison of their smooth pursuit synchronization index outcome with a traditional measure of velocity error to validate their outcome measure (Contreras et al., 2011). One study used commercial software (Oculogica, Inc.) to process their data (Howell et al., 2018) and referred to several previous studies that had also used this software to suggest its validity. However, validity of the commercial software is unclear, as it should be noted that none of the studies that were referenced examined or reported the data processing involved.

Test re-test reliability was performed in one study to examine their eye movement outcomes (Cochrane et al., 2019), but it was only performed in healthy controls. Results showed that their eye tracker (I-Portal, Neuro Kinetics Inc.) had poor to moderate reliability [0.02 to 0.71 inter-class correlation coefficient (ICC)] for saccadic accuracy and smooth pursuits, but saccadic latencies and optokinetic gains had better reliability (0.57–0.74 ICC).

TABLE 1 | Participant characteristics, mTBI diagnosis or definition, inclusion, and exclusion criteria.

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
Balaban et al. (2016)	100 acute mTBI – Aged 26.4 ± 6.7 years – 33 female/67 male – 62.4 ± 37.6 h since injury 200 Healthy Controls – Aged 28.0 ± 6.1 years – 44 female/156 male – Recruitment of mTBI from emergency rooms at civilian and military hospitals. Controls recruited from study location sites	– Diagnosis of mTBI from an emergency room staff physician – Head injury with a Glasgow Comma Scale of 14 or greater with no loss of consciousness >30 min	– Aged 18-45 years old – Within 6 days of injury Control specific; – No active medical condition – No history of significant mTBI – No ear or balance disorders	NR
Cifu et al. (2015)	60 Chronic post-concussion symptoms mTBI – Aged 23.2 ± 3.0 years – 8.5 ± 6.6 months since injury 26 Healthy controls – Recruitment from military. Controls recruited from an academic military center.	– TBI confirmed by a physiatrist following referral – Ongoing post-concussion symptoms evidenced with Rivermead Post Concussion Symptom Questionnaire	NR	– History of prior neurologic – Ophthalmologic – Other health conditions, including whether they had any subjective visual complaints, such as blurred vision, double vision, or floaters
Cochrane et al. (2019)	28 mTBI – Aged 20.7 ± 1.9 years – 11 female/17 male 87 Healthy controls – Aged 20.6 ± 1.8 years – 39 female/48 male – 23 reported mTBI history but with no current symptoms – Recruitment from community, university students who performed recreational sports and US Division 1 university men's football and women's soccer teams	NR	– Tested within 72 h to 2 weeks post-injury – Aged 18–24 years old – Maximum 2 weeks since mTBI – Active in sport	NR
Contreras et al. (2011)	12 Chronic post-mTBI symptoms – Aged 29.7 ± 7.3 years – 2.2 ± 1.8 years since injury 12 Healthy controls – Aged 27.9 ± 4.9 years – Recruitment NR	NR	– Head injuries limited to one – Blunt, isolated mTBI – No presence of posttraumatic amnesia – No cranial nerve abnormalities (except those affecting the sense of smell) – Non-intoxication	– Previous mTBI with loss of consciousness for periods longer than 24 h, – History of multiple mTBI with loss of consciousness – Pregnancy – History of drug or alcohol abuse – Pre-injury neurological or psychiatric diagnosis of an axis I or axis II disorder – General anesthesia within two weeks before testing – Seizure following trauma – Seizure disorders – Pre-injury use of psychotropic medication(s) Control specific: – No history of head injury or head trauma – Non-intoxication

(Continued)

TABLE 1 | Continued

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
DiCesare et al. (2017)	17 mTBI – Aged 16.8 ± 1.2 years – 5 females/12 males – 7.7 ± 4.7 Days since injury 17 Healthy controls – Aged 16.8 ± 0.7 – 7 females/10 males – Recruitment NR	– Recently experienced and diagnosed with mTBI (missing exact dates from 2 subjects)	NR	NR
Diwakar et al. (2015)	25 Chronic post-concussion symptoms mTBI – Aged 32.7 ± 11.2 years – 84% males – 31.8 ± 18.3 months since injury 25 Healthy Controls – Aged 31.8 ± 10.6 – 68% males – Recruitment from university TBI clinics and studies, as well as community. Controls recruited from community and other studies.	– Persistent symptoms since mTBI	– A single TBI with or without loss of consciousness within 3 months to 5.5 years prior to testing – Any persistent PCS symptoms – A normal CT or MRI for patients who went to the emergency room – A Glasgow Coma Scale (GCS) of 13–15 at time of injury, if available.	– Hospitalized for their injury – Were intubated – Had multiple TBIs – Had loss of job due to the injury – Confirmed use of psychotropic or cognitive enhancing medication – Showed evidence of malingering on the Test of Memory Malingering (i.e., cut-off score below 45 on trial 2) All subjects: – Neurological diagnosis other than mTBI – History of post-traumatic stress disorder – Neurological disorders other than TBI (e.g., seizure disorder) – Pre-morbid major psychiatric disorders (e.g., major depressive disorder) – Alcoholism or substance abuse – Attention deficit hyperactivity disorder (ADHD).
Hecimovich et al. (2019)	19 Subjects at baseline – Aged 13.9 ± 0.3 years – 0 female/19 male 6 post-injury mTBI – Recruited from Australian Rules Football Players	– Impact to the head either witnessed during the game or retrospective identified using a log book recording – Head impact was documented in log book if a subject had player-to-player or player-to-surface head contact, or whiplash-like head movement, or self-reported symptoms	NR	– A history of concussion or traumatic brain injury – A history of neurological or ophthalmological disease (other than refractive error) – A history of concussion – Neurological impairment – Learning disability – Visual dysfunction – Taking central nervous system-active medications
Hoffer et al. (2017)	106 acute mTBI – Aged 26.2 ± 6.5 years – 34 female/72 male – 64.8 ± 39.3 h since injury Follow-up at 7-10 days and 14-17 days to examine sub-acute injury period 300 Healthy controls – Aged 27.5 ± 6.5 years – 95 female/205 male – Recruitment of mTBI from emergency rooms at civilian and military hospitals. Controls recruited from study location sites	– Diagnosis of mTBI from an emergency room staff physician – Head injury with neurosensory sequelae and a Glasgow Comma Scale of 14 or greater with no loss of consciousness >30 min – Neurosensory symptoms included but were not limited to dizziness, hearing loss, headache, cognitive difficulties, and sleep disorders	– Aged 18-45 years old – Within 6 days of injury – No head injury 12 months prior to current injury – Never hospitalized for a head injury Control specific; – No active medical condition – No history of significant mTBI – No ear or balance disorders	– NR

(Continued)

TABLE 1 | Continued

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
Howell et al. (2018)	44 mTBI – Aged 14.1 ± 2.2 years – 17 female/27 male – 6.4 ± 2.5 Days since injury 35 Health Controls – Aged 14.3 ± 2.4 years – 20 female/15 male – Recruitment from two sport concussion clinics of regional children's hospital, and controls from hospital employees	– Sports medicine physician diagnosed mTBI – Defined as "a direct blow to the head, face, neck, or elsewhere on the body, resulting in the rapid onset of impairment of neurologic function"	– Within 10 days of mTBI – Between ages 8 and 18 years – mTBI via sports or mechanism involving forces similar to sports (e.g., falling from level ground, recreational activity injury)	– Concurrent injury sustained at the time of concussion – History of permanent memory loss – Significant sensory deficits (e.g., deafness or blindness) – A history of psychiatric disorders – Falling from height – Motor vehicle collision Control specific: – Diagnosed concussion within the year prior to testing – A concurrent injury limiting sport participation – History of permanent memory loss, significant sensory deficits (e.g., deafness or blindness) – History of psychiatric disorders
Johnson et al. (2015a)	9 acute mTBI 7 follow-up sub-acute mTBI – Aged 18-21 years – 3 female/4 male 9 Healthy Controls – Recruitment NR	NR	– Within 7 days of injury for acute mTBI – At 30 days for sub-acute mTBI	NR
Johnson et al. (2015b)	9 mTBI – Age range 18-21 years – 3 female/6 male 9 Healthy Controls – Age range 20-22 years – 3 female/6 male – Recruitment from Sport Concussion Program at University	NR	– Within 7 days of injury	– History of psychiatric or neurological disorders, – On any current medications
Kelly et al. (2019)	50 mTBI – Aged 15.2 (range 13-18) years – 24 female/26 male – Days since injury 22.1 (range 1 to 328) 170 Healthy Controls – Aged 15.5 (range 11–18) years – Recruitment from high-school aged athletes	– mTBI diagnosis confirmed by director of Sports Medicine Concussion Clinic (or by a neurologist in Neurology Concussion Clinic) – Defined as "a transient alteration of normal brain function typically affecting orientation and memory due to an external mechanical force, which may have involved loss of consciousness; concussion was considered equivalent to mTBI"	– Ongoing mTBI symptoms – Males and females – Aged 13 to 18 years old – Able and willing to assent or consent; a parent or legal guardian provided consent for those under 18 years old	– Brain injury resulting from a penetrating wound to the head, neck, face, or brai – History of schizophrenia or major depression – Previous concussion with incomplete symptom recovery
Maruta et al. (2010b)	17 Chronic post-mTBI symptoms – 7 females/10 males – 2.7 years since injury (range 6 weeks to 5 years) 9 Healthy Controls – Age range 19 to 31 years – 3 females/6 males – Recruitment from local concussion clinics and community.	NR	– Blunt, isolated TBI, posttraumatic amnesia, and a Glasgow Coma Scale score of 13 to 15 at time of injury.	– Pregnancy – A history of neurological or psychiatric diagnosis – A history of seizure (before the injury) – A history of drug or alcohol abuse

(Continued)

TABLE 1 | Continued

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
Maruta et al. (2016)	33 Chronic post-mTBI symptoms – Aged 34.9 ± 14.0 years 16 male, 17 female – 1.6 years since injury (range 4 months to 4.5 years) 140 Healthy Controls – Aged 36.6 ± 10.6 years 67 male, 73 female – Recruitment from health professional, university and community. Also, Brain Trauma Foundation website and newsletters from local brain injury organizations.	NR	– Males and females – At least 12 years of education – Aged 18 to 55 years old mTBI specific: – persistent problems believed to result from an isolated concussive head injury that occurred between 90 days and 5 years prior to the date of neurocognitive testing – Documented medical attention at the time of injury; PTA at the time of injury – A complete BISQ – If an LOC occurred, it did not exceed 24 h in the period following the injury. Control specific: – Have had a T-score <75 on the CAARS-S:S – A score <16 on the CES-D – A negative BISQ outcome	– A history of gross vision or hearing problems – A history of a substance abuse – A history of a neurological or psychiatric disorder – General anesthesia within the 14 days prior to neurocognitive testing – Current use of a psychotropic medication – Current pregnancy. Control specific: – Any history of a confirmed concussive head injury or BISQ-identified injury was exclusionary mTBI specific: – A history of prior concussive head injury was exclusionary only if it resulted in an emergency department visit that required conventional neuroimaging – Seizures – Other medical problems
Maruta et al. (2017)	43 Chronic post-mTBI symptoms – 22 female/21 male 5 Acute mTBI – 3 female/2 male 140 Healthy Controls – 74 female/66 male – Recruitment NR	NR	Chronic mTBI specific; – Persistent symptoms following an mTBI that occurred 90 days to 5 years before date of testing – Had post-traumatic amnesia at the time of injury – Had a loss of consciousness not exceeding 24 h in the period following the injury Acute mTBI specific; – Within 2 weeks post-injury All Subjects; – Aged 18 to 55 years old – At least 12 years of education	– Pregnant – History of drug or alcohol abuse – Neurological or psychiatric illness, or seizure.
Maruta et al. (2018)	29 mTBI – Aged 18.4 ± 2.3 years – 14 female/15 male – 5.3 ± 3.3 Days since injury – 2.8 ± 2.5 months after baseline testing 1,442 baseline tested – Recruitment from local school, university and community athletic organizations	– A diagnosis by a physician was not required. Prospective acute post-concussion enrolment was based on inclusion criteria consisting of an experience within 2 weeks of a concussion that resulted in loss of consciousness, post-traumatic amnesia, dizziness, nausea, headaches, balance problems, blurred or double vision, or daze and confusion, and on an exclusion criterion of intoxication at the time of injury.	– Participation in organized competitive athletic activity – Aged 12–30 years – Normal or corrected to normal vision, For athletes over the age 18: – A high school diploma or equivalent, or expected timely high school graduation	– A prior history of traumatic brain injury (including concussion) – Alcohol or substance abuse – A known neurologic disorder, – A psychiatric condition previously known or identified using questionnaires for attention deficit hyperactivity disorder – Depression – Anxiety disorders – A known vision-related disease or abnormality

(Continued)

TABLE 1 | Continued

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
Murray et al. (2014)	9 mTBI – Aged 16.0 ± 3.0 years – 7 female/2 male 9 Healthy controls – Aged 24.3 ±7.5 years – 6 female/3 male – Recruitment from concussion management clinics	– Diagnosed by athletic trainer or physician	– Tested 48-72 h post injury	– Abnormal behavior (expressed by an extreme emotional state) – Excessive neurological symptoms (indication of a traumatic brain injury) – The inability to safely conduct the experiment due to major bodily injury such as lacerations, bone fractures or the like
Murray et al. (2017)	10 mTBI – Aged 18.9 years – 4 female/6 male 10 Healthy Controls – Aged 18.3 years – 4 female/6 male – Recruitment from unspecified athletic population	– Diagnosed by an athletic trainer or physician	– Tested within 48 h post injury Control Specific: – Tested prior to the beginning of their respective athletic season.	– Free of any musculoskeletal and/or neuromuscular injury beyond the documented concussion injury – Had no history of psychiatric illness, Attention Deficit Hyperactivity Disorder and/or seizures – Had no documented concussion within the past 6 months as determined by self-report
Stuart et al. (2019b)	10 mTBI – Aged 30.1 ± 12.8 years – 8 female/2 male – 39.5 ± 21.7 Days since injury 10 Healthy Controls – Aged 26.3 ± 5.2 years – 8 female/2 male – Recruitment NR	– Diagnosed by a physician – Defined with following criteria "no CT scan (or a normal CT scan if obtained), no loss of consciousness exceeding 30 min, no alteration of consciousness/mental state up to 24 h post-injury, and no post-traumatic amnesia that exceeded one day"	– A diagnosis of mTBI within 12 weeks; the mechanism of injury was not be restricted, so may include whiplash if subjects passed a cervical screen. – Aged between 18–60 years old. – SCAT5 symptom evaluation sub–score ≥1 for balance, dizziness nausea, headache or vision AND a minimum total score of 15. – No or minimal cognitive impairment having ≤9 on the Short Blessed Test	– Other musculoskeletal, neurological, or sensory deficits that could explain dysfunction – Moderate to severe substance-use disorder within the past month (American Psychiatric Association 2013) – Severe pain during an initial clinical evaluation ≥7/10 subjective rating) – Current pregnancy – Unable to abstain from medications that might impair balance 24 h before testing – Contraindications to rehabilitation such as unstable c-spine – Active participation in physical therapy for their concussion, however participants could be undertaking other forms of treatment for their symptoms such as massage, acupuncture, and counseling
Suh et al. (2006)	20 Chronic mTBI – Aged 38.0 ± 11.2 years – 6 weeks–24 months post injury 6 Acute mTBI – Aged 34.2 ± 14.3 years – 8–12 Days post injury 26 Healthy Controls – Aged 30.9 ± 13.0 years – Recruitment NR	– Glasgow Coma Scale (GCS) score 13–15 at time of injury – Aged 18–60 years	– Blunt, isolated TBI – Post-traumatic amnesia (PTA) – Non-intoxication – Normal of corrected to normal vision Chronic mTBI specific; – Within 2 years post injury Acute mTBI specific; – Within 14 days post injury Control specific; – No prior history of TBI	– Multiple TBI with loss of consciousness (LOC), – Pregnancy – Drug or alcohol abuse – Neurological or psychiatric diagnosis, or seizures – General anesthesia within two weeks following trauma

(Continued)

TABLE 1 | Continued

References	Participants	mTBI diagnosis or definition	Inclusion criteria	Exclusion criteria
Webb et al. (2018)	15 mTBI – Aged range 21–26 years – 4 female/11 male – Within 2–6 days since injury 15 Healthy Controls – Age and sex matched to mTBI group	– Clinical judgement of physician and physician assistant – SCAT 3 score	– Right handed – Normal or corrected to normal vision	Control specific – Previous or current diagnosis of a neurological or neuropsychiatric deficit (including a mTBI), attention deficit hyperactivity disorder, or a documented learning impairment – Same criteria for mTBI group, except current mTBI diagnosis – History of self-reported previous mTBI
Wetzel et al. (2018)	71 Chronic post-mTBI symptoms – Aged 33.0 ± 7.0 – 1 female/70 male – 28% had injury 3 months to 1 year before study 75 Healthy controls – Aged 39.0 ± 13.0 – 17 female/58 male – Recruitment from military and community	NR	– Aged 18 to 65 years old – Persistent symptoms following an mTBI 3 months to 5 years prior to testing – Head injury caused by non-penetrating trauma or blast exposure; and resulted in a period of loss of, or a decreased level of, consciousness (up to 30 min), a loss of memory for events immediately before or after the injury (up to 24 h), or alteration in mental state at the time of the injury (becoming dazed or confused)	mTBI specific; – Individuals with contraindications to hyperbaric pressurization and HBO2, conditions that might confound outcome measures such as refractive eye surgery within 90 days prior to enrolment, or life experiences that might expose study blinding Control specific; – Known history of brain injury – Diagnosis of neurologic disorders – Active therapy for affective disorder – Behavioral disorder – Psychologic disorders – Diabetes – Chronic migraines – Headaches – Dizziness – History of combat – Post-traumatic stress disorder (PTSD) – Prescription drug use known to impact neurologic function – Atrial septal defects – Developmental delays – Habitual use of cannabis or history of illicit drug or alcohol abuse – Binocular vision not correctable to 20/50 – Deafness – Active malignancy.

NR, Not Reported; EOG, Electro-oculography; mTBI: mild Traumatic Brain Injury; TBI, traumatic brain injury; HC, Healthy control; Data are presented as means ± standard deviation unless otherwise stated.

TABLE 2 | Study Protocol, eye movement instrument, outcome measures, and definitions.

References	Test protocol	Eye movement instrument	Eye movement outcome measures	Eye movement outcome definition
Balaban et al. (2016)	Static/seated	I-Portal Neuro Otologic Test Center (Neuro kinetics Inc.) – 100 Hz – Infra-red – Binocular	– Saccades – Random saccades – Anti-saccades – Predictive saccades – Self-paced saccades – Smooth Pursuit – Optokinetic Nystagmus – Gaze horizontal	NR
Cifu et al. (2015)	Static/seated	Eyelink II (SR Research) – 500 Hz – Binocular – 3 point calibration	– Saccades – Fixation – Smooth Pursuit	Saccade – Amplitude >0.1° – Velocity >20°/s – Acceleration >400°/s^2 Fixation – When eye relatively stable – Low velocity – Low acceleration – No Directional trend Smooth Pursuit – Movement failed to meet saccadic inclusion criteria – Velocity greater than a fixation – Acceleration less than a saccade – Velocity and direction of eye movement closely matches target
Cochrane et al. (2019)	Static/seated	I-Portal Neuro Otologic Test Center chair system (Neuro Kinetics Inc.) – Binocular – 100 Hz – Infra-red	– Saccades – Smooth Pursuit – Optokinetic Nystagmus	NR
Contreras et al. (2011)	Static/seated	Eyelink II (SR Research) – 500 Hz – Binocular – Infra-red – 9 point calibration	Smooth Pursuit	Saccade – Velocity >29°/s – Acceleration >573°/s^2 – Duration 20–240 ms Smooth Pursuit – Saccades removed
DiCesare et al. (2017)	Static/seated	Tobii X2-60 Eye Tracker (Tobii) – 60 Hz – 5 point calibration	– Saccades – Fixation – Smooth Pursuit	Saccade – Velocity >30°/s Fixation – Velocity <30°/s
Diwakar et al. (2015)	Static/seated	Eyelink 1000 (SR Research) – NR	Smooth Pursuit	Saccade – Velocity >100°/s – Acceleration >1,500°/s^2
Hecimovich et al. (2019)	Static/seated	K-D Eye Tracking System, EyeTech VT3 Mini (EyeTech Digital Systems) – Infrared	– Saccades – Blinks	NR
Hoffer et al. (2017)	Static/seated	I-Portal Neuro Otologic Test Center (Neuro kinetics Inc.) – 100 Hz – Infra-red – Binocular	– Saccades – Random Saccades – Anti-saccades – Predictive saccades – Self-paced saccades – Smooth Pursuit – Optokinetic Nystagmus – Gaze horizontal	NR
Howell et al. (2018)	Static/seated	Eyelink 1000 (SR Research) – 500 Hz – Analyzed with commercial software (Oculogica, Inc.)	– Eye skew – Normalized eye skew – Eye movement variance ratio – Eye distance	NR

(Continued)

TABLE 2 | Continued

References	Test protocol	Eye movement instrument	Eye movement outcome measures	Eye movement outcome definition
Johnson et al. (2015a)	Lying down in MRI machine	ViewPoint Eye-Tracker (Arrington Research, Inc.) – 60 Hz – 16 point calibration – Analyzed with custom MATLAB codes	– Saccades – Anti-saccade – Self-paced saccade – Memory-guided saccade	NR
Johnson et al. (2015b)	Lying down in MRI machine	Viewpoint Eye-tracker MRI compatible eye tracking system (PC-60, Arrington Research, Inc.) – 60 Hz – Integrated into VisuaStim Digital Goggles	– Saccades – Reflexive saccades – Anti-saccades – Memory guided saccades – Self-paced saccades – Smooth Pursuit – Fixation	NR
Kelly et al. (2019)	Static/seated	Video Nystagmograph (VNG) (I-Portal) – 100 Hz	– Smooth Pursuit – Saccades – Predictive saccades – Anti-saccades – Optokinetic Nystagmus	NR
Maruta et al. (2010b)	Static/seated	Eye link II (SR Research) – 500 Hz – 9 point calibration – Analysis with custom MATLAB algorithms	Smooth Pursuit	Saccade – Velocity >100 °/s – Acceleration $>1{,}500$ °/s^2 Smooth Pursuit – Saccadic intrusions identified and removed (e.g., blinks)
Maruta et al. (2016)	Static/seated	Eyelink 1000 (SR Research) – NR; referred to previous methods	Smooth Pursuit	NR
Maruta et al. (2017)	Static/seated	Eyelink CL (SR Research) – NR; referred to previous methods	Smooth Pursuit	Smooth Pursuit – Saccadic intrusions identified and removed (e.g., blinks)
Maruta et al. (2018)	Static/seated	Eyelink 1000 (SR Research) – NR	Smooth Pursuit	Smooth Pursuit – Saccadic intrusions identified and removed (e.g., blinks)
Murray et al. (2014)	Dynamic/Standing	ASL Eye Tracking system (model H6, Applied Science Laboratories) – 120 Hz – Tethered system – Monocular (left eye only) – 9 point calibration	Gaze stabilization	NR
Murray et al. (2017)	Dynamic/Standing	ASL Eye Tracking system (model H7, Applied Science Laboratories) – 240 Hz – Tethered system – Monocular (left eye only)	Saccades	Fixation – 25 consecutive frames (gaze points)
Stuart et al. (2019b)	Dynamic/Walking	Tobii Pro Glasses 2 (Tobii Technology, Inc.) – 100 Hz – Head-mounted and mobile – Binocular – Analyzed using custom MATLAB algorithm – 1 point calibration	Saccades	Saccade – Velocity >240°/s – Acceleration $>3{,}000$ °/s^2 – Duration <100 ms – Distance >5° – Blinks identified and removed Fixation – Velocity <240 °/s – Acceleration $<3{,}000$ °/s^2 Duration – >100 ms
Suh et al. (2006)	Static/seated	Eyelink II – 500 Hz – Infrared – 9 point calibration	Smooth Pursuit	Saccade – Velocity >40°/s Smooth Pursuit – Saccades identified and removed

(Continued)

TABLE 2 | Continued

References	Test protocol	Eye movement instrument	Eye movement outcome measures	Eye movement outcome definition
Webb et al. (2018)	Static/seated	Eye-Trac6 (Applied Sciences Laboratories) – 360 Hz – 9 point calibration performed twice – Left eye only – Video-based eye-tracker	– Anti-saccades – Pro-saccades	Saccade – Velocity $>30°/s$ – Acceleration $>8{,}000°/s^2$ – Duration <42 ms
Wetzel et al. (2018)	Static/seated	Eyelink 1000 (SR Research) – 9 point calibration – 500 Hz	– Saccades – Self-paced saccades (reading) – Memory guided saccades – Anti-saccades – Smooth Pursuit – Fixation	Saccade – Velocity $>20°/s$ – Acceleration $>400°/s^2$ – Distance $>0.1°$ Smooth Pursuit – Velocity $>30°/s$ – Acceleration $>2{,}000°/s^2$

NR denotes not reported, mTBI, mild traumatic brain injury, s, seconds.

Outcome Measures

Reviewed studies provided outcomes on saccadic ($n = 12$), fixation ($n = 3$), smooth pursuit ($n = 13$), and nystagmus ($n = 4$) eye movements, and there were a plethora of outcomes reported for these eye movements (**Table 2**, **Supplementary Table 1**). However, the majority of the reviewed studies did not define their eye movement classifications (i.e., no thresholds or criteria for eye movement detection and measurement). Several studies (Maruta et al., 2010b; Contreras et al., 2011; Cifu et al., 2015; Diwakar et al., 2015; DiCesare et al., 2017; Wetzel et al., 2018; Stuart et al., 2019b) did provide some details regarding definitions but these substantially varied between the studies (**Table 2**, **Supplementary Table 1**). Three studies provided no outcomes specific to traditional eye movements (Suh et al., 2006; Murray et al., 2014; Howell et al., 2018), but instead reported on novel outcomes of "Gaze Stabilization" (a fixation measure), "Eye Skew" (an asymmetry measure), and "Oculomotor error" (a smooth pursuit measure) that authors developed for their individual studies. Overall, reporting of possible eye movement outcomes from the eye-tracking devices substantially varied between studies.

Interpretation of Outcomes

Eye movements (saccades, smooth pursuits, fixations etc.) were generally impaired in mTBI compared to controls or baseline tests, regardless of acute or chronic mTBI status (**Table 3**). Yet, the influence of mTBI on specific outcomes was inconsistent. For example, several studies found deficits in saccades in people with mTBI during anti-saccadic tests (Johnson et al., 2015a,b; Balaban et al., 2016; DiCesare et al., 2017; Hoffer et al., 2017; Murray et al., 2017; Webb et al., 2018), whereas others found no differences (Wetzel et al., 2018; Cochrane et al., 2019; Kelly et al., 2019). Studies that did not find differences, however, may have been impacted by methodological issues, such as grouping all stages of mTBI together (acute/sub-acute and chronic) to make a larger cohort (Wetzel et al., 2018; Kelly et al., 2019), which limits comparison and understanding of potential deficits at different stages.

Other notable methodological limitations were found in the reviewed studies that may impact outcome interpretation. Studies examined the same eye movements but with slightly different protocols. For example, smooth pursuits were examined with a range of frequencies (0.1–1.25 Hz) and the visual stimulus (e.g., colored dots or shapes on a computer or LED board) used for eye movement tasks varied across all studies (**Table 2**). Although studies reported eye movement outcomes and discussed the relationships between deficits and underlying cognitive or motor impairments due to mTBI, only two studies (Maruta et al., 2010b, 2018) correlated eye movement outcomes with symptoms or other tests for these or other (e.g., age, gender, depression state etc.) relevant features. None of the reviewed articles controlled for the impact of cognition or basic visual function (visual acuity or contrast sensitivity) on eye movements, and only one study (Stuart et al., 2019b) reported basic visual function scores. Many of the studies did not assess cognition and similarly many only reported that they excluded subjects based on visual function (i.e., eye chart screening or self-reported questionnaires) but provided no scores or results to verify this (Suh et al., 2006; DiCesare et al., 2017; Murray et al., 2017; Howell et al., 2018; Webb et al., 2018; Wetzel et al., 2018; Cochrane et al., 2019; Kelly et al., 2019). None of the studies provided any information on the use of corrective eye wear by the participants during the eye-tracking assessments, with several articles reporting that subjects had "normal or corrected to normal vision," but it was unclear if individuals with vision correction were included in reported results.

Summary of Common Study Features

In order to refine the information provided in our detailed tables (**Tables 1**, **2**) a brief overview of the most common features of the reviewed studies is presented below;

- The majority of the reviewed studies that provided mTBI diagnostic criteria involved a clinician with experience of sports injuries.

TABLE 3 | Aims and key findings.

References	Aims	Key findings
Balaban et al. (2016)	Examine oculomotor, vestibular and reaction time reflexes to diagnose mTBI compared to controls.	**Saccades impaired in mTBI** • Increased pro-saccade error rate in mTBI compared to controls • Predictive saccades had significant impairment in mTBI compared to controls, with impaired performance and increased saccadic reaction time latency
Cifu et al. (2015)	Differentiate those with self-reported chronic effects of mTBI from controls	**Saccades and smooth pursuits impaired in mTBI** • Saccades and smooth pursuit eye movements were impaired in mTBI compared with controls • Compared with controls people with mTBI had larger position errors, smaller saccade amplitudes, smaller predicted peak velocities, smaller peak accelerations and longer durations on step-wise displacement targets • Step-wise moving targets were also tracked less accurately and with a smaller primary saccade by those with mTBI compared with controls • Smooth pursuit amplitude was larger and gain was smaller in mTBI compared with controls
Cochrane et al. (2019)	Investigate oculomotor function between mTBI and control college athletes and determine measurement test re-test reliability	**Saccades impaired in mTBI** • Those with mTBI had poor saccadic accuracy and longer response latency compared with controls during horizontal and vertical saccade tasks • No difference between groups during anti-saccade, predictive saccade tasks, or horizontal smooth pursuits • Vertical smooth pursuits were subjectively more difficult for those with mTBI especially at high frequencies • Optokinetic reflex gain was not different between the groups, but 20% of the mTBI subjects were unable to complete due to becoming symptomatic during this test
Contreras et al. (2011)	Investigate the effect of cognitive load on eye-target synchronization in mTBI and controls using non-linear dynamical technique of stochastic phase synchronization	**Smooth pursuits impaired in mTBI** • Horizontal feature of smooth pursuits was not as synchronized in those with mTBI compared with controls • Performing a secondary cognitive task impacted smooth pursuits more in mTBI than controls
DiCesare et al. (2017)	Examined a systematic, automated analysis scheme using various eye-tracking tasks to assess oculomotor function in a cohort of adolescents with acute mTBI symptoms and aged-matched healthy controls	**Fixations and Smooth Pursuits impaired in mTBI** • Greater fixation accuracy error, greater initial fixation error and longer pro-saccade latencies in mTBI compared with controls
Diwakar et al. (2015)	Investigate the neuronal bases for deficient anticipatory control during visual tracking in chronic mTBI patients with persistent symptoms and healthy controls	**Smooth pursuits impaired in mTBI** • Smooth pursuit comparable between groups in continuous tracking condition • In Gap Condition smooth pursuit had larger average radius and had greater negative average phase in mTBI compared with controls • Those with mTBI took longer to respond to target reappearance than controls during gap condition • Time since injury correlated to larger gap average radius in mTBI
Hecimovich et al. (2019)	Determine the diagnostic accuracy of the King-Devick/Eye tracking test in identifying mTBI occurring from game participation and to perform a comparative analysis on saccade and blink counts for each King-Devick card individually and total counts between baseline and post-mTBI	**Saccades impaired in mTBI** • Slower time to completion of task, fewer saccades and more blinks made by those following an mTBI compared with their baseline • Assessment of the number of blinks was most sensitive to mTBI
Hoffer et al. (2017)	Expand previous baseline article findings within several days of injury, through follow-up with further sessions at 7–10 days and 14–17 days. Examine oculomotor, vestibular and reaction time measures to monitor progression of mTBI over the acute and early sub-acute period of time.	**Saccades, smooth pursuits and optokinetic nystagmus impaired in mTBI** • Predictive saccade response differentiated mTBI from controls and was useful to monitor recovery • Pro-saccade performance error rate differentiated mTBI from controls and was useful to monitor recovery • Constant velocity optokinetic nystagmus slow phase gain symmetry for 20°/s stimulation differentiated mTBI from controls and was useful to monitor recovery • Horizontal smooth pursuit absolute velocity gain symmetry differentiated mTBI from controls and was useful to monitor recovery
Howell et al. (2018)	Evaluate objective eye tracking measures among child and adolescent athletes who sustained a mTBI within 10 days of examination and a group of healthy controls	**Eye skew (asymmetry) impaired in mTBI** • Right normalized eye skew along the bottom of the box was greater in those with mTBI compared with controls

(Continued)

TABLE 3 | Continued

References	Aims	Key findings
Johnson et al. (2015a)	To expand on our previous study by performing a follow-up testing session in the subacute phase of injury for participants recently diagnosed with a mTBI	**Saccades impaired in mTBI** • Longer anti-saccade latencies, greater directional and positional errors, and larger gain in both acute and sub-acute mTBI compared with controls • Average number of self-paced saccades reduced in acute and sub-acute mTBI • Larger primary saccade gain and directional error of memory guided saccades in acute and sub-acute mTBI compared with controls • Some eye movement deficits improved in mTBI from the acute to sub-acute phases of injury
Johnson et al. (2015b)	Examine fMRI in conjunction with a battery of oculomotor tests to simultaneously assess both brain function and eye movements in the acute phase of injury ($<$7 days post injury) following mTBI	**Saccades impaired in mTBI** • Shorter pro-saccadic error latency, greater anti-saccadic directional and positional errors, and larger anti-saccadic gain in mTBI compared with controls • Average number of self-paced saccades reduced in mTBI • Greater positional error and gain of memory guided saccades in mTBI compared with controls
Kelly et al. (2019)	Test the ability of oculomotor, vestibular, and reaction time (OVRT) metrics to serve as a concussion assessment or diagnostic tool for general clinical use	**Saccades, smooth pursuits and optokinetic nystagmus impaired in mTBI** • Initiation latency was longer for horizontal smooth pursuits at 0.75 and 1.25 Hz, and for vertical pursuits at 0.5 and 0.75 Hz in mTBI compared with controls • Reduced position and velocity gain in horizontal pursuits at 1.25 Hz in mTBI compared with controls • No group difference in random horizontal or vertical saccades, or anti-saccadic, or predictive saccade tests • Percentage of saccade velocities below a normative velocity threshold was higher in mTBI compared with controls during simple reaction time task • Horizontal optokinetic nystagmus response (gain/velocity of slow-phase nystagmus) was reduced in mTBI compared with controls • During high-speed optokinetic nystagmus test; more nystagmus gain asymmetry and higher variability of gain velocity in mTBI than controls • Fast-phase nystagmus area reduced in mTBI compared with controls
Maruta et al. (2010b)	Determine whether performance variability during predictive visual tracking can provide a screening measure for mTBI	**Smooth Pursuit impaired in mTBI** • Poorer visual tracking than controls in mTBI, with large saccadic intrusions and low-velocity gains • Variability measures were correlated with a number of neuroimaging measures. • Smooth pursuit radial and tangential error variability correlated with frontal white matter track integrity and cognitive function in mTBI and controls • Gaze error variability correlated with attention and working memory measures
Maruta et al. (2016)	Characterize cognitive deficits of adult patients who had persistent symptoms after a mTBI and determine whether the original injury retains associations with these deficits after accounting for the developed symptoms that overlap with post-traumatic stress disorder and depression	**Smooth Pursuit impaired in mTBI** Increased smooth pursuit gaze position error variability in mTBI compared with controls after an attention demanding task
Maruta et al. (2017)	Characterize and compare frequency-dependent smooth pursuit velocity degradation in normal subjects and patients who had chronic post mTBI symptoms, and also examine cases of acute mTBI patients	**Smooth pursuit impaired in mTBI** • Reduced horizontal smooth pursuit gain at 0.4 Hz in chronic mTBI compared with controls • No significant difference in smooth pursuit gain at 0.33 or 0.67 Hz in acute and chronic mTBI and controls
Maruta et al. (2018)	Assess changes between pre- and within-2-week post-mTBI performances and explore their relationships to post-mTBI symptomatology	**Smooth pursuit impaired in mTBI** • Horizontal smooth pursuit gain was reduced from baseline following an mTBI • Changes in smooth pursuits with mTBI related to cognition, specifically memory-attention, and physical symptoms
Murray et al. (2014)	Measure the differences in oculomotor control between athletes post mTBI and athletes without concussion during an active balance control task	**Gaze control impaired in mTBI** • Greater gaze deviations from center in mTBI compared with controls
Murray et al. (2017)	Investigate and compare gaze stability between a control group of healthy non-injured athletes and a group of athletes with mTBI 24–48 h post-injury	**Saccades impaired in mTBI** • Greater gaze resultant distance, pro-saccadic errors and horizontal velocity in mTBI compared with controls

(Continued)

TABLE 3 | Continued

References	Aims	Key findings
Stuart et al. (2019b)	Validate a velocity-based algorithm for saccade detection in infrared eye-tracking raw data during walking (straight ahead and while turning) in people with mTBI and healthy controls	**Saccades can be measured in mTBI while walking** • Developed algorithm accurately detected and classified saccades while walking and turning in mTBI and controls
Suh et al. (2006)	Examined whether those with mTBI would have impairments in prediction during target blanking, and if deficits in eye movement correlated to cognitive deficits.	**Smooth pursuits impaired in mTBI** • Time to first saccade was shorter and intra-individual variability was greater in mTBI compared to controls • Those with mTBI had more ocular motor errors before and during blanking than controls • Ocular motor error variability was also greater in mTBI compared to controls, particularly during blanking • Cognitive outcomes significantly correlated to smooth pursuit outcomes in mTBI
Webb et al. (2018)	Evaluate pro- and anti-saccades in mTBI at an early stage (<6 days) after their injury and at a follow-up assessment.	**Saccades impaired in mTBI** • Pro-saccadic reaction time and gains were not different between mTBI and controls at initial assessment or follow-up • Pro-saccadic directional errors were significantly different between mTBI and controls • Anti-saccades reaction time longer in mTBI than controls at initial assessment but not at follow-up • Anti-saccadic directional errors were greater and gains were lower in mTBI than controls at initial assessment and follow-up
Wetzel et al. (2018)	To identify which visual tasks and measurement parameters are most sensitive in patients with symptoms following mTBI.	**Saccades, fixations, and smooth pursuits impaired in mTBI** • Shorter inter-saccadic interval duration in mTBI compared with controls • Lower absolute saccadic amplitudes and average forward saccadic amplitudes in mTBI compared with controls • Higher absolute fixation velocity and longer overall fixation duration in mTBI compared with controls • Longer regression durations in mTBI and longer forward saccadic durations • More fixations and regressions per line when reading in mTBI compared with controls • Shorter mean fixation times in mTBI compared with controls • Lower weighted smooth pursuit gains in mTBI compared with controls

TABLE 4 | Recommendations for future research.

Recommendations for future research examining eye-movements in mTBI
• Comprehensively report demographic data including; age, sex, depression, medication use, time since injury • Report study inclusion and exclusion criteria • Stratify mTBI populations based on time since injury; acute, sub-acute, chronic, post-mTBI syndrome • Report recruitment strategy; hospitals, community, athletes, military etc. • Provide a definition of the mTBI diagnosis or criteria • Report details of instrumentation used to record eye-movements, including; sampling frequency, binocular or monocular, calibration procedure, infrared or video based, desk or head-mounted • Report validity and reliability of eye-movement recording instrumentation, data processing algorithms and outcomes • Use an adequately powered sample size or data reduction techniques to appropriately report eye-movement outcomes • Define all eye-movement outcome measures • Report whether corrective lenses were used for testing • Routinely examine and control for cognitive and visual function

- Included participants tended to be free of previous mTBI, musculoskeletal, cognitive, emotional, visual, or neurological issues.
- Eye-tracker sampling frequency of 500 Hz.
- Seated/static testing using computer screens to provide visual stimuli
- The most common eye-tracker metrics were based upon the latency, gain, velocity, duration, or positional error rates of the specific eye movement assessments, with the velocity of eye movements being the most prominent outcome reported across studies.

DISCUSSION

This review examined 22 studies that reported quantified eye movements in healthy controls and mTBI subjects. We reviewed; (i) how eye-movements were measured; (ii) reported eye-movement outcomes and their definitions; and (iii) differences reported between mTBI and controls in eye-movement outcomes. Across all of the reviewed studies there was a lack of basic methodological reporting, as there was little consensus or reporting of participant mTBI classification (acute/sub-acute or chronic), demographic characteristics (age, sex, time since injury etc.) and inclusion or exclusion criteria. This limits the generalizability of results to mTBI populations and influences the reproducibility of the methods and results

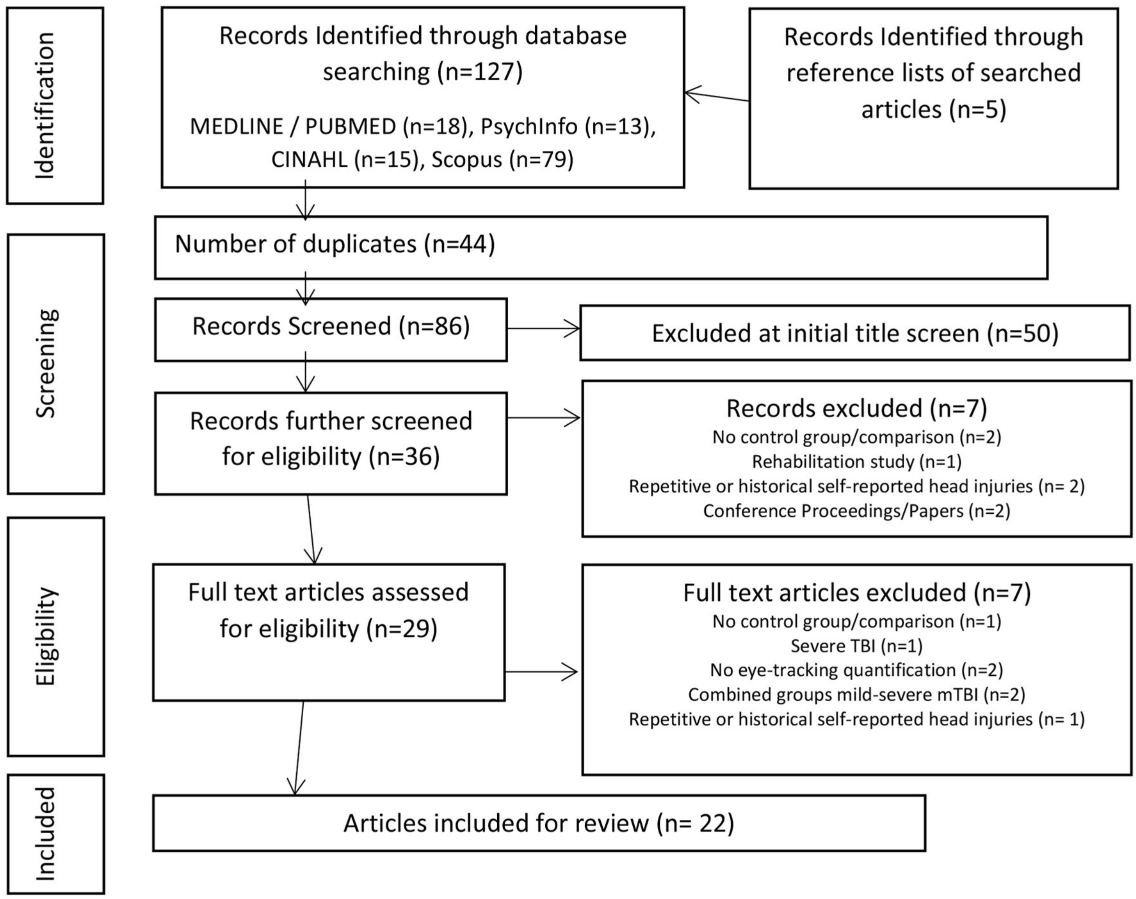

FIGURE 2 | PRISMA flow chart of study design (Adapted from Moher et al., 2009).

of the reviewed studies. Despite these limitations, this review has demonstrated that eye-movement measurement in mTBI is emerging, but further work is required to establish the validity and reliability of instrumentation and methods to derive eye-movement outcomes, as well as the nature of eye-movement impairments in mTBI.

Instruments

There is currently no "gold standard" instrument for eye-movement measurement, which is likely the reason for the numerous different instruments used in the reviewed studies. The majority of studies used static infra-red eye-tracking devices in constrained seated activities (e.g., chin rest in place in front of a computer screen), but several studies did show progression to unconstrained dynamic eye-tracking protocols (Maruta et al., 2010b, 2016; Stuart et al., 2019b). High resolution (>100 Hz) mobile eye-tracking during functional activities (e.g., walking or standing) may provide deeper understanding of the impact that subtle eye-movement deficits may have on those with mTBI.

Within the reviewed studies eye-tracking instrumentation sampling frequency substantially varied, which impacts on instrument validity. For example, accurate saccadic detection requires a minimum of 50 Hz and 200 Hz to accurately measure saccadic durations (Andersson et al., 2010; Leube et al., 2017). However several of the reviewed studies only had high enough sampling frequency (60 Hz) to detect saccades (Andersson et al., 2010) but not to accurately measure all of the reported features (Johnson et al., 2015a,b; DiCesare et al., 2017), which limits understanding of subtle deficits that may be missed as a result.

Importantly, clear evidence of the validity and reliability of instrumentation is essential for confidence in reported outcomes. We found that the reviewed studies did not adequately address this, with no studies reporting the validity or reliability of their instrumentation, and four studies inadequately reporting eye-movement outcome validation. Reporting the validity and reliability of eye-tracking instruments is advocated due to the influences of technological [e.g., parallax and calibration error (Pelz and Canosa, 2001; Nystrom et al., 2013)] and physiological [e.g., head or body movement (Zhu and Ji, 2005; Marx et al., 2012)] factors that can impact measurement. Generally, our review revealed a lack of detail regarding instrument design (e.g., binocular, monocular etc.), calibration procedures, sampling frequencies, control for artifact movement etc. To improve the quality of research in this emerging area, there is a need for reporting of the validity and reliability of instruments used to measure eye-movements in mTBI.

Outcomes

At present there are also no "gold standard" algorithms or definitions for the detection and measurement or reporting of eye-movements (Larsson et al., 2015; Stuart et al., 2019a). This may explain why many of the reviewed studies did not provide definitions for their reported eye-movement outcomes and why reported definitions lacked consensus. As a result, velocity thresholds for saccade detection varied from 20 to 240°/s, with high speeds used for more dynamic tasks (e.g., walking) to rule out the influence of vestibular-ocular reflexes on outcomes. Similarly, eye-movement assessment protocols varied between studies, with different smooth pursuit frequencies, various visual stimuli, overlap or no-overlap designs, different amplitudes of step targets, or speeds and durations of projected dot patterns. The definition of eye-movement outcomes and the protocol used to derive outcomes impacts the generalizability of findings, as valuable information may be discarded or irrelevant data included depending on the thresholds set or the stimulus used. For example, a velocity-based algorithm with a 240°/s threshold will detect saccades over ∼5° (Holmqvist et al., 2011), but below this data would be classified as a fixation. However, depending on the specific aims of the study, this algorithm may not be relevant or may not provide an accurate portrayal of performance. This was evident within the reviewed studies where different frequencies of smooth pursuit examination led to studies not finding deficits in mTBI on the same testing paradigms, such as continuous tracking where Diwakar et al. (2015) found no difference at 0.4 Hz but Kelly et al. (2019) found a difference at 1.25 Hz. Creating a gold-standard for eye-movement outcome detection and measurement reporting is challenging due to the variations in instrumentation and different protocols used. Nonetheless, based on the findings within this review, we feel it is necessary for consensus to be adopted for mTBI literature. Such consensus should include the reporting of eye-movement definitions and use of standardized methods [e.g., internationally recognized anti-saccade protocol Antoniades et al., 2013 or algorithms for comprehensive smooth pursuit evaluation (Larsson et al., 2015)] for examining eye-movements.

Within the reviewed studies there was a wide range of eye-movement outcome measures reported, which highlighted the emerging and exploratory nature of eye-movement measurement in mTBI. The majority of the reviewed studies examined smooth pursuits or saccades, with few studies examining fixation and optokinetic nystagmus eye movement outcomes. Focus on smooth pursuits and saccades is likely due to the large amount of underpinning neural regions involved in performance (Ventura et al., 2016), with saccades and pursuits sharing very similar functional architecture within the central nervous system (Krauzlis, 2004). Fixations and saccades have an intimate relationship, as fixations are the pauses in between saccades (Krauzlis et al., 2017), and similarly smooth pursuits could be classified as fixations as they are pauses on moving objects, which may be the reasons why fixations tended to be overlooked within assessments in mTBI. Alternatively, nystagmus eye movements may not have been examined in many studies due to difficulties in monitoring this type of eye movement with infrared eye-trackers. For example, measurement is influenced by head position (Pettorossi et al., 2011), and electro-oculography is usually used due to accuracy and high sampling frequency requirements (Haslwanter and Clarke, 2010). In addition, stimuli that evoke sustained nystagmus eye movements commonly exacerbate mTBI-related symptoms, with reviewed studies reporting having to stop testing, as a result, which led to reduced cohort sizes for further investigation (Cochrane et al., 2019). Similarly, many of the reviewed studies had small ($n < 30$) mTBI cohorts and as a result the number of outcomes reported may lead to inappropriate statistical analysis or reporting due to the number of performed statistical comparisons (e.g., Type I or II statistical error; von Der Malsburg and Angele, 2017). Similar to other behavioral measures (e.g., gait; Verghese et al., 2007), use of data reduction techniques, such as principle component or factor analysis, in future studies may help to reduce the risk of inappropriate outcome reporting by developing relevant eye-movement domains or factors for further analysis.

Despite the huge number of outcome measures reported, many of the outcomes were reported in a task-dependent manner. For example, static seated eye-movement assessments tended to comprehensively report many outcomes from long testing protocols, whereas dynamic standing or walking tasks tended to report a small number of largely saccadic outcomes (e.g., saccade number, velocity, amplitude; Murray et al., 2014, 2017; Stuart et al., 2019b). This task-dependent reporting of eye-movement outcomes likely stems from the complexity of data processing and analysis with increasingly dynamic tasks (Zhu and Ji, 2005; Stuart et al., 2014b, 2019a). Unlike controlled static seated assessments, dynamic tasks introduce other factors (e.g., head movement, vestibular-ocular reflexes, lighting conditions of testing) that can impact recordings and need to be controlled for as these factors have been demonstrated to influence eye-tracking outcomes (Stuart et al., 2017). Comparison of several studies that reported saccade velocity indicated that there may be task-dependent mTBI impairments. For example, seated studies reported reduced saccadic velocity in mTBI compared to controls (Cifu et al., 2015; Cochrane et al., 2019; Kelly et al., 2019), whereas dynamic studies reported the opposite (i.e., greater saccadic velocity in mTBI; Murray et al., 2017). However, due to the limited number of studies available for review and methodological variations, definitive conclusions cannot currently be drawn. This confirms the need to appropriately quantify eye-movements in mTBI during a range of different tasks to uncover impairments that are relevant to performance of "real-life" activities.

Interpretation of Outcomes

Generally, the reviewed studies showed that saccades, smooth pursuits, fixations and nystagmus were impaired in mTBI compared to controls. However, eye-movement outcome interpretation was complicated by many methodological limitations, particularly the inconsistent or lack of reporting of basic demographic and mTBI-related information (e.g., mTBI diagnosis criteria, time since injury etc.). There is currently no universally accepted definition or diagnostic criteria for mTBI (Carroll et al., 2004; Management of Concussion/mTBI and Working Group, 2009; Mccrory et al., 2017; Eisenberg and Mannix, 2018; Voormolen et al., 2018; Chancellor et al., 2019), which is likely the reason why the majority of studies did not describe the criteria that were met or how/who provided an mTBI diagnosis. However, many of the reviewed studies also provided very little demographic information regarding their participants, with some studies not reporting basic features such as participant sex or specific time since mTBI (e.g., days, weeks, months, or years since injury). Lack of reporting accompanied by variable inclusion and exclusion criteria between studies makes the generalization across the literature difficult, and may explain some of the conflicting reports of specific eye-movement deficits (i.e., reports of anti-saccadic impairment was variable). Lack of a standardized mTBI diagnosis criteria and reporting of basic features makes interpretation of outcomes complex (King, 2019), therefore studies should report these features as fully as possible to aid understanding.

There were a vast number of outcomes being recorded and reported, which ranged from relatively standard (e.g., pro-saccades, anti-saccades, smooth pursuits etc.) to novel [e.g., eye skew (Howell et al., 2018), gaze stabilization (Murray et al., 2014), oculomotor error (Suh et al., 2006)] outcomes. Development and application of novel eye-movement outcomes may allow deficits to be uncovered that may otherwise not be found (Harezlak and Kasprowski, 2018). However, the lack of reporting on novel outcome validation and data processing in the reviewed studies limits the generalizability of results and does not allow replication in other cohorts. Our findings suggest that validity and reliability assessment of novel outcome measures should be reported alongside standardized eye-movement outcomes from traditional testing batteries, which would situate novel outcomes in the context of traditional measures to aid interpretation.

We were surprised that only two studies (Maruta et al., 2010b, 2018) assessed for cognitive function and only one study reported data on visual function (Stuart et al., 2019b), with other studies only reporting that participants had "normal or corrected to normal vision" (Suh et al., 2006; DiCesare et al., 2017; Murray et al., 2017; Howell et al., 2018; Webb et al., 2018; Wetzel et al., 2018; Cochrane et al., 2019; Kelly et al., 2019). Eye-movements are underpinned by cognitive processes (Hutton, 2008; Mele and Federici, 2012), even from an early stage before the automatic bottom-up cascade of visual processing occurs (Baluch and Itti, 2011). Cognitive function was shown to relate to eye-movement performance in mTBI in several reviewed studies (Suh et al., 2006; Maruta et al., 2010b, 2018), with cognitive deficits leading to abnormal performance on quantified eye-movement examinations. Eye-movements may therefore be a proxy for cognitive function in mTBI, but without assessment and controlling for cognitive function within eye-movement analysis these links may be missed (Stuart et al., 2014a). Similarly, impairments in basic visual functions, such as visual acuity and contrast sensitivity, have been found to lead to abnormal eye-movement performance (Williams et al., 1995; Gottlob et al., 1996; Palidis et al., 2017). Visual acuity deficits can be corrected with prescription glasses or contact lenses (Sloan, 1951), however the reviewed studies provided no details regarding whether participants used visual correction during testing. This is important as visual correction, through glasses and contact lenses, can impact infrared eye-tracking due to the refraction of infrared light that is used to detect the location of the participants pupil, which would lead to inaccurate tracking and lost data collection ability (Stuart et al., 2014b, 2016; Fuhl et al., 2016). Age (Munoz et al., 1998), depression (Emslie et al., 1990), and medication use [e.g., opioids (Grace et al., 2010)] have also been implicated in eye-movement performance in various populations. Therefore, the measurement and reporting of basic demographic features, cognitive and visual function is required when investigating eye-movements in mTBI.

Test Protocols

Previous eye-tracking studies have generally involved static seated eye-movement assessment tasks (Pelz and Canosa, 2001; Maruta et al., 2010a), which have provided valuable information regarding potential deficits in mTBI compared to controls. However, while these experiments allow for complete experimental control, they lack functional validity because eye-movements in the real-world are goal-oriented (Salverda et al., 2011) and often occur during co-ordination of multiple motor, cognitive and visual processes (Hayhoe et al., 2003; Hayhoe and Ballard, 2005; Ventura et al., 2016). Although we found that segmentation of individual eye-movement features revealed some eye-movement impairments in mTBI, inconsistencies in reported deficits may be due to compensatory mechanisms (i.e., using additional attentional resources to improve performance of eye-movement tasks) similar to those found in aging research (Wiegand et al., 2014). Whereas, when individuals are required to complete complex real-world tasks (e.g., walking, turning, balancing etc.), that simultaneously involve motor, cognitive and visual processes, deficits may become prominent as they may be unable to compensate, consistent with results from the dual-task literature in mTBI (Cicerone, 1996; Howell et al., 2013). Future studies should therefore robustly examine eye-movements within mTBI during a range of static and dynamic tasks to further understand the functional impact of deficits.

Many previous studies of eye-movements in mTBI have incorporated subjective, clinical assessments that can be performed is any environment, such as the VOMS (Mucha et al., 2014) or King-Devick reading test (Leong et al., 2015; Galetta et al., 2016; Walsh et al., 2016). These clinical tests provide valuable information concerning the aggravation of mTBI-related symptoms when performing eye-movements (Capó-Aponte et al., 2018), but provide limited quantifiable information to measure deficits or monitor recovery. These subjective or symptom-based eye-movement examinations provide only global performance measures and symptom scores following an mTBI, but results cannot highlight subtle changes in performance and may be limited due to the reliance on self-report by those with mTBI (Lovell et al., 2002; Heitger et al., 2007). In contrast, the 22 studies included in this review examined eye-movements using quantitative eye-tracking technology that can provide information related to subtle changes in eye-movements, and link them to specific mechanisms behind impairments through experimental manipulation. Future adoption of quantitative eye-tracking technologies within clinical practice will allow eye-movement examination to become standardized and may detect deficits that could be missed with traditional clinical techniques.

CONCLUSION

Aspects of eye-movements are impaired following an mTBI, as demonstrated by the reviewed studies that quantified impairments in either saccadic, smooth pursuit, fixation or nystagmus eye movements. While there is evidence from these studies, it is not yet strong enough to adopt quantitative eye-movement assessment within clinical practice. This review has highlighted that methodological issues across the current literature limit the understanding and generalizability of the reported findings in mTBI. There is a need for consensus on methods used and reporting of eye movement data, including eye-movement instruments, data collection procedures, processing algorithms and analysis methods are required. Comprehensive reporting of demographics, mTBI-related features, and confounding variables are also recommended for future work in this area (**Table 4**). Development and implementation of a standardized approach to quantitative eye-movement examination will ensure accurate and appropriate data interpretation. This will allow robust evidence to be established that can be implemented in future clinical practice.

AUTHOR CONTRIBUTIONS

SS wrote the first draft and revisions of the manuscript. SS, LP, and DM designed the search strategy and conducted the literature search. SS and LK designed, implemented, and oversaw the topic area. SS, LP, DM, RP, JC, and LK were involved in interpretation of the data, writing the manuscript and revisions, final approval of the version to be published, and agree to be accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2020.00005/full#supplementary-material

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Eye and Head Movements of Elite Baseball Players in Real Batting

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In baseball, batters swing in response to a ball moving at high speed within a limited amount of time—about 0. 5 s. In order to make such movement possible, quick and accurate trajectory prediction followed by accurate swing motion with optimal body-eye coordination is considered essential, but the mechanisms involved are not clearly understood. The present study aims to clarify the strategies of eye and head movements adopted by elite baseball batters in actual game situations. In our experiment, six current professional baseball batters faced former professional baseball pitchers in a scenario close to a real game (i.e., without the batters informed about pitch type in advance). We measured eye movements with a wearable eye-tracker and head movements and bat trajectories with an optical motion capture system while the batters hit. In the eye movement measurements, contrary to previous studies, we found distinctive predictive saccades directed toward the predicted trajectory, of which the first saccades were initiated approximately 80–220 ms before impact for all participants. Predictive saccades were initiated significantly later when batters knew the types of pitch in advance compared to when they did not. We also found that the best three batters started predictive saccades significantly later and tended to have fewer gaze-ball errors than the other three batters. This result suggests that top batters spend slightly more time obtaining visual information by delaying the initiation of saccades. Furthermore, although all batters showed positive correlations between bat location and head direction at the time of impact, the better batters showed no correlation between bat location and gaze direction at that time. These results raise the possibility of differences in the coding process for the location of bat-ball contact; namely, that top batters might utilize head direction to encode impact locations.

Keywords: baseball batting, eye movements, hand-eye coordination, head movements, predictive saccades

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INTRODUCTION

When we intercept or hit a moving object, we have to estimate its trajectory and initiate action corresponding to the appropriate position and timing. Baseball batting is one of the most difficult interception tasks that humans can perform. In baseball, the pitcher throws a ball toward the home plate, which is about 18 m away, and the batter hits the ball passing through the home plate with a bat (**Figure 1A**). When the pitcher throws the ball at 160 km/h, the time from ball-release to bat-ball contact is <400 ms (**Figure 1B**). The angular velocity of the ball exceeds 800 deg/s (**Figure 1C**), so it is presumably impossible to track the ball during its entire flight. Within that period, the batter has to estimate the ball trajectory and generate swing motion with accurate

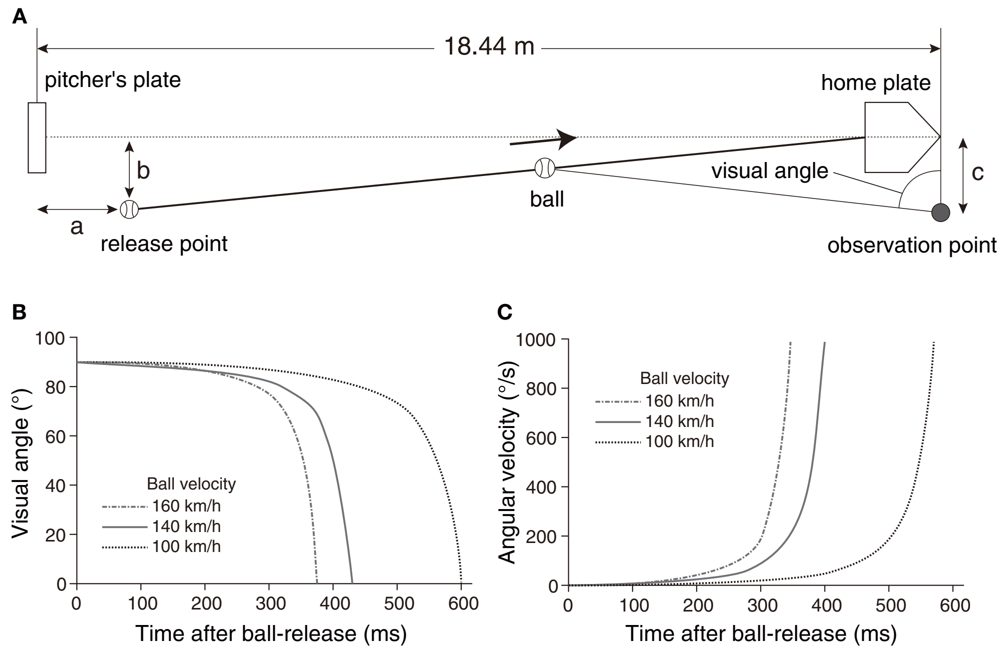

FIGURE 1 | (A) Geometric relationship around a pitcher and a batter. The pitcher releases the ball at a release point toward the home plate, and the player looks at the ball from the observation point. The parameters a = 1.8 m, b = 1.0 m, and c = 1.0 m were used for the simulation on ball trajectories. **(B)** Simulation results of visual angle of the ball from the observation point with different ball velocities (100, 140, 160 km/h). **(C)** Simulation results of angular velocities of the ball from the observation point with different ball velocities (100, 140, 160 km/h).

spatial and temporal bat controls. Moreover, since the batter is also required to adjust to many types of pitch (fastball, breaking ball, changeup, etc.), it is more difficult to predict the trajectory of the ball in an actual game. As a result, even most professional league batters do not reach the batting average of 30%. However, some batters (though only a limited number) leave a batting average of 30% or more every year. Here, focusing on the visual strategy of professional baseball players, we attempted to figure out whether there are differences in the strategy between highly elite players and other elite players.

Gaze movement strategies are known to vary depending on the type of hitting sport. In baseball, Fogt and Zimmerman (2014) measured eye movement and head rotation when a baseball batter sees a thrown ball (without a swing) and found that batters track the ball mainly using head rotation rather than eye movement. A recent study by Higuchi et al. (2018) showed similar results, even when batters actually hit the ball thrown by a pitching machine. In contrast, in cricket, where batters hit the ball after it has bounced on the ground, the batters continuously track the ball in the fovea for a while after the ball is released and then make a predictive saccade toward the area where the ball will bounce (Land and McLeod, 2000; Croft et al., 2010; Mann et al., 2013). Predictive saccades have also been observed in other hitting sports where ball bounces occur, such as tennis (Williams et al., 1998), table tennis (Ripoll et al., 1986; Land and Furneaux, 1997), and squash (Hayhoe et al., 2012). Thus, the role of the predicted saccade is considered to facilitate tracking of the ball after bouncing by looking at the predicted ball-bounce location, which has more information directly related to performance.

Previous studies have shown that gaze movement strategies are related to hitting and interception performance. Land and McLeod (2000) revealed that cricket batters utilize a predictive saccade toward the future ball-bounce position, and better batters initiate a predictive saccade earlier and track the ball more precisely. Mann et al. (2013) reported that elite cricket batters show an exquisite head-ball coupling movement that keeps the ball direction from the head constant. Bahill and LaRitz (1984) measured eye and head movements when baseball batters faced a physically simulated ball without swinging and showed that the batter followed the ball using both smooth pursuit eye movements and head rotation, where professional batters had better tracking ability than amateur batters. Furthermore, in laboratory studies, the accuracy of smooth pursuit eye movement has been shown to be positively correlated with perceptual localization (Spering et al., 2011) and manual interception of moving targets (Fooken et al., 2016).

Although many studies have been done on gaze movement strategies in hitting sports, there has been little focus on elite batters in real batting situations, especially in baseball. Elite batters may present an ideal strategy to underpin performance in a strict environment close to the actual game. Moreover, the factors behind what it takes to be an outstanding batter (vs. a good batter) remain unclear. Considering these points, we measured the eye and head movements of two groups of professional baseball batters (top league and farm league), including a scenario close to the actual game; batters are not announced the pitch type in advance. We expected that the presence or absence of prior information about pitch types may affect gaze movement strategies, considering the finding that eye movements are influenced by the predictability of the target trajectory (Findlay, 1981; Kowler et al., 1984; Becker and Fuchs, 1985; Shelhamer and Joiner, 2003). The presence or absence of prior pitch information could reveal differences in skill levels that would not be apparent in a simple predictable ball trajectory.

METHODS

Participants

Six professional baseball field players from Nippon Professional Baseball (NPB), the top baseball league in Japan, took part in the off-season. Three participants belonged to top teams (Top 1–3: $M = 26.7$ years) and the other three to farm teams (Farm 1–3: $M = 24.7$ years) in the most recent season. Only Farm 2 was a right-handed batter, and the others were all left-handed. The level difference between the top group and the farm group was distinctive. The top group players had more than 40 at-bats in the top league games, and the farm group players never played as batters in the top league games in the previous season. NPB players can be considered highly elite, even if they belong to the farm league. Baseball is one of the most popular sports in Japan, which ranks top in the World Baseball Softball Confederation ranking in 2019. The number of NPB players, including the top league and farm league, is only about 800. All the participants provided written informed consent prior to the experiments. This study was approved by the Ethics and Safety Committees of NTT Communication Science Laboratories and were in accordance with the Declaration of Helsinki.

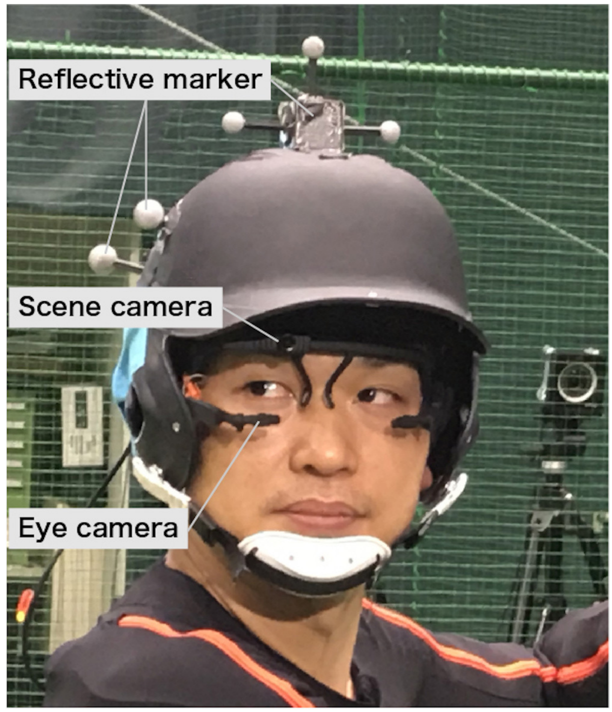

FIGURE 2 | Participant wearing experimental equipment. The eye-tracker is equipped with eye cameras (for recording images of eyes) and a scene camera (for recording participants' view). The helmet is attached with reflective markers for motion capture. The helmet is tightly fixed to the participant's head with chin strap and headband. Written informed consent was obtained from the individual for the publication of this image.

Apparatus

The experimental setup is shown in **Figure 2**. Participants wore a batting helmet and a wearable eye-tracker (Pupil headset, Pupil Labs GmbH, Germany). The eye-tracker recorded the eye movements of the right eye with an eye camera at a sampling rate of 200 Hz and the video from the participant's point of view with a scene camera at a sampling rate of 120 Hz. During the experiment, we monitored gaze locations and the image of the eye camera in real-time, and recalibrated the eye-tracker whenever the camera slipped. The movements of the participant's head and the bat were measured by recording the position of reflective markers attached to the helmet and the top of the bat, respectively, at a sampling frequency of 240 Hz with an optical motion capture system (Optitrack, NaturalPoint, Inc., United States). The helmet was fixed tightly to the head with a headband and chin strap to prevent contact between the eye-tracker and helmet and to achieve accurate measurement of head motions during swing motions. Events such as ball releases and bat-ball contacts were recorded using a high-speed camera at a sampling rate of 300 Hz. Time synchronization among these devices was achieved by lighting LEDs simultaneously at the time of the initiation of the motion capture system. Pitch speed was measured by a 3D Doppler radar system (TrackMan Baseball, TrackMan, Inc., Denmark).

Procedure and Design

Former professional pitchers threw against participants. One participant (Farm 1) faced Pitcher 1 (fastball: $M = 104.9$ km/h, $SD = 1.40$ km/h; curveball: $M = 95.2$ km/h, $SD = 1.42$ km/h), and the other participants faced Pitcher 2 (fastball: $M = 128.8$ km/h, $SD = 1.38$ km/h; curveball: $M = 104.9$ km/h, $SD = 1.40$ km/h). Prior to experimentation, the eye-tracker was calibrated using "manual marker calibration" provided in the eye-tracker's operating software. Specifically, participants were instructed to stand in the batter box and look at a calibration target placed 1.5–2 m in front of them. The researcher changed the target positions so as to cover all ball trajectories. The number of calibration points was set to more than 10. This calibration procedure was performed every time the eye-tracker slipped. In the experiment, the pitcher threw either a fastball or a curveball under the *known condition*, in which the pitch type was told to the participant in advance, and the *unknown condition*, in which the pitch type was not told to the batter in advance. Thus, the unknown conditions are closer to an actual game situation, reducing the predictability of the ball trajectory and making the task more difficult. Since we tested only fastball in the known condition, there were three experimental conditions in total: *known fastball*, *unknown fastball*, and *unknown curveball*. These three conditions were held in random order. Participants were instructed to hit all strike balls. The experiment was repeated until there were 11 bat-ball contacts for each of the three conditions.

Data Analysis

The coordinate system was defined as shown in **Figure 3**, similar to Higuchi et al. (2018). The direction of the Y_{field} axis was set parallel to the pitcher-home plate direction, and that of the X_{field} axis was orthogonal to the Y_{field} axis. The origin of the X_{field}-Y_{field} coordinate was set in the center of the head, so it moved with the participant's translational movements. The effect of the head translation on gaze shift was not evaluated because its contribution was relatively small compared to the head rotation. The effect of the head translation on the ball direction (θ_{ball}) is taken into account because it was calculated on the basis of scene camera images mounted on the participant's head. The data of the left-handed batters were inverted to fit this coordinate system.

The head direction (θ_{head}) indicates the angle between the head direction and the X_{field} axis. Three out of eight motion markers attached on the helmet formed a transverse plane, and the head direction was calculated on the basis of the positions of the three markers projected on the ground. The motion capture data were resampled to match the sampling frequency of the eye position data. The ball (θ_{ball}) and gaze (θ_{eye}) directions were defined relative to the head direction (θ_{head}). The ball positions were manually digitized from the footage of the scene camera and interpolated with third-order spline interpolation so as to match the sampling frequency of the gaze position data. The gaze position data were exported as x-y coordinates in the scene camera image and smoothed with a second-order Savitzky-Golay filter with a window size of nine points. Finally, the ball and gaze position expressed in the scene camera coordinates were converted into angular parameters relative to the head while taking into account the head tilt, obtained from motion capture data, and correcting the distortion caused by the wide lens. Therefore, the ball and gaze direction in the field coordinate systems can be expressed as ($\theta_{head} + \theta_{ball}$) and ($\theta_{head} + \theta_{eye}$), respectively. Please note that $\theta_{head} + \theta_{ball}$ is independent of the participant's head direction.

Eye movements exceeding the maximum velocity of 150 deg/s and the maximum acceleration of 6,000 deg/s^2 were defined as saccades; we adopted conservative criteria to detect only distinct saccades. Saccade detection was further verified by visual inspection. The onset of a saccade was defined as the time at which the acceleration of the saccade reached its maximum value. Only data from trials where a bat-ball contact occurred were subject to further analyses (to align data at the time of the bat-ball contact). Trials that yielded no correct data were also removed. For each participant and condition, the number of trials used in the analysis was at least eight out of 11 trials in which a bat-ball contact occurred.

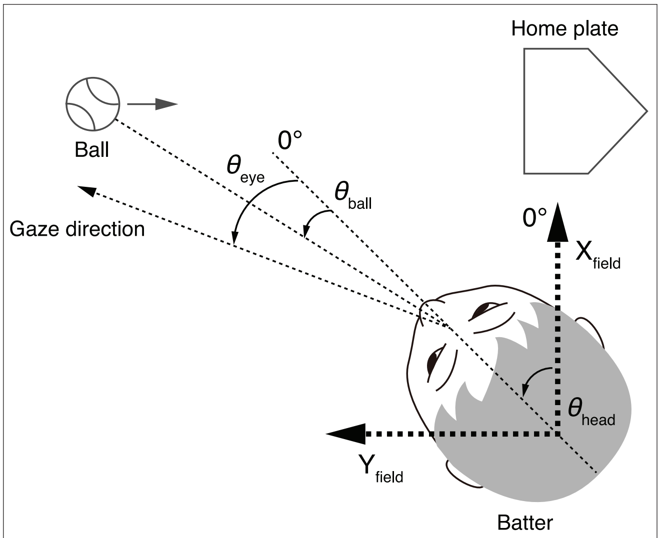

FIGURE 3 | Geometry of parameters. Directions of Y_{field} axes are parallel to the pitcher-home plate directions, and X_{field} axis is vertical to Y_{field} axis. The origin of the X_{field}-Y_{field} coordinate was set in the center of the head. θ_{eye}, eye position; θ_{ball}, ball direction relative to head center; θ_{head}, head direction (angle subtended by head direction and X_{field} axis).

Statistical Analyses

For each participant and each condition, mean values were calculated for the cumulative error between the gaze and the ball positions during the 300 ms before the bat-ball contact, the time of the first saccade, and the contribution of the eye movements to the total amount of gaze shift from ball release to bat-ball contact. For these three variables, to examine the effects of the participant level and pitch conditions, we performed a 2 (top league batters and farm league batters) × 3 (known fastball, unknown fastball, and unknown curveball) mixed analysis of variance (ANOVA). Bonferroni-corrected *post hoc t*-tests with the alpha level of 0.05 were used for multiple comparisons.

To investigate the special relationships between visual strategies and swing motions, we conducted correlation analyses calculating Pearson's correlation coefficients between the bat-top positions and the three variables related to visual strategies (eye position θ_{eye}, head direction θ_{head}, gaze direction $\theta_{head} + \theta_{eye}$) at the time of bat-ball contact. In order to increase the number of samples, data of all three pitch conditions have been combined.

RESULTS

The mean head direction and the gaze position of the known fastball, unknown fastball, and unknown curveball trials aligned at the time of the bat-ball contact are shown in **Figures 4–6**, respectively. General characteristics seen in all participants and conditions are as follows. Participants tracked the ball smoothly for a while after the ball release and at some point, started a saccade, and a quick head movement to shift gaze position to the future ball position (predictive saccades and head rotations). Participants mainly used their head movements to track the ball until they began saccadic eye movements. Participants showed predictive saccades in almost every trial. Top 1 showed a typical vestibulo-ocular reflex, where the head is rotated toward the flight direction of the ball, and the eyes are moved in the opposite direction while stabilizing the gaze at the ball position (about −400 to −200 ms in **Figures 4–6**). Farm 2 had a gap of about 5

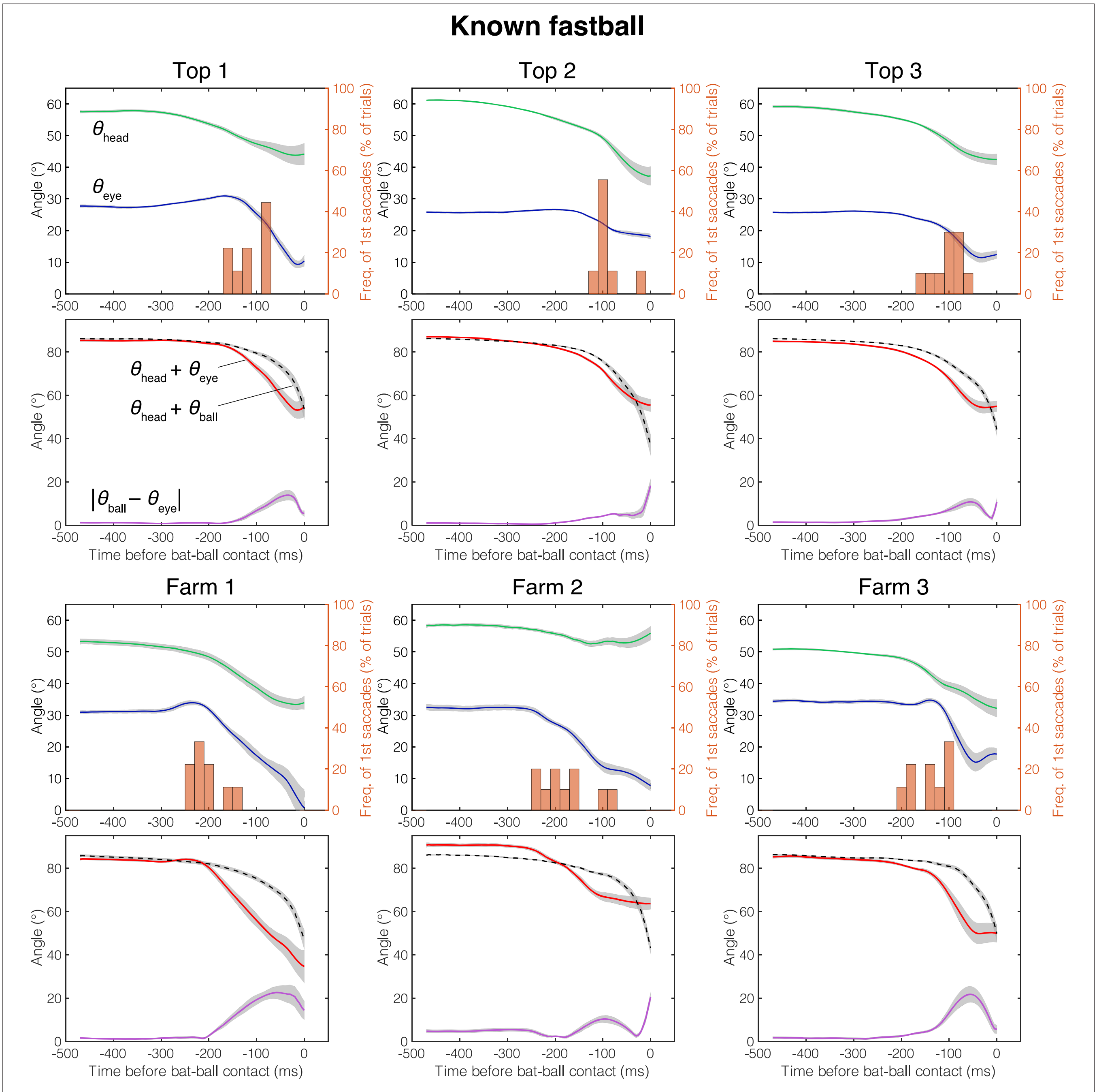

FIGURE 4 | Mean eye position, gaze direction, and head direction for each player in known fastball condition. Green line, head direction (θ_{head}); Blue line, eye position (θ_{eye}); Red line, gaze direction ($\theta_{head} + \theta_{eye}$); Dotted line, ball direction in field coordinate ($\theta_{head} + \theta_{ball}$); Purple line, Horizontal error between gaze and ball ($|\theta_{eye} - \theta_{ball}|$); Histogram, percentage that first saccade occurs; Gray shaded area, standard error. Time is aligned with the time at bat-ball contact.

degrees between ball and gaze position between 480 and 250 ms before the bat-ball contact, suggesting that the ball was being tracked without foveation.

Figure 7A shows the cumulative error between the gaze and the ball positions ($|\theta_{ball} - \theta_{eye}|$) during 300 ms before the bat-ball contact for each participant. To evaluate the effects of the batter level (top batters vs. farm batters) and pitch conditions (difference in the predictability of ball trajectory) on tracking performance, a two-way mixed ANOVA was conducted on the cumulative error. The result showed a marginally significant difference in that the top league batters had better tracking performance than the farm league batters [$F_{(1, 4)} = 6.77$, $p = 0.06$, $\eta_G^2 = 0.59$]. On the other hand, no main of the pitch conditions [$F_{(2, 8)} = 2.09$, $p =$

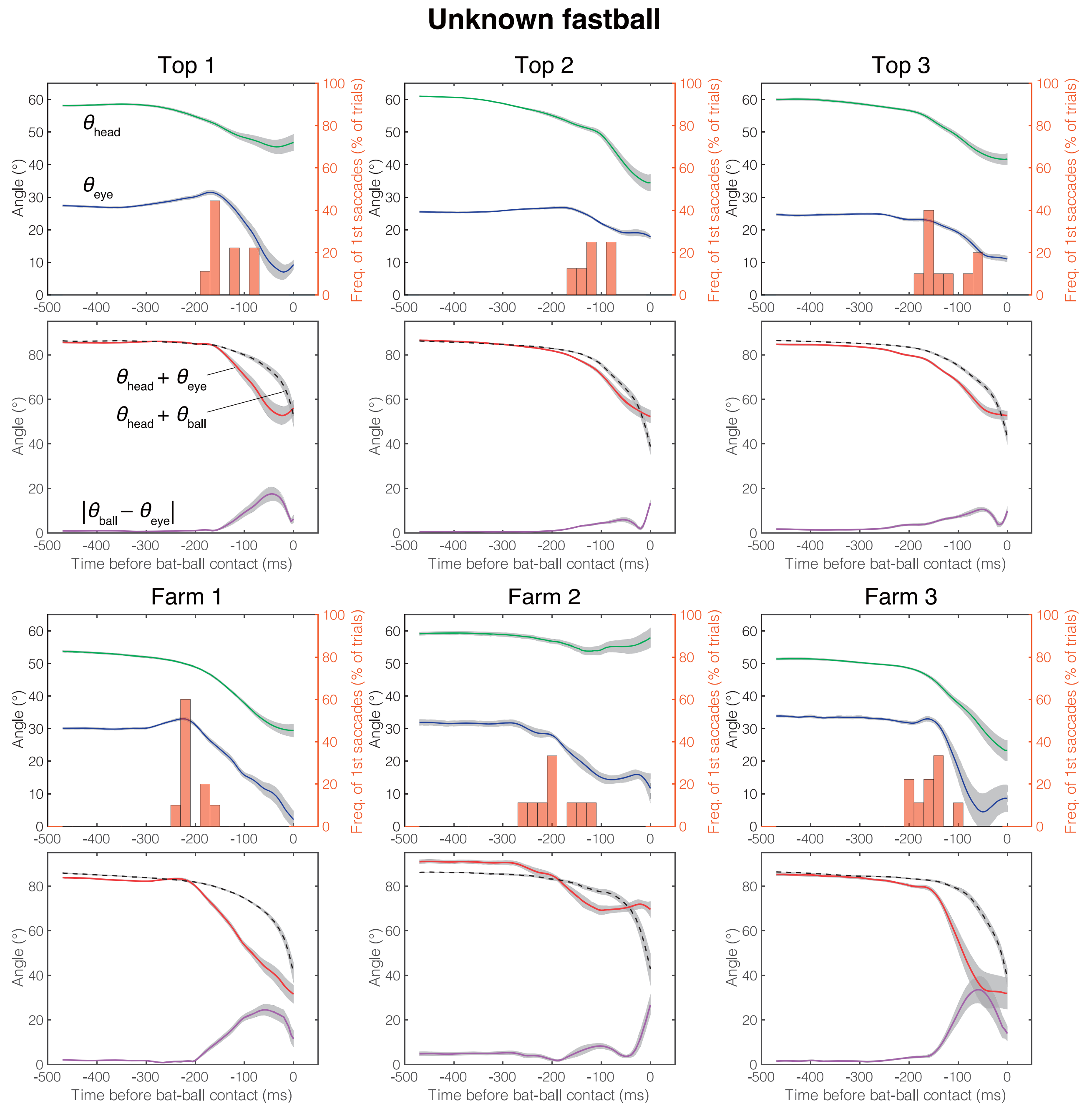

FIGURE 5 | Mean eye position, gaze direction, and head direction for each player in unknown fastball condition. Green line, head direction (θ_{head}); Blue line, eye position (θ_{eye}); Red line, gaze direction ($\theta_{head} + \theta_{eye}$); Dotted line, ball direction in field coordinate ($\theta_{head} + \theta_{ball}$); Purple line, Horizontal error between gaze and ball ($|\theta_{eye} - \theta_{ball}|$); Histogram, percentage that first saccade occurs; Gray shaded area, standard error. Time is aligned with the time at bat-ball contact.

0.19, $\eta_G^2 = 0.06$] or interaction was found [$F_{(2, 8)} = 0.85$, $p = 0.46$, $\eta_G^2 = 0.03$].

The mean initiation time of the first saccade in each trial is shown in **Figure 7B**. For all participants and pitch conditions, the first saccades were started about 80–220 ms before the bat-ball contact time. A two-way mixed ANOVA on initiation times of the first saccade with the groups and conditions as factors revealed that the farm batters made their initial saccade earlier than the top batters [$F_{(1, 4)} = 9.92$, $p = 0.03$, $\eta_G^2 = 0.69$]. Moreover, a significant main effect was found for different conditions [$F_{(2, 8)} = 4.96$, $p = 0.04$, $\eta_G^2 = 0.11$]. *Post-hoc* tests showed that the first saccades were initiated significantly earlier in the unknown fastball condition than in the known one [$t_{(4)} = 6.20$, $p < 0.01$]. The differences between the other pairs were not

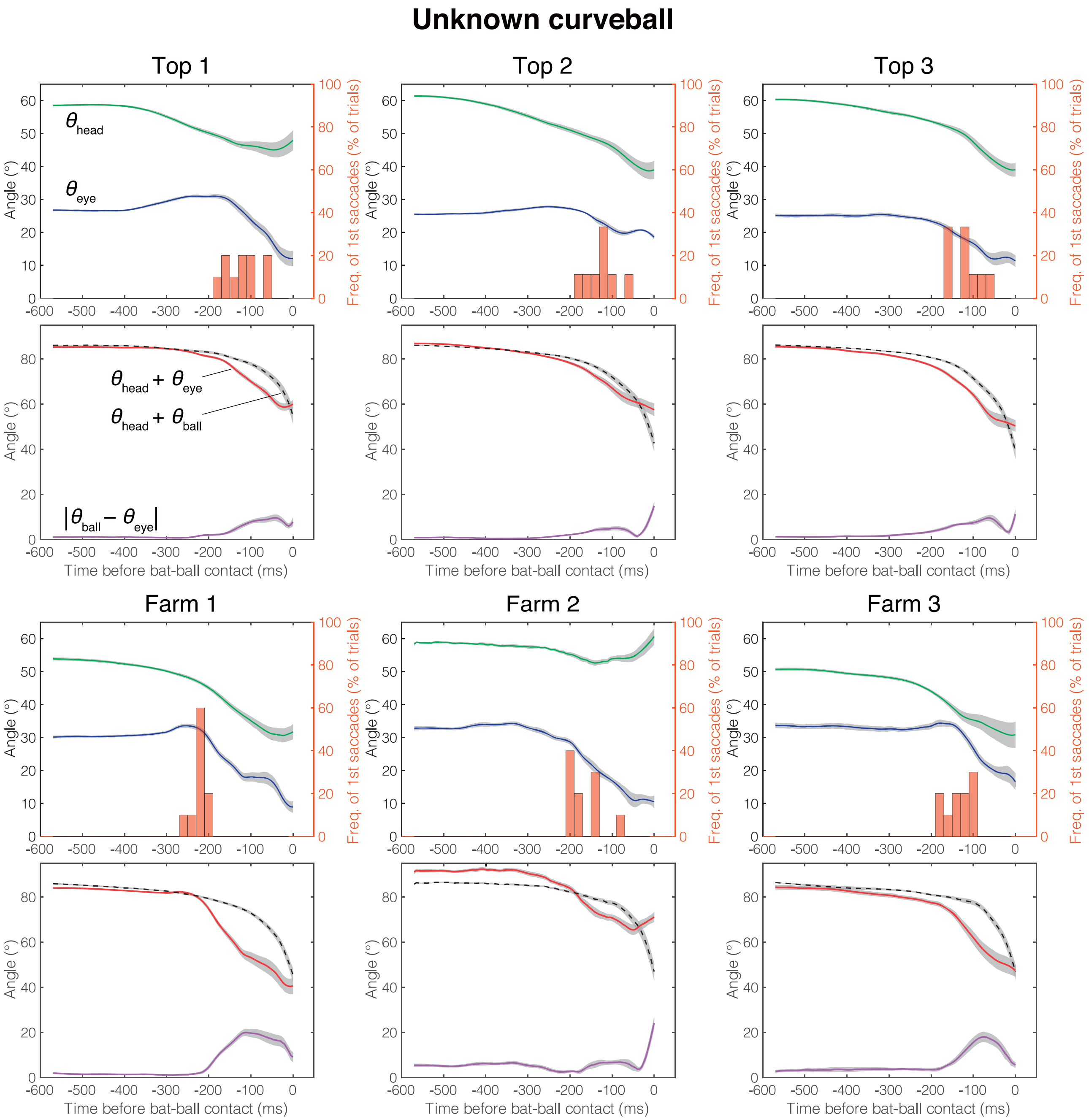

FIGURE 6 | Mean eye position, gaze direction, and head direction for each player in unknown curveball condition. Green line, head direction (θ_{head}); Blue line, eye position (θ_{eye}); Red line, gaze direction ($\theta_{\text{head}} + \theta_{\text{eye}}$); Dotted line, ball direction in field coordinate ($\theta_{\text{head}} + \theta_{\text{ball}}$); Purple line, Horizontal error between gaze and ball ($|\theta_{\text{eye}} - \theta_{\text{ball}}|$); Histogram, percentage that first saccade occurs; Gray shaded area, standard error. Time is aligned with the time at bat-ball contact.

significant [known fastball vs. unknown curveball: $t_{(4)} = 1.92$, $p = 0.13$; unknown fastball vs. unknown curveball: $t_{(4)} = 0.96$, $p = 0.39$]. No interaction effect was found [$F_{(2, 8)} = 1.26$, $p = 0.33$, $\eta^2_G = 0.03$].

The contribution of eye movements (i.e., the effect of change in θ_{eye}) to the change in gaze direction ($\theta_{\text{head}} + \theta_{\text{eye}}$) from ball release to bat-ball contact was also examined (**Figure 7C**). The shifts of these angular variables were calculated by subtracting the values at bat-ball contact from those at ball release. The contribution of eye movement varies widely from about 25% to over 100% among participants. The value above 100% (as seen in Farm 2) means that, at the time of bat-ball contact, the head was rotated in the opposite direction to the ball flight (see the green line of Farm 2 in **Figures 4–6**). No main effect

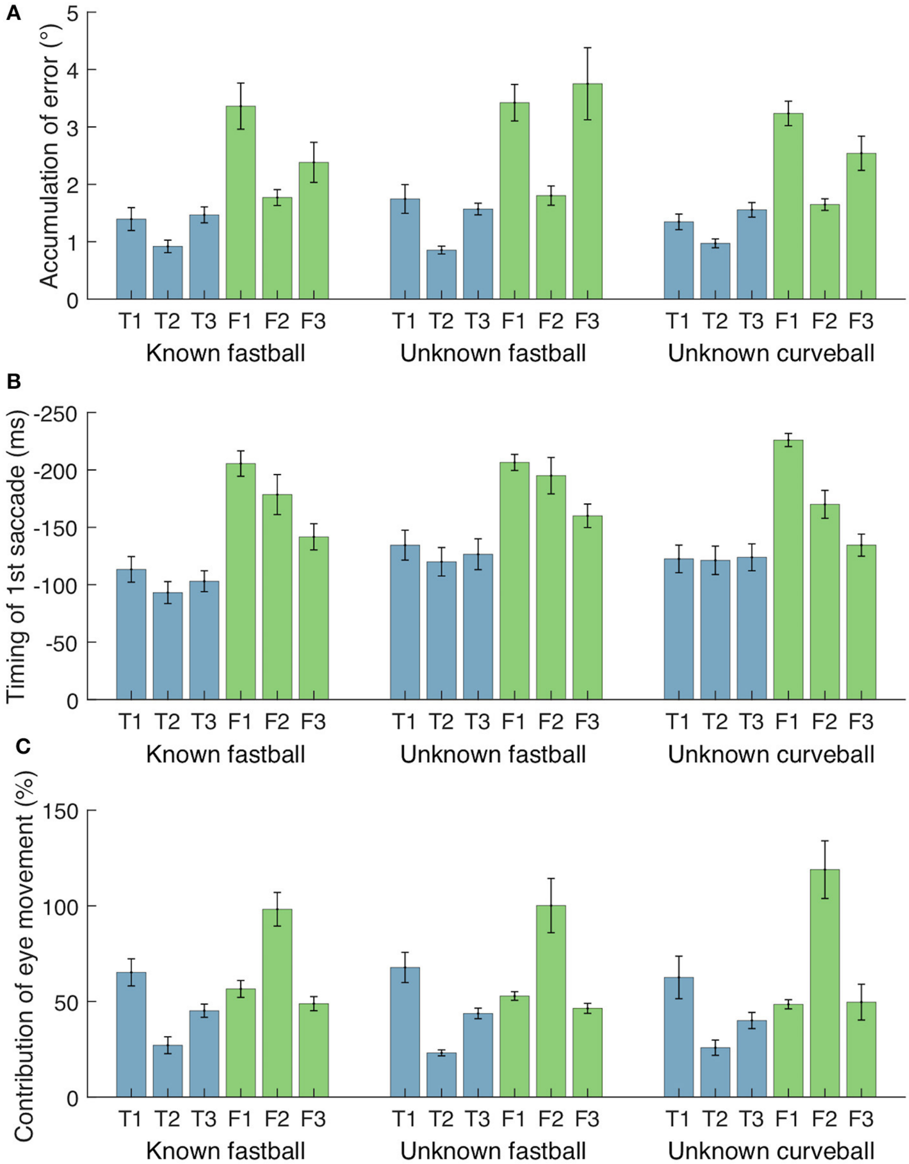

FIGURE 7 | Accumulative error between gaze and ball, timing of first saccade, and contribution of eye movements for each participant and condition. **(A)** Accumulation of gaze-ball error during 300 ms before bat-ball contacts. **(B)** Initiation time of first saccades from bat-ball contacts. **(C)** Contribution of eye movements (effect of change in θ_{eye}) to the change in gaze direction ($\theta_{\text{head}} + \theta_{\text{eye}}$) from ball release to bat-ball contact. Error bars represent standard error.

of the group condition [$F_{(1, 4)} = 1.25$, $p = 0.33$, $\eta_G^2 = 0.23$] or the pitch condition [$F_{(2, 8)} = 0.17$, $p = 0.85$, $\eta_G^2 < 0.01$] was observed. The interaction effect was also not found [$F_{(2, 8)} = 0.90$, $p = 0.44$, $\eta_G^2 < 0.01$].

The results of correlation analyses for the special relationships between the bat-top positions and the three variables related to visual strategies (eye position θ_{eye}, head direction θ_{head}, gaze direction $\theta_{\text{head}} + \theta_{\text{eye}}$) at the time of bat-ball contact are shown in **Figure 8**. For the bat position (x-axis), zero means the bottom position of the home plate, a positive value means the pitcher direction, and a negative value means the catcher direction. All participants showed a significant correlation between bat positions and gaze direction ($R = 0.55$–0.82) and bat positions and head directions ($R = 0.58$–0.80). However, only the Farm batters (Farm 1 and Farm 2) showed a significant correlation between bat positions and eye directions ($R = 0.77$ and $R = 0.68$, respectively).

DISCUSSION

In this study, we examined the eye and head movements of six professional baseball batters in a real batting task. We found that the batters estimated the ball trajectory by a combination of eye movements and head rotations while constantly utilizing predictive saccades to future ball locations. These results were

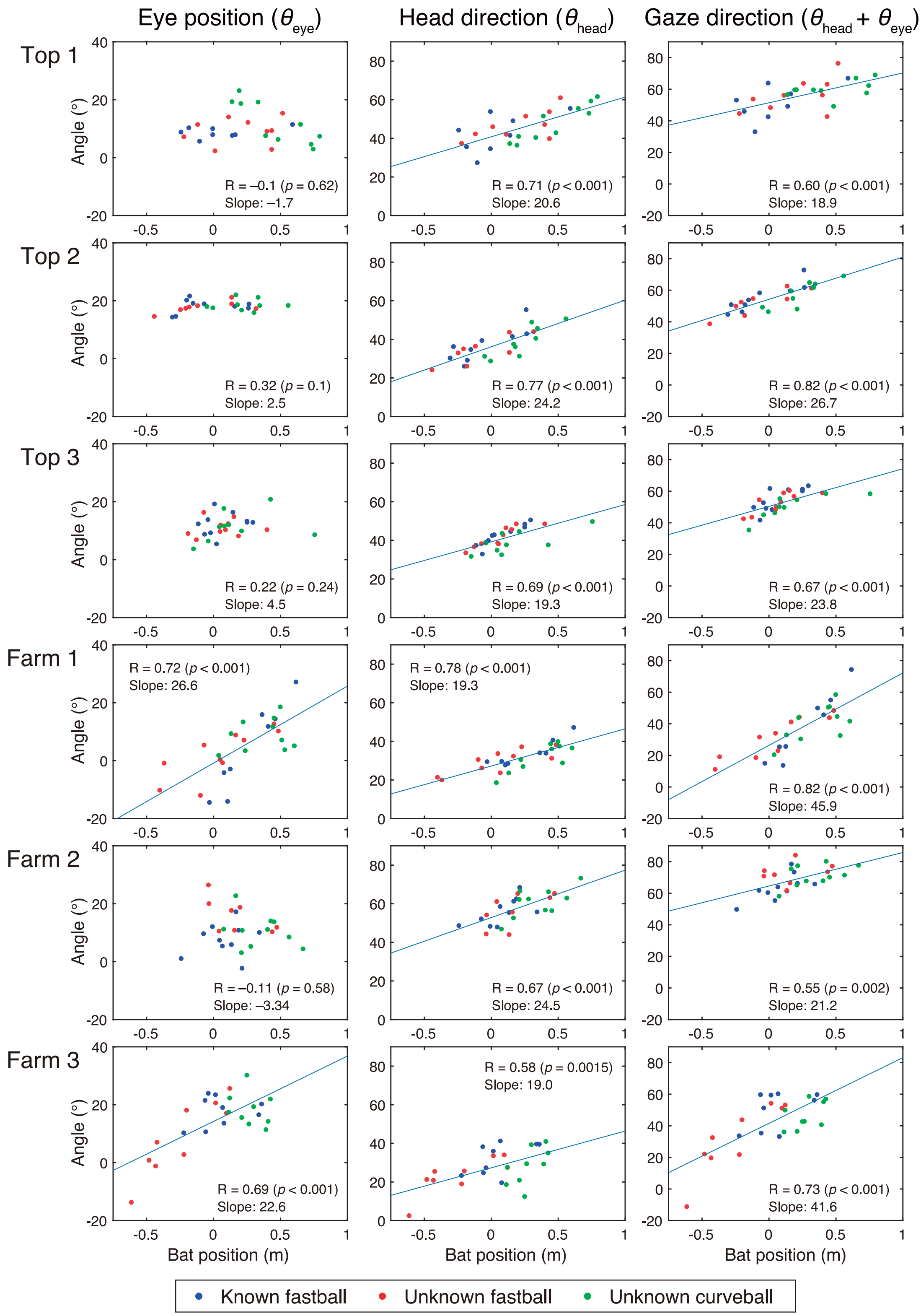

FIGURE 8 | Correlation between bat positions and eye positions, head directions, and gaze directions at time of bat-ball contact. Horizontal axis shows bat top position at bat-ball contact. Zero means the bottom position of the home plate, a positive value means the pitcher direction, and a negative value means the catcher direction. Vertical axis varies depending on the column. Eye position (θ_{eye}), head direction (θ_{head}), and gaze direction ($\theta_{head} + \theta_{eye}$) are shown from the left column. Plot colors correspond to the experimental conditions: blue for known fastball, red for unknown fastball, and green for unknown curveball. Regression lines are shown when correlations are statistically significant.

consistent regardless of the batters' level (top/farm) or the pitch conditions (known fastball/unknown fastball/unknown curveball). For a certain period after the ball release, most batters followed the ball using head rotation rather than eye movements. These results are consistent with behaviors observed in top cricket (Mann et al., 2013) and baseball (Fogt and Zimmerman, 2014) batters. About 50–250 ms before the bat-ball contact, all participants made a predictive saccade to around the future ball trajectory in almost every trial. Bahill and LaRitz (1984) also showed that baseball batters sometimes make a predictive saccade when they face a physically simulated ball. However, here, we found that elite baseball batters utilize a predictive saccade almost every time in real batting situations.

The differences due to the skill level of the batters were confirmed in the gaze movement strategies. Top league batters initiated predictive saccades significantly later than farm league batters. Moreover, the top league batters tended to have a smaller error between gaze and ball than farm league batters. Since the gaze-ball error was largest during the saccade period (**Figures 4–6**), the top league batters, intentionally or not, would utilize a strategy to foveate the ball longer by delaying the generation of a predictive saccade. Previous studies on behavioral differences due to the batter's skill level have mostly compared groups with a huge gap in skill (e.g., professional vs. amateur). Thus, this result is surprising in that observable differences related to skill level were found even among highly elite batters. Land and McLeod (2000) reported that professional cricket batters initiate a predictive saccade to ball bounce locations earlier than amateur batters, unlike our results. In cricket, visual information of the ball before the bounce would be less important than that after the bounce, so batters might start predictive saccades earlier, preparing for tracking the ball after the bounce. The advantages of better tracking ability have also been demonstrated in laboratory experiments (e.g., Spering and Montagnini, 2011; Fooken et al., 2016; Spering and Schütz, 2016). Even so, similar results in the real field and with elite batters raise the possibility that these characteristics (better tracking abilities yielded by late predictive saccades) form the basis of what it takes to be a top batter.

Keeping an eye on the ball longer leads to a more accurate estimation of the ball trajectory. However, the period of visual information during ball flight available for swing movement is constrained by the latency of the visuomotor response. Simple reaction time to a light flash, for example, typically take 200 to 250 ms (Meyer et al., 1988). In contrast, in the case of adjustment of a reaching movement (in response to a sudden target shift or jump), the reaction times will be much shorter (up to 110 ms; Brenner and Smeets, 1997). Interestingly, in this study, the top league batters started saccades about 120 ms before the bat-ball contact. This timing is very close to the reaction time seen in the online adjustment response. In baseball batting, it is easy to imagine that online bat control plays an important role in light of the fact that batters sometimes stop the swing after starting it—although how far batters can change the swing motion withstanding the inertia of an accelerated bat remains a critical question. In addition, considering that new visual information cannot be obtained during a saccade due to saccade suppression, the top batters, who obtain visual information by keeping their eye on the ball up to the time limit that can be reflected in action, may have adopted the optimal eye movement strategy. The farm batters, on the other hand, made the predictive saccade (or shift the gaze away from the ball) earlier than the top batters. This means that the farm batters might miss available visual information. High-level pitchers often throw a ball whose trajectory looks a fastball until it starts curving just in front of a batter (e.g., moving fastball). For example, if a batter can track a ball 100 ms longer (a ball travels about 3–4 m in this period), the adjustability for such kind of pitches will increase.

Saccade timing in the unknown fastball condition was significantly earlier than that in the known fastball condition. The predictability of ball trajectories in the unknown conditions is assumed to be lower than that in the known condition. Many previous studies have suggested that the target can be tracked more easily when its trajectory is more predictable (Findlay, 1981; Kowler et al., 1984; Becker and Fuchs, 1985; Shelhamer and Joiner, 2003). Although we cannot provide a clear answer as to why the time of predictive saccades is earlier in the unknown condition, our results demonstrate that the time of predictive saccades is affected by prior knowledge of target trajectory. Furthermore, no significant difference was observed in the timing of the predictive saccades between unknown fastball and unknown curveball, even with a large difference in ball speed (about 15–25 km/h). These results suggest that the predictive saccades are not driven by external factors (e.g., ball position, velocity) but rather by some internal factors such as prior information of ball trajectories and swing motion.

All batters showed a correlation between bat positions and head directions at the time of bat-ball contact. On the other hand, while two of the three farm batters showed a correlation between bat position and eye position, none of the top batters showed the same correlation. This suggests that the top batters may encode the location of a bat-ball contact on the basis of their head direction, while the farm batters encode it on the basis of the combination of head direction and eye position. When reaching a target, we need to calculate the limb-centered target location by combining target locations expressed by eye-centered, head-centered, and torso-centered coordination (Land and Tatler, 2009). The top league batters may skip part of this process by keeping their eye position relative to the head constant. This shortcut might shorten the visuo-motor delay, and therefore, top league batters foveate the ball longer by delaying the initiation of the predictive saccades. Most participants continued to rotate their head until the bat-ball contact, so it is plausible that they made head rotation according to the prediction of ball trajectories. Neurons encoding head directions (head-direction cell) have been found in several brain regions of various mammals (Taube et al., 1990; Robertson et al., 1999; Yoder and Taube, 2009), some of which have been reported to encode future head directions (Blair and Sharp, 1995). One possibility is, therefore, that the head-direction cell signals of future head directions are used for adjustment of swing motions.

While all participants always adopted predictive saccades, their functional significance is not clear. A straightforward interpretation would be that by moving the gaze position in advance, more detailed visual information on a bat and/or a ball is obtained. Bahill and LaRitz (1984) offered the same interpretation. However, as mentioned earlier, considering the delay in the visuo-motor process, it seems impossible to reflect the very last visual information in the swing motion. The time between the ball passing through gaze location and the bat-ball contact is <50 ms, which is much less than the possible reaction time in online adjustment responses. However, learning of the ball and/or swing trajectories from the visual information obtained after predictive saccades would be useful for future plays. Another possibility is to make the representation of an impact position by locating their gaze in advance. During a reaching movement, the gaze reaches a target location before the hand in order to represent a target location in the eye-centered coordinate (Crawford et al., 2004). Similar mechanisms might work in baseball batting. A saccadic movement to the predicted impact point could pre-encode the position information in the brain with the eye-centered coordinate.

In this study, we measured the eye and body movements of professional baseball batters during baseball batting in a situation similar to actual games, and we found that even among highly skilled batters, there were differences in their gaze shifting and hand-eye coordination strategies. In addition, we revealed that this subtle but important difference in skill level was primarily related to the timing of the predictive saccade detected in almost all trials, unlike the previous studies (Fogt and Zimmerman, 2014; Higuchi et al., 2018). These previous studies have shown that batters mainly use head rotations but our results show that the contributions of eye movements to the total gaze sift varied from about 20% to more than 100% depending on batters (**Figure 7C**). However, it is not clear from the results of the present experiment whether the reason for the discrepancy with the previous studies is due to the difference in participants (e.g., amateur vs. professional) or experimental conditions (e.g., pitching machines vs. human pitchers). Thus, it is necessary to further study the gaze shift strategy with a broader range of participants and various experimental settings. In addition, the functional significance of the predictive saccades also remains a matter of speculation. In this regard, we expect that further understanding will be gained by reproducing extreme conditions such as those found in sports in laboratory experiments where factor control is relatively simple. Furthermore, because the number of participants in this type of study is often limited, we cannot rule out the possibility that this study might not capture all the characteristics of elite baseball batters. Thus, further studies are also needed in this respect. In any case, this is the first study assessing the body-eye coordination among highly skilled batters, and measuring the behaviors of highly skilled batters in extreme conditions such as this study is critical to understand the optimal strategy of body-eye coordination. Above all, these insights can help improve the skills of top batters.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by NTT Communication Science Laboratories Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

YK, HU, and MK conceived and designed the experiments and interpreted data. YK and HU performed the experiment. YK conducted data analysis and drafted the manuscript. HU and MK edited and revised the manuscript, and approved the final version.

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On the Influence of Action Preference on Female Players' Gaze Behavior During Defense of Volleyball Attacks

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Knowledge of an opponent's action preference may affect visual anticipation of their action outcome. Specifically, if an opponent acts according to their purported preference, anticipation may be facilitated. Conversely, if an opponent does not act according to their purported preference, anticipation may be unaffected or even harmed. The underlying perceptual-cognitive mechanisms of that effect, however, remain unclear. Here we tested the hypothesis that players might change their gaze behavior once provided with preference information. To this end, 27 female volleyball players anticipated the direction of attacks in two test blocks with 40 videos each. Videos were shown on a large screen and stopped 240 ms prior to hand-ball-contact. Participants simulated defensive reaction while their gaze was recorded using a mobile eye-tracker. One female attacker directed 75% of shots diagonally (25% longline), while another female attacker distributed shots equally to both directions. After block one, half of the participants were informed that either both attackers preferred diagonal shots in 75% of occasions (group preferred) or that both attackers distributed shots equally across directions (group non-preferred). Analysis of decision behavior (i.e., proportion of diagonal decisions), but not prediction accuracy (i.e., proportion of correct predictions), revealed that those instructions led both groups decide differently according to the purported preferences from block 1 to block 2. Analysis of gaze behavior did not reveal group-specific effects across blocks or attackers with/-out action preference. Findings underline the influence of contextual information on anticipation, but they leave open whether the availability of contextual information similarly affects gaze behavior.

Keywords: anticipation, contextual information, eye-tracking, decision behavior, congruence, decision making, situational probability

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INTRODUCTION

Anticipation in team sports such as volleyball is considered a crucial component for success (Allard and Starkes, 1980; Abernethy, 1987). At the latest since the penalty shootout at the 2006 World Cup between Germany and Argentina, when German goalkeeper Jens Lehmann was given leaflets about the possible shooting directions of the Argentinian shooters, public awareness of the potential utility of contextual information in sports has increased and its added value for anticipation scientifically questioned (Cañal-Bruland and Mann, 2015). Here, contextual information is considered as supplementary information from which probabilities for action arise apart from an actor's kinematics. By now, growing evidence suggests that, in addition to kinematic cues provided by an opponent's movement, contextual information also influences anticipation performance (Loffing and Cañal-Bruland, 2017). For example, game score (Farrow and Reid, 2012), individual action preferences (Navia et al., 2013; Mann et al., 2014; Helm et al., 2020), pattern of previous outcomes (Loffing et al., 2015b), or an opponent's on-court position (Loffing and Hagemann, 2014; Loffing et al., 2016; Huesmann and Loffing, 2019) were found to affect anticipation of an opponent's action intention in different sports. The investigation of the influence of an opponent's action preference on anticipation is particularly interesting here, because in high-performance sports data about opponents is collected and processed in the run-up to a game for an in-depth match planning (McGarry et al., 2013). Data is also even generated during a match, made available to coaches and further passed on to the athletes in timeouts (Zetou et al., 2008). The idea behind providing athletes with opponent-related information during competition is to facilitate their performance.

Mann et al. (2014) studied the effect of an opponent's action preference on skilled female handball goalkeepers' visual anticipation of throw direction in 7 m handball penalties before and after a short-term training intervention. In the training intervention, one group (PR) was shown videos of two shooters who had an action preference for one corner, the other group (N-PR) was shown videos of the same shooters who distributed the balls equally across corners. Thus, contextual information was varied through action preference. In the tests, the same two shooters were shown, with one of them preferentially throwing to the same corner as in the training intervention and the other having no preference. Pre- to post-test comparison revealed that contextual information conveyed during training affected directional anticipation. Participants in the PR-group decided more often on the (assumed) preferred corner in the post- than the pre-test. Moreover, from pre- to post-test accuracy increased against the thrower with congruent behavior (i.e., preference in tests and training), but it decreased against the thrower with incongruent behavior (i.e., no preference in tests but in training). Performance of the N-PR-group did not markedly differ from pre- to post-test, suggesting that preference information picked-up during training is likely to explain performance changes in the PR-group (for similar findings see e.g., Loffing et al., 2015b; Gredin et al., 2018; Runswick et al., 2019).

The perceptual-cognitive mechanisms underlying the above-mentioned effect of action preference on anticipation have not yet been satisfactorily clarified. One explanatory approach suggests a confirmation bias whereby information that meets expectations is specifically selected and processed, while information that does not meet expectations is ignored (Nickerson, 1998). Because contextual information is available before anticipation-relevant kinematics unfold (Cañal-Bruland and Mann, 2015), this could trigger an expectation that leads to a confirmation bias for incongruent events, ultimately resulting in a performance decrease. In tentative support of this idea, using an anticipation task in cricket Runswick et al. (2019) found that skilled batters were more susceptible to the effect than less-skilled batters, possibly because the former are more reliant on and better in using contextual information.

The manipulation of contextual information might also result in a variation of visual-perceptual measures. McRobert et al. (2011) showed in a cricket-batting task that skilled participants under high context conditions (i.e., same bowler in six consecutive trials) had shorter mean fixation duration than under low context conditions (i.e., different bowlers in consecutive trials). According to the authors' apostrophe *post-hoc* explanation experts know where to find cues for the expected action and can then pick them up more efficiently, which is reflected in the shorter fixation duration. No differences in the mean number of fixations were observed. This study, however, did not compare gaze behavior in congruent vs. incongruent situations. Gredin et al. (2018) did so by asking expert and novice soccer players to anticipate an attacker's running or pass direction in a defensive situation in football. In addition to the player in possession of the ball, another opponent was shown who was covered by another teammate. In one test condition comprising six sub-blocks, information about the ball dribbling player's action tendency for either passing to the other player or continued dribbling was communicated explicitly both orally and visually on a screen before each sub-block. In another test condition, stimuli were identical to the other condition but no explicit information on action tendencies were given prior to sub-blocks. Examination of participants' visual dwell time revealed that experts, but not novices, looked less at the player in possession of the ball but more at the two players (i.e., opponent and teammate) without the ball when provided with explicit contextual information relative to when not. This was particularly evident in the first, but not the second half of a trial.

Taken together, both studies provide preliminary evidence that gaze behavior may vary depending on context. However, it remains unclear whether gaze behavior differs between congruent and incongruent events and whether such possible effect is reflected in anticipation performance differences as well. The aim of this study was to investigate whether the provision of information about an opponent's action preference has the purported positive effect on anticipation and to explore the effect of action preference on gaze behavior using the example of defense in volleyball attacks under congruent or incongruent conditions. The focus of our gaze analysis was on the number of fixations and the duration of the last fixation. The number of fixations was considered relevant as the pick-up of visual information occurs during fixations. The duration of the last fixation was chosen because the most important kinematic information of a movement is available in the final phase of a movement (Alder et al., 2014; Loffing et al., 2015a). Using a similar experimental design as Mann et al. (2014), here skilled volleyball players were asked to simulate the defense of attacks against opponents with and without action preference in two consecutive blocks. Between blocks, one group (PR) received information that both attackers had an action preference in favor of the diagonal direction, while another group (N-PR) received information that the attacks were evenly distributed. For group PR but not group N-PR, we expected decision behavior to change in favor of contextual information and prediction accuracy to increase for congruent events and to decrease for incongruent events (Mann et al., 2014; Loffing et al., 2015b; Gredin et al., 2018; Runswick et al., 2019). Regarding gaze measures, due to the exploratory nature of this study with regard to possible effects at the visual-perceptual level, no hypotheses were formulated a priori.

METHOD

Participants

A total of 27 female volleyball players (M_{age} = 24.8 years; SD = 4.7) from the second to fifth German volleyball league took part in the study. At the time of testing, they had an average of 12.9 years of playing experience (SD = 4.7) and completed, on average, 3 training units per week (SD = 0.7). The final sample was restricted to 24 participants because three participants had to be excluded prior to data analysis[1]. The study was carried out in accordance with the recommendations of and the protocol was approved by the local Commission for Research Impact Assessment and Ethics at the Carl von Ossietzky University of Oldenburg. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Test Stimuli

The test stimuli were videos of volleyball attacks performed by two different female players from the fourth German volleyball league. The attacks were embedded in a real game situation. The ball was taken by the outside hitter and played to the setter. The setter set the ball to the opposite (attacker) who hit the ball either longline or diagonal. Attackers were supposed to attack as if in a real game situation. Attack situations were recorded using a video camera (Panasonic HC-V270), which was positioned on a tripod (1.5 m high) two meters behind the baseline and one meter away from the sideline in the other half of the field (for an illustration see **Figure 1**).

A total of 25 video sequences were prepared for each attacker, 10 longline strokes and 15 diagonal strokes each. The video sequences started at the moment of ball-hand-contact during ball reception of the outside hitter and were occluded 240 ms before ball-hand-contact of the attacking player. The occlusion point was determined based on pilot testing with three skilled volleyball players (all different to those tested in the main experiment), who anticipated the ball flight direction for attacks occluded at different time points. In the main study, temporal occlusion at 240 ms before hand-ball-contact was chosen as accuracy of anticipation under that condition was found sufficiently above chance but below perfect performance in the pilot study. So, that temporal occlusion condition was expected to not lead to floor or ceiling effects in accuracy in the main study, thus leaving enough space for accuracy variation between test blocks as a consequence of the manipulation of the opponents' action preference.

[1]Three participants were excluded prior to the data analysis. One participant assumed that misinformation was given between block 1 and block 2 and assumed a distribution of 75% longline balls instead. The other two participants were excluded due to technical problems with the mobile eye-tracker during testing.

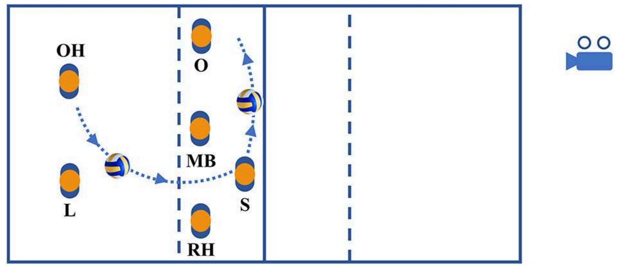

FIGURE 1 | Representation of the play situation on the field with ball path (dotted line) and player positions (S, setter; O, opposite; OH, outside hitter; L, libero; RH, right side hitter; MB, middle blocker).

Apparatus

During testing, videos were back-projected (Acer X137WH) onto a rear projection screen (Stumpfl Flex Rear MO, 3 × 4 m) with a size of 2.17 × 3.85 m. Participants stood two meters in front of the screen so as to create a game situation as real as possible in terms of viewing angle. Participants' gaze behavior was recorded using the SMI Eye Tracking Glasses 2.0. Glasses were calibrated using a three-point calibration. To this end, participants stood two meters in front of a wall with four markers attached to it. The markers were arranged in a square with a side length of one meter, with the middle of the square being 1.7 m above ground. Participants were instructed to keep their head stable and only move their eyes toward each marker. The calibration was performed before the practice trials prior to the first block and checked before the second block. During testing, the eye-tracker's calibration was continuously controlled by asking participants to fixate a small cross on the screen prior to each trial.

Procedure

In the experiment the participants went through three phases: test block 1, an information phase and test block 2 (see **Table 1** for an illustration). For a given participant, blocks 1 and 2 were identical. In the tests, 20 videos of each attacker were presented in random order. The videos of the two different attackers were selected in such a way that one attacker had an equal distribution of shot directions (no action preference), while the other attacker hit 75% of the balls (i.e., 15 videos) in the diagonal direction (action preference). An attacker's action preference was counterbalanced across participants. In each group one attacker was shown whose attack direction matched with the information given between the blocks (congruent condition), while for the other attacker attack distribution did not match with the information given (incongruent condition).

Participants stood 2 m in front of the screen in a typical defensive position, wearing their volleyball specific clothes, and they were asked to put themselves into the game situation. The video sequences started once participants indicated they were ready for the next trial. Their task was to anticipate the direction of the attack by performing a defensive movement as in a real game and verbalizing the predicted stroke direction afterwards. The defensive movement should be timed as in a real

TABLE 1 | Experimental design.

Group	Block 1	Information	Block 2
N-PR	Attacker 1 with a distribution of 50%:50% (diagonal:longline)	Both attackers distribute strokes equally longline and diagonal (no preference)	Attacker 1 with a distribution of 50%:50%
	Attacker 2 with a distribution of 75%:25%		Attacker 2 with a distribution of 75%:25%
PR	Attacker 1 with a distribution of 50%:50%	Both attackers have a preference for diagonal strokes (in 75% of occasions)	Attacker 1 with a distribution of 50%:50%
	Attacker 2 with a distribution of 75%:25%		Attacker 2 with a distribution of 75%:25%

Note that shot distribution in the tests was varied between the two attackers and counterbalanced across participants.

game situation. The first direction of the defensive response was recorded by the experimenter. Participants were not given any performance feedback on any trial. Before the start of block 1, the participants underwent eight practice trials. Performance on those trials was not considered in later analysis. As for test trials no feedback was given to participants.

Between the two test blocks explicit information about the attackers' strike preference was given as text and graphically on the screen. Almost half of the participants were informed that both attackers had no action preference and hit as often diagonally as longline (group N-PR; $n = 13$). The other half of participants was informed that both attackers had an action preference in favor of diagonal strokes and that 75% of the attacks were struck diagonally (group PR; $n = 11$). Participants were allocated randomly to one of the two groups.

Block 2 was identical to block 1 in that the same videos were presented, however in a newly randomized order, and that the participants' task also was the same. Upon completion of block 2, participants completed a questionnaire in which they were asked, among others, to indicate what they thought was the particular aim of this study.

Data Analysis

Anticipation Performance

Anticipation performance was operationalized by prediction accuracy and decision behavior. Prediction accuracy was measured as the proportion of correct direction prediction, ranging between 0 (no correct prediction at all) and 1 (perfect performance). Decision behavior, in turn, was determined as the proportion of decisions for diagonal strokes, again ranging from 0 (no diagonal prediction) to 1 (only diagonal predictions). Both variables were analyzed because changes in prediction accuracy must not necessarily go in the similar direction as changes in decision behavior and vice versa (Loffing and Hagemann, 2014; Mann et al., 2014). Both variables were subjected separately to a 2 (Group: PR vs. N-PR) x 2 (Block: block 1 vs. block 2) x 2 (Action Preference: attacker with vs. without action preference) mixed ANOVA with repeated measures on the last two factors. Alpha level was set to 0.05 for all tests.

Gaze Behavior

Gaze behavior was measured via the mean number of fixations across the full length of a video and the mean duration of the last fixation in a video. It was analyzed by the program "Begaze 3.7" from SMI. Both variables were subjected separately to a 2 (Group: PR vs. N-PR) x 2 (Block: block 1 vs. block 2) x 2 (Action Preference: attacker with vs. without action preference) mixed ANOVA with repeated measures on the last two factors. Alpha level was set to 0.05 for all tests.

RESULTS

Results from the post-experiment questionnaire revealed that five out of 24 participants revealed the study objective almost correctly, suspecting that the study aimed at investigating the influence of additional information on anticipation or gaze behavior. Two of these participants belonged to the N-PR group and three to the PR group.

Anticipation Performance

The 2 (Group) x 2 (Block) x 2 (Action Preference) ANOVA on *decision behavior* revealed a significant main effect for Group, $F_{(1,22)} = 6.22$, $p = 0.021$, $\eta_p^2 = 0.22$. Overall, the group PR made more decisions in favor of the diagonal direction than the group N-PR. In addition, there was a significant Block x Group interaction, $F_{(1,22)} = 28.84$, $p < 0.001$, $\eta_p^2 = 0.57$. In block 1, both groups decided equally often on diagonal strokes. In block 2, however, group PR decided considerably more often on diagonal shots (according to the information given in-between), whereas group N-PR made fewer diagonal decisions than in block 1 and compared to group PR (see **Figure 2A**). None of the remaining main effects or interactions were found to be significant.

For *prediction accuracy*, the descriptive data related to the attacker without an action preference do not show noticeable differences between blocks 1 and 2 irrespective of group (block 1: $M = 0.694$, $SD = 0.128$; block 2: $M = 0.706$, $SD = 0.127$; see **Figure 2B**). With regard to the attacker who had an action preference, descriptively the groups showed different developments from block 1 to block 2. Specifically, accuracy in group PR increased (block 1: $M = 0.705$, $SD = 0.172$; block 2: $M = 0.791$, $SD = 0.097$) and it decreased in group N-PR (block 1: $M = 0.700$, $SD = 0.162$; block 2: $M = 0.665$, $SD = 0.105$) (see **Figure 2C**). A 2 x 2 x 2 mixed ANOVA, however, did not reveal significant results for any main effect or interaction.

Exclusion of the five participants who suspected the study objective correctly from the above analyses does not lead to noticeable changes in the results for anticipation performance.

Gaze Behavior

The 2 (Group) x 2 (Block) x 2 (Action Preference) ANOVA on the *number of mean fixations* revealed a significant main effect

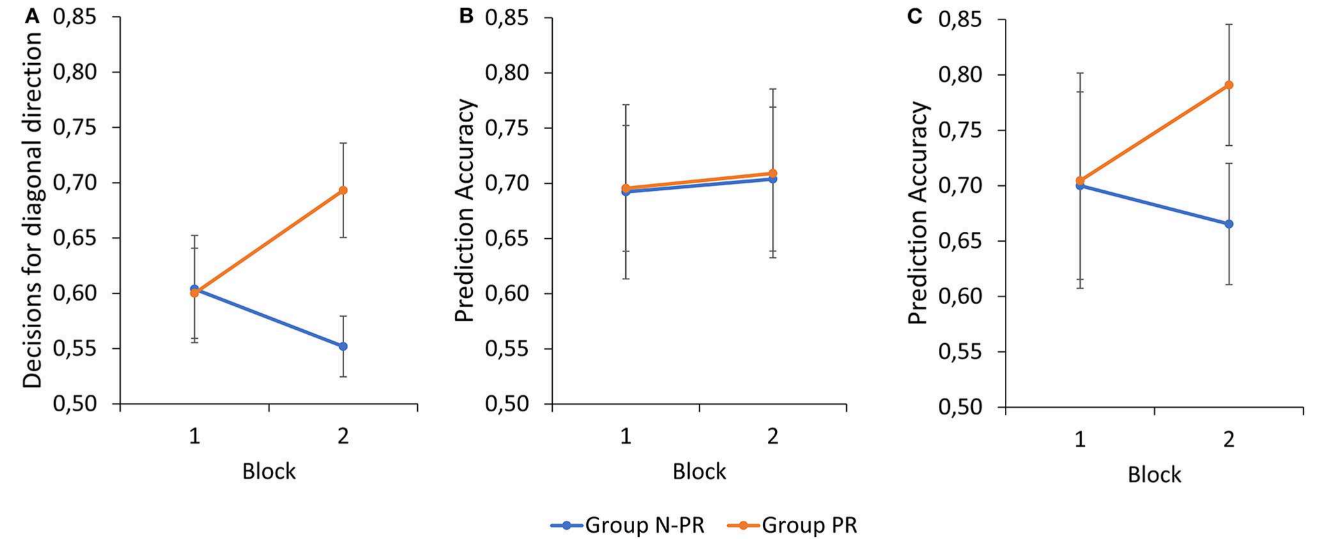

FIGURE 2 | (A) Mean proportion of decisions for diagonal strokes as a function of Block and Group. Mean prediction accuracy against an attacker **(B)** without and **(C)** with an action preference as a function of Block and Group. Error bars denote 95% confidence intervals of the mean.

for Block, $F_{(1,22)} = 10.82$, $p = 0.003$, $\eta_p^2 = 0.33$, and Action Preference, $F_{(1,22)} = 5.43$, $p = 0.029$, $\eta_p^2 = 0.20$. Participants made more fixations in block 1 compared to block 2 (block 1: $M = 7.45$, $SD = 1.38$; block 2: $M = 6.96$, $SD = 1.47$) and they fixated more against the attacker with an action preference ($M = 7.30$, $SD = 1.44$) than when confronted with the attacker who had no preference ($M = 7.11$, $SD = 1.45$). None of the remaining main effects or interactions were found to be significant.

The 2 x 2 x 2 ANOVA on the *duration of the last fixation* revealed a significant main effect for Action Preference, $F_{(1,22)} = 5.93$, $p = 0.023$, $\eta_p^2 = 0.21$. On average, participants made a longer last fixation against the attacker without an action preference ($M = 910.95$ ms, $SD = 415.33$ ms) as opposed to an attacker with an action preference ($M = 831.08$ ms, $SD = 347.30$ ms). None of the remaining main effects or interactions were found to be significant.

If the five participants who suspected the study objective correctly were excluded from the above analyses of gaze measures, the results would marginally change in that the main effect for Action Preference on *the number of mean fixations* ($p = 0.102$) and *duration of the last fixation* ($p = 0.132$) would no longer be significant.

A detailed list of all statistical values obtained from the analysis of all 24 participants is included in the **Supplementary Materials**.

DISCUSSION

Previous research suggests that contextual information can have a positive or negative influence on anticipation, depending on whether the occurring event is congruent or incongruent with the expected event based on prior contextual information (Mann et al., 2014; Loffing et al., 2015b; Gredin et al., 2018; Runswick et al., 2019). The underlying perceptual-cognitive mechanisms of this effect, however, remain vastly unclear. The aim of this study was to explore whether the provision of information on an attacker's action preference in volleyball would affect gaze behavior, apart from the hypothesized influence on anticipation performance, in a simulated volleyball defense situation.

With regard to anticipatory performance, it could be shown that the provision of information on action preference influenced decision behavior, as there was a block x group interaction. In the first block, both groups opted equally frequently for diagonal strokes, in the second block participants of group PR showed more frequent decisions in favor of the instructed direction. These findings go in line with other studies (Mann et al., 2014; Loffing et al., 2015b; Runswick et al., 2019) and support the idea that instructing about opponents' action preferences influences visual anticipation. While the exact mechanism underlying that effect remain unclear, recent explanations center around a Bayesian approach (Loffing and Hagemann, 2014; Gredin et al., 2019; Helm et al., 2020) or heuristics such as confirmation bias (Rajsic et al., 2015; Runswick et al., 2019).

However, such an effect was only found for decision behavior, but could not be confirmed at the level of statistical significance for prediction accuracy. Descriptively, information about an action preference facilitated prediction accuracy if the attacker actually had an action preference (congruent condition), but there was no detrimental effect on accuracy in case an attacker actually did not have a preference. These findings do not go in line with the findings of Mann et al. (2014), who found that knowledge about opponents' action preferences also influenced prediction accuracy. Overall, data on decision behavior suggest that action preference information is integrated in to predictions, because participants of group PR decided more often in favor of the instructed direction in block two; however doing so does not necessarily lead to considerably better (congruent condition) or worse (incongruent condition) decisions in terms of accuracy.

Gaze behavior measures were not found to statistically vary depending on Group in combination with other factors. Instead, only conceptually less relevant main effects for the factor Block on the number of fixations and for the factor Action Preference on both gaze measures were found. The Block effect possibly reflects participants' adaptation to the experimental task in general. Action preference information was given between test blocks and information differed between groups PR and N-PR. With this in mind and considering further that no feedback was provided to participants on the outcome of an attack during testing, the main effect for Action Preference and the absence of an interaction effect with Group and/or Block is difficult to explain. To avoid unreasonable speculation about possible explanations, we refrain from discussing these findings any further.

Two methodological issues that limit the interpretation of gaze measures need to be highlighted. First, attacks were always performed from the same field position (see **Figure 1**). This reduced uncertainty in the setter's action (i.e., where she set the ball to) and attack location, both possibly leading to low variability in participants' gaze behavior and ultimately lowering the chances of detecting potential variation in gaze measures between blocks and groups against attackers with and without an action preference. Second, the size of videos and the distance of participants to the projection screen were chosen such that the visual angle of the players in the videos was as close as possible to the visual angle of players viewed from a backcourt position in a real match. This resulted in a large part of an attacker being within the foveal and near peripheral field of view, which does not permit a meaningful detailed analysis of gaze orientation toward different parts of an attacker's bodily regions (Piras et al., 2010, 2014; Afonso et al., 2012; Schorer et al., 2013). These issues may need to be considered in future research on the visual-perceptual consequences of the manipulation of contextual information for visual anticipation.

All in all, in line with the previous findings (Mann et al., 2014; Loffing et al., 2015b; Gredin et al., 2018; Runswick et al., 2019) we found that contextual information influences anticipation performance; particularly decision behavior, but not prediction accuracy to a similar extent. That effect was not accompanied by systematic changes in gaze behavior, at least not in the number of fixations and the duration of the last fixation. Importantly, this does not ultimately mean that there is no effect on a perceptual level and also it would be premature to infer that the effect of action preference on anticipation performance is likely due to biases occurring at later information processing stages. For this purpose, it would be necessary to further investigate how the respective types of information (i.e., kinematic and contextual information) are combined. In this respect, Helm et al. (2020) postulate a Bayesian approach and oppose an "either or strategy" by which they exclude simple heuristics and an equal weighting model as alternative explanations. While the effect of knowledge of an opponent's action preference on anticipation performance appears quite robust (cf. Mann et al., 2014; Loffing et al., 2015b; Gredin et al., 2018; Runswick et al., 2019), identification of its underlying perceptual-cognitive mechanisms remains a challenging task for future experimental research. The latter is suggested relevant for the development of strategies on how to integrate contextual information (e.g., action preferences) into training and match preparation to ensure athletes use this information most effectively (Gray, 2015).

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

TL, FL, and JS contributed conception and design of the study. TL organized the database, performed the statistical analysis, and wrote the first draft of the manuscript. FL and JS wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2020.00006/full#supplementary-material

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Visual Cues Promote Head First Strategies During Walking Turns in Individuals With Parkinson's Disease

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Anticipatory eye movement promotes cranio-caudal sequencing during walking turns. Clinical groups, such as Parkinson's disease (PD), do not produce anticipatory eye movements, leading to increased risk of falls. Visual cues may promote anticipatory eye movement by guiding the eyes into the turn. This study examined if visual cues could train anticipatory eye movement. Ten neurotypical young adults and 6 adults with PD completed three blocks of walking trials. Trials were blocked by visual condition: non-cued baseline turns (5 trials), visually cued turns (10 trials), and non-cued post turns (5 trials). A Delsys Trigno (Delsys, Boston, MA) recorded horizontal saccades at 1024 Hz via electrooculography (EOG). Two Optotrak cameras (Northern Digital Inc., ON, Canada) captured body segment kinematics at 120 Hz. Initiation of segment rotation with respect to ipsilateral foot contact (IFC1) prior to the turn was calculated. Neurotypical young adults (NYA) produced typical cranio-caudal rotation sequences during walking turns. Eyes led (407 ms prior to IFC1), followed by the head (50 ms prior to IFC1), then trunk and pelvis. In contrast, PD produced no anticipatory eye or segment movement at baseline. During pre-trials the eyes moved 96 ms after IFC1 and segment movement was initiated by the pelvis followed by trunk and head segments. After visual cue training however, PD produced anticipatory eye movements 161 ms prior to IFC1, followed by the head 88 ms following IFC1 but ahead of trunk and pelvis onset. These results suggest visual cues assist in producing cranio-caudal control during walking turns in PD.

Keywords: visual cues, walking turns, kinematics, Parkinsons' disease, motor control, locomotion ability

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INTRODUCTION

Changing direction, or turning, while walking is a critical aspect of mobility. Turns can comprise up to 45 percent of the total steps taken in a given day (Glaister et al., 2007). To complete a turn while walking the central nervous system (CNS) must coordinate reorientation of the body's segments in the new direction of travel, while at the same time maintaining postural control and the stepping sequence (Patla et al., 1999; Mellone et al., 2016). The most common turning angle used during activities of daily living is a 90-degree turn which is also considered the most unstable given the rapid change in direction that can lead to lateral falls (Mellone et al., 2016).

Turning while walking is defined as having a robust cranio-caudal segment sequence resulting in a head first turning strategy (Spildooren et al., 2017) or steering synergy (Patla et al., 1999; Ambati et al., 2016). This strategy requires independent control of the segments, increasing the complexity of control by the CNS, but also allows individuals to respond to perturbations (Assaiante and Amblard, 1995). It is therefore no surprise that turning while walking becomes difficult through the natural aging of the CNS as well as for individuals with CNS deficits and/or diseases. For example, individuals with Parkinson's disease present an "en-bloc" turning strategy defined as the ascending organization of segment reorientation where the head and body reorient at the same time (or as one) in a blocked or single unit fashion (Assaiante and Amblard, 1995; Spildooren et al., 2017). The use of this strategy serves to minimize the degrees of freedom the CNS must control and aids in postural control. However, in real life situations where adjustments in movement are made quickly, an "en-bloc" strategy may be unsafe and lead to more falls (Assaiante and Amblard, 1995; Wright et al., 2012; Akram et al., 2014).

The Role of Vision in Turning While Walking

During walking and turning, gaze shifts, and reorientation of the head to the new direction of travel prior to turning the body provides the CNS with a frame of reference to assist reorientation of the rest of the body (Hollands et al., 2002). Neurotypical young adults can initiate gaze redirection up to 1000 ms prior to turning (Grasso et al., 1998; Reed-Jones et al., 2009). However, individuals with Parkinson's disease, unlike neurotypical young adults, do not anticipate a turn by moving their eyes and head in the direction of the turn. Instead, individuals with PD maintain the eyes straight ahead until the onset of the turn and use an "en-bloc" turning strategy (Ambati et al., 2016). These observations suggest that en-bloc segment coordination may result from a lack of anticipatory redirection of the eyes. Therefore, developing visual cueing strategies to specifically target anticipatory eye movement while turning may promote use of a head first turning strategy thereby reducing fall risk.

The purpose of this study was to explore how discrete external visual cues would influence acute turning abilities in a group with PD. It was anticipated that the use of discrete external visual cueing would promote eye movement and result in a cranio-caudal rotation sequence deterring PD from using an "en-bloc" movement strategy. In addition to PD, a neurotypical young adult (NYA) group was also examined to understand how the use of visual cues may influence individuals who already use robust cranio-caudal sequencing during walking turns.

MATERIALS AND METHODS

Participants

This study consisted of two sample groups. A neurotypical young adult (NYA) group consisting of 5 male and 5 female volunteers (22.4 +/− 1.4 years), and a group of individuals affected by Parkinson's disease (PD) consisting of 3 male and 3 female (60.8 +/− 11.7 years) whose H&Y stages ranged from 1-3 (Bhidayasiri and Tarsy, 2012) as assessed by the Unified Parkinson's Disease Rating Scale (UPDRS) questionnaire (Goetz et al., 1995). Prior to the study, all participants were screened to identify any medical conditions which would put them at risk by participating in the study. If a risk factor was detected, the participant was excluded for safety reasons. Approval was obtained from the University of Prince Edward Island Research Ethics Board and all participants provided informed written consent prior to data collection. Data collection was conducted in accordance with the World Medical Association's Declaration of Helsinki.

Experimental Set-Up

A course consisting of a straight walkway leading to a 90-degree left turn was constructed. The dimensions of the straight walkway were 0.95 meters in width and 2.29 meters in length. The walkway after the turn was 1.37 meters in length (See **Supplemental Data** for schematic and pictures). Participants were instructed to proceed down the walkway at an unconstrained self-selected pace until they reached the 90-degree left turn.

Four discrete external visual cues (large high contrast numbers 1, 2, 3, 4), printed on 11 × 17 inch paper and laminated, were placed on the laboratory wall with a barrier being used to obstruct three of the four cues (2, 3, 4) from the participants' view. Cue 2 became visible to the participant just before they entered the turn while cue 3 and 4 were visible once the participant proceeded into the turn. Hiding the visual cues was done to promote anticipatory eye movements during turning and to eliminate visual searching and/or sampling at the beginning of the trials.

Two Optotrak (Northern Digital Inc., Waterloo, ON) cameras captured three-dimensional kinematic data at 120 Hz. Five triangular rigid bodies with three active Infrared Emitting Diode (IRED) markers were secured to the anterior aspect of the head, trunk, pelvis and right, and left foot of the participant. A further marker was placed on each heel for heel contact event detection. A Delsys Trigno (Delsys, Boston, MA) Wireless Electrocardiography (ECG) sensor was used to record electrooculography (EOG) at a frequency of 1024 Hz. The electrode was placed on the lateral aspect of the orbit to track horizontal movement of the eye. Calibration of EOG was done with a 9-point calibration reference frame typically used for eye tracking devices so that forward gaze produced steady baseline data, a shift of the eyes to the right produced positive values and a shift of the eyes to the left produced negative values.

Protocol

Participants were instructed to proceed to the starting line of the course in preparation for each trial. The researcher counted down from three, at which point the participant walked toward the turn. At the turning point, they completed a left turn around the 90-degree angle.

Participants were permitted up to three practice trials before data collection began. These practice trials were used to determine the start foot (first step in trial) so that the left foot would fall at the point in the walkway for the participant to begin the turn.

Walking trials consisted of three sets of blocked trials: Five pre trials where participants walked and turned on the walkway in their own manner ("pre"), followed by ten trials with visual cues in place ("cued"), and finally five post trials where visual cues had been removed ("post").

On completion of the first 5 pre trials, participants were asked to stand or sit near the starting line of the course for a short 5-min break. During this break, the visual cues (1, 2, 3, 4) were placed in their appropriate locations. After this break, the participant was asked to stand at the start position and instructed to "look at the cues as they became visible". During this set of trials, as the participant walked down the course toward the turn, they saw a visual cue on the wall in front of them with the number 1 on it. As they approached the turn, proceeded into the turn, and completed the left turn, cues 2, 3, and 4 located on the wall, became visible to the participant. This protocol was carried out for the ten cued trials. Following completion of the cued trials each participant was allotted a mandatory 15-min break in the testing which allowed for a brief washout period. During this break, the neurotypical young adult participants sat quietly, whereas, all participants with PD sat and completed the Activities-Specific Balance Confidence (ABC) Scale (Powell and Myers, 1995). All PD reported high levels of confidence (70–100%) and the ABC scale was not used in further data analyses. Once the 15-min break was completed, participants proceeded back to the starting line of the course for the final set of trials. The same protocol was used as those of the initial pre trials.

Data Reduction

The turn movement was defined by the ipsilateral foot contact (IFC1) prior to change in direction (onset) to the ipsilateral foot contact (IFC2) following the change in direction (completion), as used in previous work (Patla et al., 1999; Ambati et al., 2016). Refer to **Supplementary Figure 1** in supplementary files for further definition. Foot contacts were determined as the zero crossing following minima of the heel marker vertical velocity.

All kinematic data were exported from First Principles (Northern Digital Inc., Waterloo, ON) collection software and imported into a custom Matlab program. Kinematic data were smoothed using a second-order, dual-pass Butterworth filter with a low-pass cut off of 7 Hz. Yaw angular displacement (about the global vertical axis) were calculated for the head, trunk and pelvis using the triad markers placed on each segment. These were numerically differentiated to determine angular velocities at each instant in time. Time of turn onset was then estimated as the local minima of each segment's yaw angular velocity prior to reaching maximum angular velocity during the turning motion. Segment onsets were referenced with respect to IFC1 by subtracting each segment onset time from IFC1 time (milliseconds) as per previously published work (Patla et al., 1999; Hollands et al., 2002; Ambati et al., 2016). Intersegment timing, differences between when adjacent segments initiated rotation, were examined by comparing the onset of the inferior segment to that of the superior segment. In addition to timing variables, magnitude of segment rotation, and turn time (duration of the turning movement) were calculated. Turn magnitude was the final angular displacement of the segments at IFC2 (completion of turn). Turn time was calculated by subtracting time at IFC2 from IFC1.

Analysis of EOG focused on horizontal saccadic eye movement. Saccade onset was determined from the zero-crossing of the first minima in the EOG data. EOG data was manually inspected by a single rater. This onset time was then calculated with respect to IFC1 as per the body segments. Representative raw eye data are presented in **Figure 1**. The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

Statistical Analyses

All participants reached a maximum segment rotation magnitude of 1.6 rads (91.7 degrees) and fully completed the 90 degree turn. Rotation magnitudes were not analyzed further.

A general linear model repeated measures analysis of variance (ANOVA) was used to examine the effects of visual cues *within* each of the participant groups: the neurotypical young adult group and the group with Parkinson's disease. This model was used because the interest of this study was not to compare between these two groups, but rather to understand the effects of the visual cues within each group. For each group the independent variable *visual cues* had 3 levels: pre, cued, and post. The dependent variables - onset times of the eyes, head, trunk, and pelvis were assessed using a univariate model. Alpha level was set at 0.05 and Greenhouse-Geisser corrections were used when assumptions of sphericity were violated. Pair-wise comparisons were made using Bonferroni corrections for multiple comparisons. For all statistical reporting the effect size is included (n^2).

To address the question of whether a top-down segment sequence was used we compared the onset time of the inferior segment to the onset time of the superior segment using paired sample t-tests. For example, a paired sample t-tests between the eyes and head were completed for each of the conditions pre, cued, and post. Non-significant differences between adjacent segment onset times suggest segments moving closer together (more en bloc) whereas significant differences suggest segments moving more independently.

To investigate the role condition played in the time required for NYA and PD to complete the 90-degree left turn, a general linear model repeated measures ANOVA was used with the independent variable visual condition set at 3 levels: pre, cued, and post and the dependent variable of time to complete the turn.

RESULTS

In order to address our research questions, data reporting is presented in a two-step manner. First, we describe the changes that occurred in the neurotypical young adult group as the group served as our baseline. Next, we describe the PD sample to determine how the visual cues altered their turning control.

Comparison Within the Neurotypical Young Adult Sample

Raw eye data from a representative NYA (**Figure 1**) illustrates the distinct saccades made by NYA in the pre-trials. These distinct saccades were observed for all trials in NYA. Examination of eye and body segment rotation onset was done through repeated measures analysis with all dependent variables entered into the model. Analysis of segment onset time revealed no significant differences for EOG [$F_{(1.808, 16.276)} = 1.800$; $p = 0.198$; $n^2 = 0.167$]; Head [$F_{(1.894, 17.044)} = 1.195$; $p = 0.324$; $n^2 = 0.117$]; Trunk [$F_{(1.598, 14.386)} = 1.090$; $p = 0.348$; $n^2 = 0.108$]; Pelvis [$F_{(1.812, 16.307)} = 2.551$; $p = 0.113$; $n^2 = 0.221$].

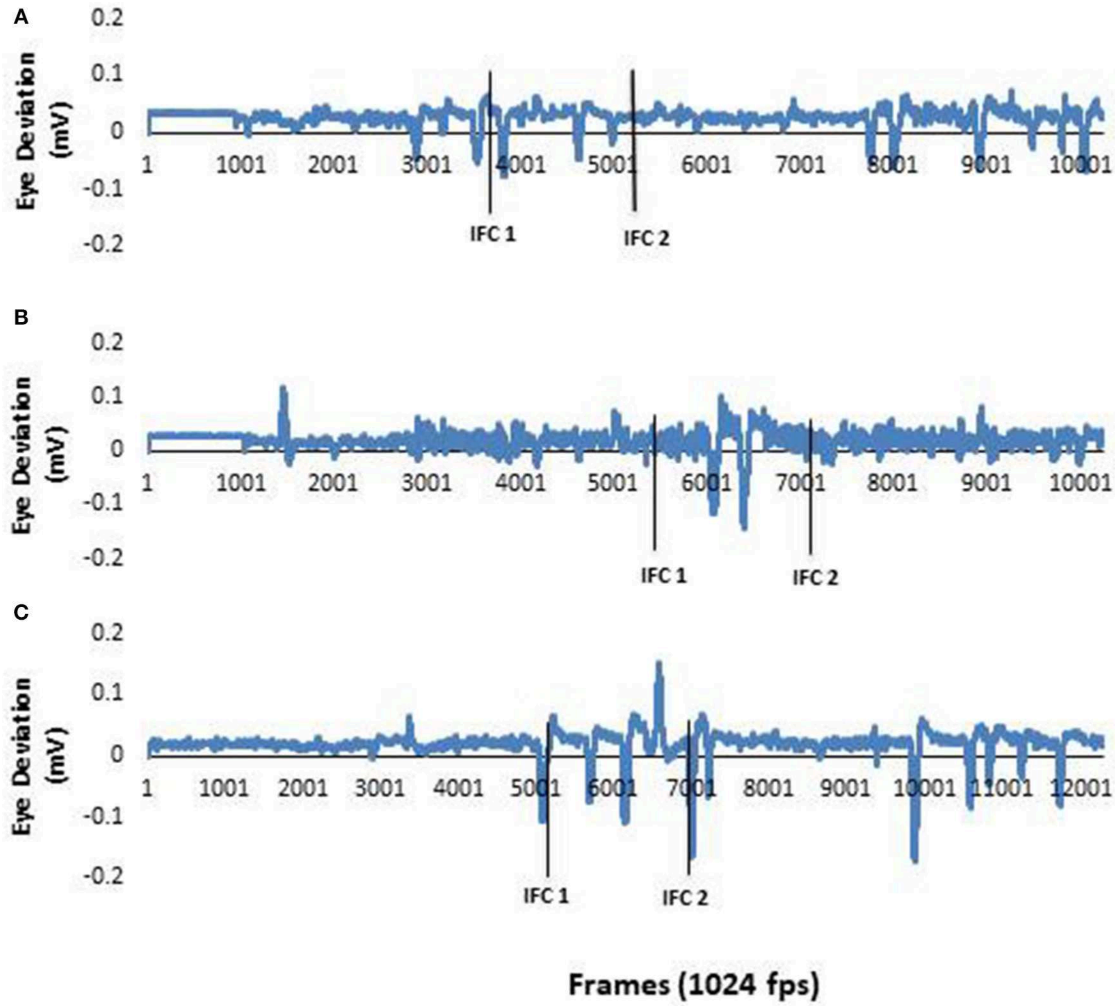

FIGURE 1 | (A) EOG data from a typical neurotypical young adult participant. As the healthy young adult participants eye movements were active throughout the study, these data represent information collected in all three conditions. **(B)** EOG data from a typical PD participant during a pre-trial. There was no horizontal eye movement in the first half of the recording. This demonstrated there was no anticipatory eye movements used by the PD during this trial. **(C)** EOG data from a PD participant in **(B)** during a post trial. This figure clearly shows anticipatory eye movement during the trial. The first solid black line represents ipsilateral foot contact I (IFCI) and the second solid black line represents ipsilateral foot contact 2 (IFC2). The two lines together window the 90 degree left tum.

While onset times were not significantly different between conditions, there were some differences in timing worth noting as a result of visual cueing. Mean onset time (ms) for EOG during the pre, cued, and post trials were −407 ± 116 SEM, −3 ± 171 SEM, and −210 ± 169 SEM prior to IFC1 respectively (**Figure 2**), indicating that in the cued trials it took longer for the initial eye movement to occur. Mean onset time (ms) for head rotation were −50 ± 53 SEM, −27 ± 52 SEM, and −127 ± 75 SEM for the pre, cued, and post trials. These results indicated that NYA participants rotated their heads prior to the 90-degree left turn in all conditions; however, the earliest rotation was in the post trials (**Figure 2**). In all conditions, the eyes and head always led the body during turning, demonstrating robust use of the head first or steering synergy as defined by the literature (Grasso et al., 1998; Patla et al., 1999; Hollands et al., 2002; Reed-Jones et al., 2009).

Paired samples T-tests for intersegment coordination indicated there was a significant difference ($p = 0.011$) between EOG and head in the pre-trials but not in the cued ($p = 0.889$) or post trials ($p = 0.637$) (**Figure 2**). The head and trunk produced significant differences for the pre and post trials, but not for the cued trials (pre: $p = 0.001$, cue: $p = 0.210$, post: $p = 0.002$). The trunk and pelvis showed non-significant differences for the pre and cued trials, whereas a significant difference was found for post trials (pre: $p = 0.082$, cue: $p = 0.134$, post: $p = 0.012$).

Finally, the time to complete the turn was examined between conditions (**Figure 3**). Results indicated that condition did not affect the time needed to complete the 90-degree walking left turn [$F_{(1.905, 17.147)} = 0.496$; $p = 0.609$; $n^2 = 0.052$].

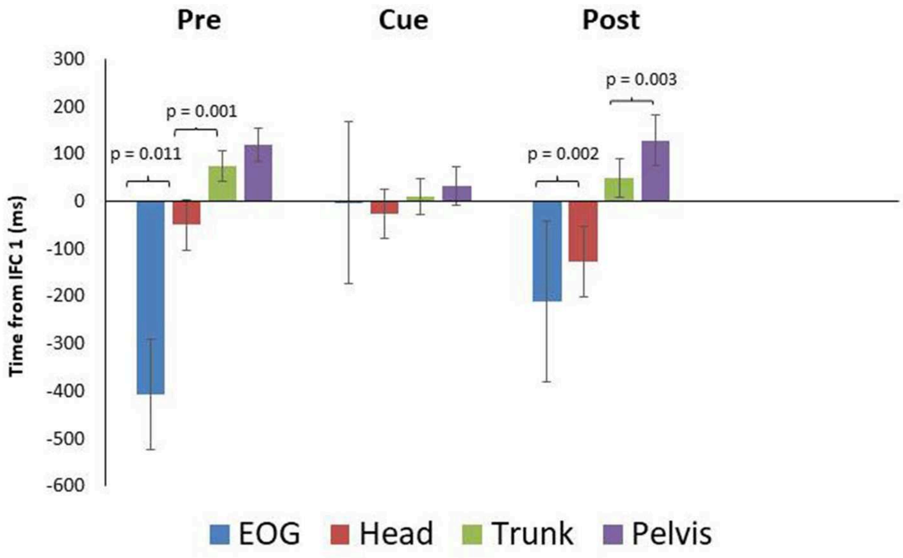

FIGURE 2 | Eye and segment rotation onset (mean ± SE) with respect to IFC 1 of the walking turn for the neurotypical young adult (NYA) participants. Negative values indicate onset prior to initiation of the turn while positive values indicate onset after the start of the turn (IFC 1) as defined in this study. NYA produced a cranio-caudal rotation sequence throughout the trials. Anticipatory eye movements were delayed during trials with visual cues.

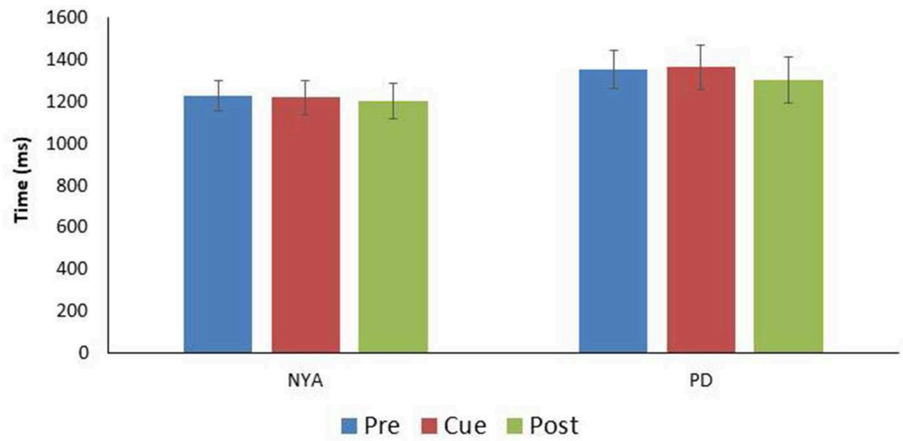

FIGURE 3 | Comparison turn time (time between IFC1and IFC 2) for the two experimental groups (mean ± SE). Note there were no significant differences in turn time between the conditions within either group.

Comparison Within the Parkinsonian Sample

Raw eye data from a representative PD (**Figure 1**) illustrates the absence of distinct saccades in the pre-trials. In contrast distinct saccades were observed in post trials. Repeated measures analysis indicated no significant effects of visual condition on EOG [$F_{(1.260, 6.302)} = 0.927$; $p = 0.396$; $n^2 = 0.156$]; Head [$F_{(1.033, 5.165)} = 1.521$; $p = 0.272$; $n^2 = 0.233$]; Trunk [$F_{(1.936, 9.681)} = 1.391$; $p = 0.293$; $n^2 = 0.218$]; Pelvis [$F_{(1.279, 6.395)} = 2.092$; $p = 0.199$; $n^2 = 0.295$].

PD means for EOG were 96 ± 253 SEM, 210 ± 203 SEM, and−161 ± 109 SEM ms for the pre, cued and post trials, respectively. These data indicate PD did not produce anticipatory eye movement in the pre and cued trials as onset times followed IFC1. For post however, PD did produce anticipatory eye movement (**Figures 1**, **4**). Head rotation initiated at 168 ± 43 SEM, 157 ± 49 SEM, and 88 ± 36 SEM ms following IFC 1 for each condition (pre, cued, and post) respectively (**Figure 4**). These data indicate that PD began to rotate their heads earlier with visual cues, with the earliest head rotation occurring in post trials. Trunk and pelvis onsets got progressively later as eye and head onsets got earlier from pre to cued to post trials (**Figure 4**). These results indicate PD began turning (in pre trials) with the pelvis and trunk moving first supporting more of an ascending

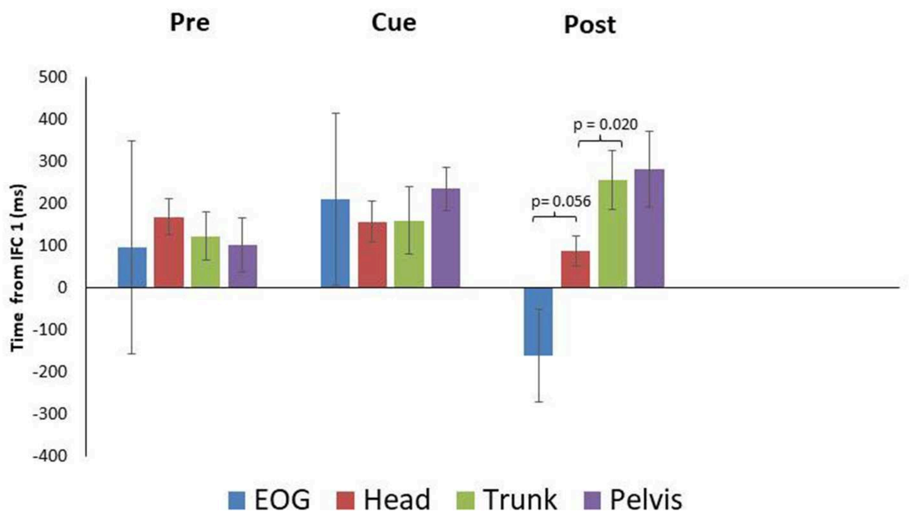

FIGURE 4 | Eye and segment rotation onsets (mean ± SE) with respect to IFC 1of the walking turn for the Parkinsonian {PD} participants. Negative values indicate onset prior to initiation of the turn while positive values indicate onset prior to the start of the turn as defined in this study. PD produced a bottom up rotation sequence during pre-trials. However, following walking turns with visual cues (Cue), anticipatory eye movements and a cranio-caudal rotation sequence were observed (Post).

bottom up turning control but finished trials (after visual cue training) with better top-down head first turning control.

Paired samples T-tests indicated a non-significant difference between EOG and head for the pre and cued trials, with marginal significance in post trials (pre: $p = 0.753$, cue: $p = 0.762$, post: $p = 0.056$) (**Figure 4**). The head and trunk produced a non-significant difference for the pre and cued trials, however, a significant difference was observed for the post trials (pre: $p = 0.124$, cue: $p = 0.956$, post: $p = 0.020$). The trunk and pelvis showed non-significant differences for all conditions (pre: $p = 0.137$, cue: $p = 0.164$, post: $p = 0.538$). The estimated marginal means indicted that the head rotated prior to the eyes in the cued (−53 ms) trials, however in the pre (72 ms), and post (249 ms) trials, the head rotated subsequent to the eyes.

Finally, the time to complete the turn was examined between conditions (**Figure 3**). Results indicated that condition did not affect the time needed to complete the 90-degree walking left turn [$F_{(1.905, 17.147)} = 0.496$; $p = 0.609$; $n^2 = 0.052$].

DISCUSSION

The purpose of this study was to explore the use of discrete external visual cues to promote eye movements during a walking turn in a group with PD, thus reinforcing a head first strategy (Ambati et al., 2016; Spildooren et al., 2017). Neurotypical young adults were examined as a basis for understanding how visual cues may influence robust turning control. Interestingly the results suggest that the greatest effect of using visual cues during walking turns in a PD group was in trials following their use when the cues were removed (i.e., a post training effect).

Neurotypical Young Adults

Neurotypical young adults naturally produce a head first strategy (Patla et al., 1999; Hollands et al., 2002; Ambati et al., 2016; Spildooren et al., 2017). Given this, we wanted to see how NYA would react to discrete external visual cues during walking turns. It was hypothesized NYA would not significantly alter turning behaviors between cued and non-cued trials. Results support this hypothesis partially. There were no significant main effects of condition on the onset of segment rotation with reference to IFC1. However, NYA did show significant differences in intersegment onset times. NYA produced anticipatory eye movement prior to head rotation onset as per the head first turning strategy in both pre and post conditions (**Figure 2**). However, there were some changes in the behavior of the eyes and head when visual cues were present that warrant discussing for future studies.

The paired samples T-test indicated there was a significant difference between mean EOG and head onset in the pre-trials, but non-significant differences were found for cued and post trials. Data presented in **Figure 2**, suggest the cued trials slightly delayed NYA anticipatory eye movement. This slight delay in anticipatory eye movement did recover in the post trials once the cues were removed. These data suggest the appearance of the second discrete external visual cue was either later than normal for the neurotypical young adults, who in pre-trials began eye movement ∼400 ms prior to IFC1, and/or that the instructions given to follow the numbers altered normal eye control in NYA. Therefore, instructions and timing of visual cues are a critical consideration when studying endogenous visual cues. Small differences in these factors could limit comparisons between studies.

PD Participants

Individuals with PD are known to fixate on objects while turning which impedes anticipatory eye movements ahead of the turn, resulting in altered segment coordination during turning (Ambati et al., 2016; Stuart et al., 2017). This was evident, in the pre-trials of our study where anticipatory eye movements were not observed (**Figure 1**), and the resulting sequence of body reorientation occurred from the pelvis up (**Figure 4**). During cued trials some changes in sequences were observed though not statistically significant. However, it was on the removal of the discrete external visual cues for the post trials that a classic anticipatory eye and head first turning strategy was observed in PD (**Figure 4**). This was further supported by the differences between eye-head and head-trunk rotation onsets. This was a very interesting result and was the major contribution of this preliminary study to future work. It could be that visual cues do in fact train eye movements successfully and it would be interesting to see with longer post intervals how long PD retain anticipatory eye behavior following training.

Several limitations should be addressed moving forward from this preliminary report. The most notable was the low sample size of the PD group ($n = 6$). Secondly, only 90 degree left turns were studied. The decision to limit the turns to one side was made for two reasons: (1) to limit fatigue in PD (including left and right would double the trials and increase lab time); (2) previous research in turning has collapsed left and right turns because of non-significant differences. Gait speed was not controlled rather a self-selected pace was used. The decision to use a self-selected pace was made because auditory cues (e.g., a metronome) alter gait and turning control in PD (Spildooren et al., 2017), and the purpose of the current study was to examine visual cues. Despite not controlling gait speed, the time to turn was not significantly different between conditions. As this was a within group and within participant experimental design any differences across groups and participants in gait speed did not influence the use of time data. Analysis of EOG was very simple and greater analyses of these data could provide interesting research avenues.

Overall, this exploratory study is the first to examine the use of discrete external visual cues placed along a 90-degree walking turn with the goal of producing coordinated turning in individuals with PD. The results highlight that even the simplest design of discrete external visual cues can produce anticipatory eye movement and a head first turning strategy in PD. However, the positive effects of using visual cues with walking turns seems to be most evident *post* training, once visual cues are removed from the environment. These results have interesting implications for the use of visual cues during turning movements in studies aiming to improve turning control in populations who have difficulty. In addition, the results of this study further support the hypothesis that eye movement has a critical role in the motor control of turning movements.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Prince Edward Island Research Ethics Board. Written informed consent was obtained from the individual for the publication of any potentially identifiable images included in this article.

AUTHOR CONTRIBUTIONS

RR-J, TB, and JP contributed substantially to the conception and design of the work. RR-J, TB, JP, and MM contributed substantially to the analysis and interpretation of data for the work. All authors contributed to the drafting of the work or revising it critically for important intellectual content and provided approval for publication of the content and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2020.00022/full#supplementary-material

Data Sheet 1 | A schematic of the experimental layout. Each square represents 0.15 meters. Optotrak cameras are coded in blue and the four cues (0°, 40°, 60°, 90°) in yellow.

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Using "Enzan No Metsuke" (Gazing at the Far Mountain) as a Visual Search Strategy in Kendo

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In Kendo (Japanese fencing), "Enzan no Metsuke" is an important *Waza* (technique) that is applied by expert Kendo fighters. It involves looking at the opponent's eyes with "a gaze toward the far mountain," taking in not only the opponent's face but also his or her whole body. Over the last few decades, a considerable number of studies on visual search behaviors in sport have been conducted. Yet, there are few articles that examine visual search behaviors in combat sports, such as martial arts. This study aimed to analyze the visual search strategies used by expert Kendo fighters through sparring practices to discuss what "Enzan no Metsuke" is under experimental, but natural (*in situ*), conditions. Ten experts, 10 novices, and one *Shihan* (a master of Kendo) participated in this study. The fighters wore a mobile eye tracker and faced a real opponent. They were instructed to do the following in five different sessions: prepare themselves, practice their offense and defense techniques, and fight in a real *Shiai* (match). The results indicated differences in the visual search strategies between the *Shihan*, experts, and novices. The *Shihan* and experts fixated on their opponent's eyes or head region most of the time and adopted a visual search strategy involving fewer fixations of longer duration. Conversely, novices set their eyes mainly on the opponent's *Shinai* (sword). Only the *Shihan* always looked at the opponent's eyes, even during the preparation, offense, and defense sessions. *Shihan* and experts set their "visual pivot" on the opponent's eyes quietly, even when the opponent tried to attack with the *Shinai*. Novices, however, moved their eyes up and down based on the influence of their opponent's movements. As these results indicate, novices tried to search for detailed information about their opponent and processed visual information depending on their focal vision, whereas *Shihan* and experts absorbed information not from their opponent's eyes but from their entire body by utilizing their peripheral vision; this means that *Shihan* and experts could see an opening or opportunity and react instantaneously by using "Enzan no Metsuke."

Keywords: eye movements, Kendo, peripheral vision, visual pivot, expertise, Enzan no Metsuke

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INTRODUCTION

In most sporting situations, players have to make quick, accurate decisions under severe spatial and temporal constraints. Successful sporting performance requires efficient and accurate execution of movement patterns and the ability to perceive important information from a complex and constantly changing environment. For instance, players of a ball game, like soccer, or basketball, must act on the visual information presented by the ball, their opponents, and their teammates (Williams et al., 1999). The process of obtaining information accurately and rapidly from selected areas of the visual display is known as a "visual search." Reports reveal that expert players do not move their eyes randomly; rather, they adopt visual search patterns based on deliberate perceptual strategies (e.g., Bard and Fleury, 1976; Williams et al., 1999; Vickers, 2007). Over the last few decades, a considerable number of studies examining visual search behaviors in sport have been conducted. Mann et al. (2007) conducted a meta-analysis on experts' perceptual-cognitive skills in their chosen sport. Results revealed that they tended to rely on fewer fixations of longer duration compared with less-skilled players or novices.

Conversely, Mann et al. (2009) showed that expert football (soccer) players had superior decision-making skills with more search fixations of shorter duration when viewing aerial video footage as opposed to a player's perspective. In this situation, it appears that skilled athletes optimize their performance through searching more locations (Williams and Jackson, 2019). Recently, Kredel et al. (2017) reported that eye-tracker studies have increased and that field studies conducted under *in situ* conditions, or those with larger degrees of external validity, contributed to developing an understanding of players' visual information input in sport-related tasks.

Currently, few studies have examined visual search behaviors in combat sports such as boxing, kung fu, karate, and judo (Ripoll et al., 1995; Williams and Elliott, 1999; Piras et al., 2014; Milazzo et al., 2016b; Hausegger et al., 2019). Ripoll et al. (1995) showed that expert boxers adopted a more efficient search pattern compared to non-experts and tended to maintain foveal fixation as a "visual pivot" on central regions of the opponent's body while using their peripheral vision to acquire information from the hands and feet regarding the initiation of an attack. Williams and Elliott (1999) also reported that expert karate fighters exhibited superior anticipation compared to non-experts when experiencing varying levels of anxiety and that they "anchored" their fovea on the central regions of their visual display while using their peripheral vision to monitor their opponent's limb movements. Thus, these articles suggest a correlation between the level of expertise and the fighter's visual search strategy. Milazzo et al. (2016b) reported that expert karate fighters spent more time fixating on their opponent's head and the torso with a low search rate, as opposed to novices, who spent more time fixating on the pelvis and the front hand of their opponent with a high search rate. Similarly, expert judo fighters used a search strategy involving fewer fixations of longer duration and spent more time fixating on the lapel and face compared to their novice counterparts (Piras et al., 2014). Expert kung fu fighters (like Tae Kwon Do fighters) attack mostly with their legs anchored and their gaze focused at the lower region of their opponent to monitor the relevant cues for kicking attacks (Hausegger et al., 2019).

Considering these studies, fixating on the opponent's head and trunk region and anchoring the gaze on a specific location to use their peripheral vision for picking up relevant cues, like a suspected punch or a kick, is a functional visual strategy in contact sports.

FIGURE 1 | The concept of "Enzan no Metsuke." It is said that "Enzan no Metsuke" is one of the most important *Waza* whereby fighters look at their opponent with a gaze toward the mountains in the distance, taking in not only their opponent's face but their whole body as well.

The *Waza* technique is used in Kendo (also known as the Way of the Sword and the art of Japanese Samurai Swordsmanship) and is especially applied by expert Kendo fighters. In Kendo, the sequence of perception to *Waza* is described as *Ichi gan* (first for eye), *Ni soku* (second for feet), *San tan* (third for abdomen or center), and *Shi riki* (fourth for power). Sight is the first element of any technique, and the way Kendo fighters watch their opponents is crucial to the success of their attack. "Metsuke" means the point of observation or the way of seeing. It is said that "Enzan no Metsuke" (gazing at the far mountain) is one of the most important *Waza* whereby fighters look at their opponent with a gaze toward the mountains in the distance, taking in not only their opponent's face but their whole body as well (**Figure 1**). Salmon (2013), a Kendo fighter, explains this concept in the following way "If we stare at the target we are going to strike, we give our opponent obvious notices of our intention. If we look just at his or her face to try to understand their next action, we may miss the signals he gives when he starts to move hands or feet. If we look just at feet or hands, we can be easily tricked by movement designed to get our attention. If we look at the point of the *Shinai*, there is even more chance that we may be fooled by a feint" (p. 46). Therefore, the gaze should see everything without focusing on any one point. Fighters are instructed in "Enzan no Metsuke" to fix their gaze on their opponent's eyes and utilize their peripheral vision in order to pick up information from the whole-body movements of their opponents frequently in practice, and they try to practice while thinking about it. However, studies have yet to analyze the visual search behavior of "Enzan no Metsuke" from the viewpoint of empirical scientific research.

In this paper, I explain the visual search behavior of "Enzan no Metsuke" by investigating the differences in the visual search

FIGURE 2 | Experiment scenes (**Left**, common distance ∼2.5 m between fighters in S1, S3, S4, and S5; **Right**, *Tsubazeriai* distance, which is extremely close, the swords were tangled, and the average interpersonal distance was ∼1 m in S2).

strategies between expert Kendo fighters and novices, especially including *Shihan*, who is a Kendo master under the live Kendo practice and competitive *in situ* conditions. Analysis of how they use their eyes and the visual pivot technique to gain informative and efficient visual information will also be included. Our main hypothesis was that expert Kendo fighters adopt a visual search strategy that involves fewer fixations of longer duration and the use of peripheral vision based on the findings of previous studies regarding visual search behaviors in combat sports (Ripoll et al., 1995; Williams and Elliott, 1999; Piras et al., 2014; Milazzo et al., 2016b; Hausegger et al., 2019).

MATERIALS AND METHODS

Participants

Twenty Kendo fighters in university and one Shihan (a master of Kendo) were recruited as participants. The expert group contained 10 fighters from the university team (mean age = 20.4 years; SD = 1.4) with an average of 13.7 years (SD = 3.2) of prior Kendo experience. They had been awarded the fourth Dan, which is a relatively high rank in a grading system that consists of six basic grades called Kyu (sixth to first) and eight advanced grades called Dan (first to eighth). The novice group contained 10 fighters (mean age = 20.8 years; SD = 1.3) with an average of 3.9 years (SD = 1.4) of prior Kendo experience only in physical education class but who had no prior competitive level experience. Only one Shihan, aged 65 years, who was awarded the eighth Dan and Hanshi title, which is the highest attainable rank, was included. He had mastered and completed the principle of the Sword and had outstanding knowledge of Kendo. Therefore, he participated in this study as a special reference and was not examined using statistical analysis. The experimental protocol was approved by the institutional ethics committee of Keio University SFC, and the tenets of the Declaration of Helsinki were observed. Written informed consent was obtained from each participant, and all fighters reported normal vision or corrected-to-normal vision.

Apparatus

Visual search behaviors were recorded using a lightweight eye movement registration system EMR-9 (NAC Image Technology Inc., Tokyo, Japan). The system utilized the pupil and corneal reflex method at 60 Hz. Its precision was <0.1 degrees in both the horizontal and vertical directions. Data were stored on the SD card in the recording unit and then transferred onto a computer. For the analysis of performance during each session, all behaviors of participants were recorded using an external video camera situated at a distance of 5 m away from the center of the court.

Procedure

The task and constraints of the experimental conditions were explained to the participants before each trial. It was confirmed before the experiments that all participants had knowledge of "Enzan no Metsuke" regardless of whether they had mastered it in the right manner or not, and they were not instructed about "Enzan no Metsuke" during the experiments. They performed an individual, generalized warm-up, and the EMR-9 system was fitted. Initially, the system was calibrated and validated with a nine-point reference grid presented ∼2.5 m in front of the fighters, which is the average interpersonal distance between two fighters (Yamamoto et al., 2016) (**Figure 2**). All participants competed against the same one opponent from the expert group who behaved in a manner similar to a real match situation. At the beginning of each trial, participants and the opponent were precisely positioned face-to-face in an upright posture. They then competed in a real match situation for a few minutes. Gaze accuracy was maintained by having participants fixate on constant reference points before and after every trial, so that a recalibration could be performed, if necessary.

Five different sessions (S) which were similar tasks to those in usual sparring practices for Kendo fighters, were conducted, and all of the data that were analyzed in each session were the same length of time for all participants: Preparation (S1; 18 s) was performed after the fighters took a standing bow and *sonkyo* (crouching down with the sword) at a distance. They then stood up and came closer to take a posture with the cutting edge of the sword facing toward their opponent with the sword tips crossing slightly. It was not required for them to do any additional attacks or defenses. S1 lasted about 20 s, and the data of last 18 s were analyzed because the fighters tended to move their eyes outside of the opponent's body areas, which included useless data such as no fixation during the time they stood up, walked to the opponent, and took a posture in the initial part of the session. Close-contact (S2; 18 s) was performed with the fighters in the *Tsubazeriai* situation (close together with swords tangled, and the average interpersonal distance was ∼1 m at this time) (**Figure 2**) and trying to push their opponent back to create another chance for them to attack. Fighters were required to strike their opponent's *Men* (Kendo head armor) once while quickly moving backward to make a proper space. Each attack was repeated until success, and the number of attempts was counted. S2 lasted from about 20–30 s, and the data of the last 18 s were analyzed. Offense practice (S3; 12 s) was performed when fighters were required to strike their opponent's *Men*, *Do* (side trunk covered by a stomach and chest protector), and *Kote* (lower forearm covered by a gauntlet), once for each. Each attack was repeated until success, and the number of attempts was counted. It took about 5 s for each attack, and the data of the last 4 s were analyzed. Defense practice (S4; 12 s) was performed three times when the fighters started to defend against their opponent's *Kote* attack. The number of blocked attacks was counted. It took about 5 s for each attack, and the data of the last 4 s were analyzed. *Shiai* (S5; 60 s) was performed when the fighters competed in almost the same manner as a real match (barring attacks to the *Men*). The session actually lasted from 1.5 to 4 min from the time the referee called *Hajime* (begin) until the referee called *Yame* (stop) when one of the fighters was awarded two points. The data of the last 60 s were analyzed because some of the experts already got two points after <2 min from *Hajime*. By reference to previous research (Nakamura et al., 2014), the number of offensive techniques (striking an opponent before the opponent initiates an attack), counter techniques (striking an opponent after rendering the opponent's attacks ineffective), defensive techniques (defending against the opponent's attack), and awarded points (scored if the participant struck an opponent accurately) were counted.

Data Analysis

The number of attempts in S2 and S3, the number of blocked attacks in S4, and the number of offensive, counter, and defensive techniques and awarded points in S5 were evaluated as the performance during each session. The between-group differences across each of these measures were analyzed separately using Welch's t-test and Cohen's d effect size measures for each task. Also, a success rate, which was the number of successes divided by number of attempts, was calculated for each session.

Eye movement data encoded by the EMR-9 system were analyzed frame-by-frame to obtain the visual search rate and percentage viewing time values. The fighters' visual fields were divided into specific areas to derive the fixation location: *Men, Do, Shinai* (a sword), *Kote*, lower body, or other, which was included to account for those fixations that did not fall within any of the above areas. The visual angle of the height of the opponent (181 cm) held at normal interpersonal distance is ∼39.8 degrees. The area of *Kote*, which is the smallest area of interest, subtends ∼3.4 degrees. It was only during S2, when the fighters were in the *Tsubazeriai* situation, that location was more specifically categorized to the upper or lower side of the *Men*, middle of the *Men* (eyes), throat, *Do*, upper arm, *Kote*, *Shinai*, or other, because the fighters, particularly the novices, tried to move their eyes over more specific locations at close-up interpersonal distance in S2 (**Figure 3**). The visual angle of the height of the opponent at this distance is ∼84.3 degrees. The area of the middle of the *Men* (eyes), which is the smallest area of interest, subtends ∼3.2 degrees. Fixation was defined as the period when the eye remained stationary within 1 degree of movement tolerance for a period >99 MS (three video frames) (Vickers, 2007). All trials were taken into consideration for the mean number of fixations, mean fixation duration, and mean number of fixation locations per trial as search rate. The mean number of fixation locations is the average number of locations fixated on according to the categorized areas of the display.

For further analysis, the percentage of viewing time, which is the total amount of time fighters spent viewing each area of the visual display, included the above mentioned fixation locations during all trials (Ward et al., 2002; Roca et al., 2011). The between-group differences across each of these search rate measures (number of fixations, fixation duration, and number of fixation locations) were analyzed separately using Welch's t-test and Cohen's d effect size measures for each task. The percentage viewing time was analyzed using a mixed two-way ANOVA for each task in which the fixation locations were the within-subject factors and groups were the between-subject factors. Mauchly's sphericity test was used to validate the ANOVA, and partial eta-squared values (η_p^2) were used to reflect the strength/magnitude related to the effect of these factors. The sources of any interactions were examined using *post-hoc* comparisons with Shaffer's modified sequentially rejective Bonferroni procedure. The significance level was set at $\alpha = 0.05$.

RESULTS

Performance

The number of attempts, the number of blocked attacks, and the number of offensive, counter, and defensive techniques and awarded points between expert and novice groups are shown in **Table 1**. There were significant group differences for the number of attempts in S2, $t_{(12.13)} = 2.63$, $p = 0.022$, $d = 1.18$, and S3, $t_{(13.17)} = 4.84$, $p < 0.002$, $d = 2.16$. Similarly, there were significant group differences for the number of blocked attacks in S4, $t_{(17.86)} = 7.96$, $p < 0.001$, $d = 3.56$. Additionally, there were significant group differences in S5 for the number of counters; $t_{(16.82)} = 4.19$, $p < 0.001$, $d = 1.87$, the number of defensive techniques, $t_{(18)} = 2.42$, $p = 0.025$, $d = 1.08$; and the number of awarded points, $t_{(13.75)} = 3.54$, $p < 0.003$, $d = 1.58$. Experts and *Shihan* performed better than novices in all sessions, with a high success rate.

Search Rate

The mean number of fixations, mean fixation duration, and mean number of fixation locations between expert and novice groups

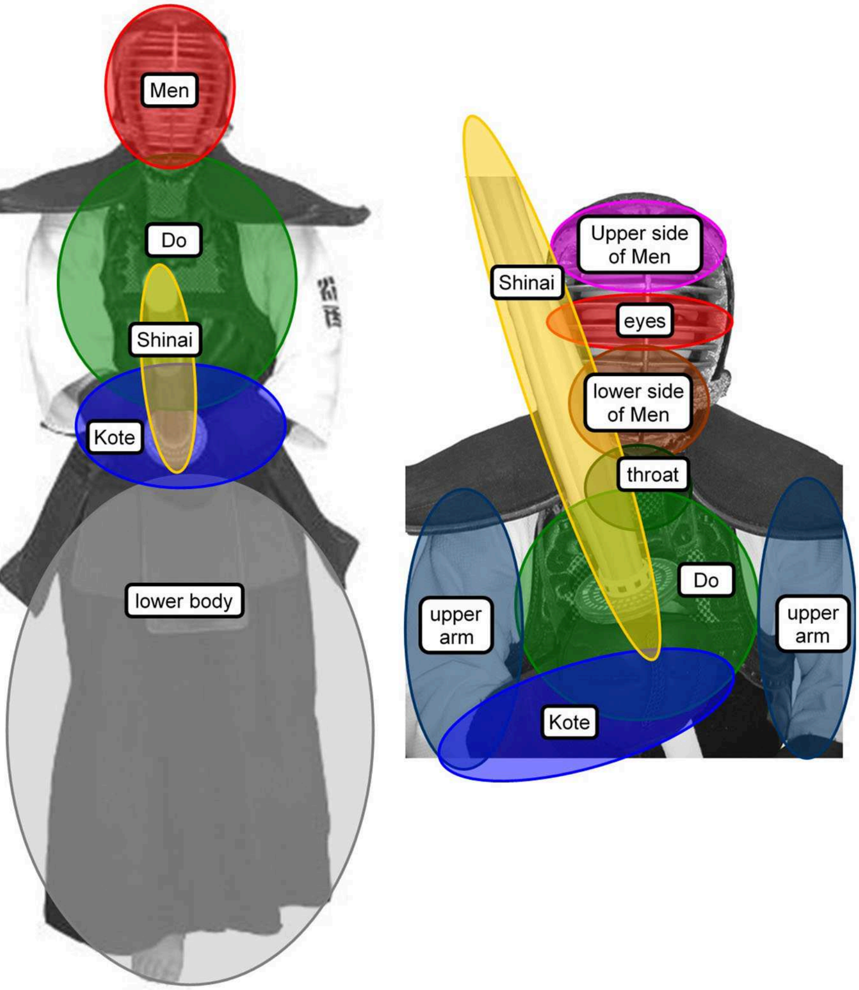

FIGURE 3 | The area of fixation location chosen for the study (**Left**, the five areas considered the whole body in S1, S3, S4, and S5; **Right**, a more specific eight areas in the *Tsubazeriai* distance in S2).

on each task are shown in **Table 2**. There were significant group differences for the mean number of fixations per trial in all sessions: S1, $t_{(17.16)} = 15.77$, $p < 0.001$, $d = 7.06$; S2, $t_{(10.6)} = 6.85$, $p < 0.001$, $d = 3.06$; S3, $t_{(13.74)} = 3.81$, $p < 0.01$, $d = 1.70$; S4, $t_{(13.22)} = 7.72$, $p < 0.001$, $d = 3.45$; and S5, $t_{(9.72)} = 18.61$, $p < 0.001$, $d = 8.32$. Similarly, there were significant group differences for the mean fixation duration per trial in all sessions: S1, $t_{(9.03)} = 4.03$, $p < 0.01$, $d = 2.07$; S2, $t_{(9.08)} = 3.89$, $p < 0.01$, $d = 1.74$; S3, $t_{(12.37)} = 2.81$, $p = 0.02$, $d = 1.26$; S4, $t_{(9.40)} = 4.68$, $p < 0.01$, $d = 2.09$; and S5, $t_{(9.03)} = 4.53$, $p < 0.01$, $d = 2.03$. Additionally, there were significant group differences for the mean number of fixation locations per trial in all sessions: S1, $t_{(9)} = 5.71$, $p < 0.001$, $d = 2.56$; S2, $t_{(17)} = 7.80$, $p < 0.001$, $d = 3.49$; S3, $t_{(14.31)} = 2.60$, $p = 0.021$, $d = 1.16$; S4, $t_{(16.29)} = 5.58$, $p < 0.001$, $d = 2.50$; and S5, $t_{(12.91)} = 5.02$, $p < 0.001$, $d = 2.24$. In most cases, experts employed a less exhaustive visual search strategy involving fewer fixations of longer duration and a smaller number of fixation locations than the novice group. Additionally, the results of the *Shihan* data showed very few numbers of fixation and longer fixation durations in all sessions, even though the data were not analyzed statistically.

Percentage Viewing Time

Figure 4 illustrates the differences in the percentage of viewing time for both groups in all sessions. A violation of the sphericity assumption for mixed measures ANOVA was found in S1, S2, S3, and S5 using Mauchly's sphericity test, S1, $W = 182.79$, $p < 0.001$; S2, $W = 1{,}362.99$, $p < 0.001$; S3, $W = 166.06$, $p < 0.001$; and S5, $W = 189.79$, $p < 0.001$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser epsilon for suggested violation (S1, $\varepsilon = 0.28$; S2, $\varepsilon = 0.19$; S3, $\varepsilon = 0.50$; S5, $\varepsilon = 0.34$). Significant differences were observed for the Group × Fixation location interaction in S1, $F_{(1.41,25.3)} = 70.98$, $p < 0.001$, $\eta_p^2 = 0.80$; S2, $F_{(1.53,27.55)} = 36.47$, $p < 0.001$, $\eta_p^2 = 0.67$; S3, $F_{(2.49,44.9)} = 43.61$, $p < 0.001$, $\eta_p^2 = 0.71$; S4, $F_{(5,90)} = 50.25$, $p < 0.001$, $\eta_p^2 =$

TABLE 1 | Mean (SD) number of attempts in S2 and S3, number of blocked attacks in S4, and number of offensive, counter, and defensive techniques and awarded points in S5 between expert and novice groups.

	Shihan	Expert	Novice
S2: close-contact			
Number of attempts	1	1.2 (0.42)	2.1 (0.99)
Success rate	100.0%	83.3%	47.6%
S3: offense task			
Number of attempts	3	3.3 (0.67)	5.5 (1.27)
Success rate	100.0%	90.9%	54.5%
S4: defense task			
Number of blocked attacks	3	2.5 (0.53)	0.7 (0.48)
Success rate	100.0%	83.3%	23.3%
S5: *Shiai* (match)			
Number of offensive techniques	7	7.1 (1.20)	6.3 (1.42)
Number of counter techniques	3	2.5 (1.08)	0.7 (0.82)
Number of defensive techniques	3	3.1 (0.74)	3.9 (0.74)
Number of awarded points	2	1.2 (0.79)	0.2 (0.42)

The success rate is the percentage of required success divided by the number of attempts.

TABLE 2 | Mean (SD) number of fixations, mean fixation duration, and mean number of fixation locations per trial across groups in all sessions (trial duration).

	Number of fixations	Fixation duration (ms)	Number of fixation locations
S1: preparation (18 s)			
Shihan	2.00	8,999	1.00
Expert	5.60 (2.76)	3,199 (1,691.94)	2.30 (1.49)
Novice	23.20 (2.20)	717 (72.79)	5.00 (0.00)
S2: close-contact (18 s)			
Shihan	2.00	8,999	1.00
Expert	5.60 (2.76)	3,112 (1,995.63)	2.70 (0.82)
Novice	26.40 (9.20)	649 (134.77)	6.00 (1.05)
S3: offense task (12 s)			
Shihan	4.00	2,633	1.00
Expert	6.40 (1.84)	1,678 (740.80)	3.10 (0.74)
Novice	11.10 (3.45)	958 (326.57)	3.80 (0.42)
S4: defense task (12 s)			
Shihan	2.00	6,049	1.00
Expert	4.30 (2.87)	2,808 (1,498.79)	1.50 (0.53)
Novice	20.00 (5.75)	566 (222.18)	3.10 (0.74)
S5: *Shiai* (match, 60 s)			
Shihan	11.00	5,166	3.00
Expert	12.70 (3.30)	4,459 (2,759.19)	2.50 (1.08)
Novice	112.00 (16.55)	501 (105.33)	4.40 (0.52)

0.74; and S5, $F_{(1.68,30.3)} = 81.40$, $p < 0.001$, $\eta_p^2 = 0.82$. *Post-hoc* tests revealed that experts spent a greater percentage of the time fixating on *Men*, $F_{(1,18)} = 81.69$, $p < 0.001$, $\eta_p^2 = 0.82$, whereas novices spent more time watching the *Shinai*, $F_{(1,18)} = 96.29$, $p < 0.001$, $\eta_p^2 = 0.84$; *Kote*, $F_{(1,18)} = 530.57$, $p < 0.001$, $\eta_p^2 = 0.97$; and lower body, $F_{(1,18)} = 25.56$, $p < 0.001$, $\eta_p^2 = 0.59$ in S1. Similarly, in S2, experts spent significantly more time fixating on the eye, $F_{(1,18)} = 45.59$, $p < 0.001$, $\eta_p^2 = 0.72$, while novices spent more time on *Do*, $F_{(1,18)} = 8.60$, $p = 0.009$, $\eta_p^2 = 0.32$; upper arm, $F_{(1,18)} = 8.31$, $p = 0.001$, $\eta_p^2 = 0.32$; *Kote*, $F_{(1,18)} = 5.67$, $p = 0.03$, $\eta_p^2 = 0.24$; and *Shinai*, $F_{(1,18)} = 105.64$, $p < 0.001$, $\eta_p^2 = 0.85$. In S3, experts focused more on *Men*, $F_{(1,18)} = 100.38$, $p < 0.001$, $\eta_p^2 = 0.85$, and novices focused more on *Do*, $F_{(1,18)} = 15.33$, $p < 0.01$, $\eta_p^2 = 0.46$; *Shinai*, $F_{(1,18)} = 18.17$, $p < 0.001$, $\eta_p^2 = 0.50$; and *Kote*, $F_{(1,18)} = 54.16$, $p < 0.001$, $\eta_p^2 = 0.75$. In S4, experts fixated more on *Men*, $F_{(1,18)} = 201.72$, $p < 0.001$, $\eta_p^2 = 0.92$, whereas novices fixated more on *Shinai*, $F_{(1,18)} = 33.05$, $p < 0.001$, $\eta_p^2 = 0.65$, and *Kote*, $F_{(1,18)} = 16.58$, $p < 0.001$, $\eta_p^2 = 0.48$. Furthermore, experts spent significantly more time viewing *Men*, $F_{(1,18)} = 153.16$, $p < 0.001$, $\eta_p^2 = 0.89$ in S5, while novices spent more time viewing *Do*, $F_{(1,18)} = 32.56$, $p < 0.001$, $\eta_p^2 = 0.64$; *Shinai*, $F_{(1,18)} = 34.95$, $p < 0.001$, $\eta_p^2 = 0.66$; and *Kote*, $F_{(1,18)} = 80.84$, $p < 0.001$, $\eta_p^2 = 0.82$. Irrespective of the session, the expert group spent significantly more time fixating on the *Men* or eye in S2. In contrast, the novice group spent more time fixating on the *Shinai* in most cases. Additionally, the *Shihan* set his line of sight on his opponent's *Men* or eye in all sessions.

DISCUSSION

The aim of this study was to elucidate the visual search behavior of expert and novice Kendo fighters under *in situ* conditions, to scientifically demonstrate "Enzan no Metsuke" during a real match of Kendo. We hypothesized that experts demonstrate superior performance with a more efficient visual search strategy involving fewer fixations of longer duration and the use of peripheral vision compared with their novice counterparts. The results of this study reveal that experts set their eyes on the opponent's "eye," which is inside the *Men* most of the time during Kendo practice, and they employed a less exhaustive visual search strategy involving fewer fixations of longer duration and a smaller number of fixation locations. In contrast, the novices tended to search for detailed information on the opponent under the influence of their opponent's sword and body movements, and the results of the search rate showed that they made a great number of short fixations and used a large number of fixation locations.

As mentioned previously, looking into the eyes of the opponent has been emphasized as one of the most important *Waza*, not only in Kendo but in almost all of *Budo* (martial arts in Japan) as well. Ozawa (1997) stated that "you should not focus your eyes on one point; rather, you should focus on the body as a whole, taking your partner's eyes as a central point" (p. 41). It is considered that "Enzan no Metsuke" allows Kendo fighters to use peripheral vision and pick up advanced cues from the whole-body movements of their opponents (**Figure 1**). In this study, detailed peripheral visual processing of fighters from eye movement data could not be examined, because of the limitation of *in situ* experimental situations. Still, the results of performance analyses revealed that experts could act or react

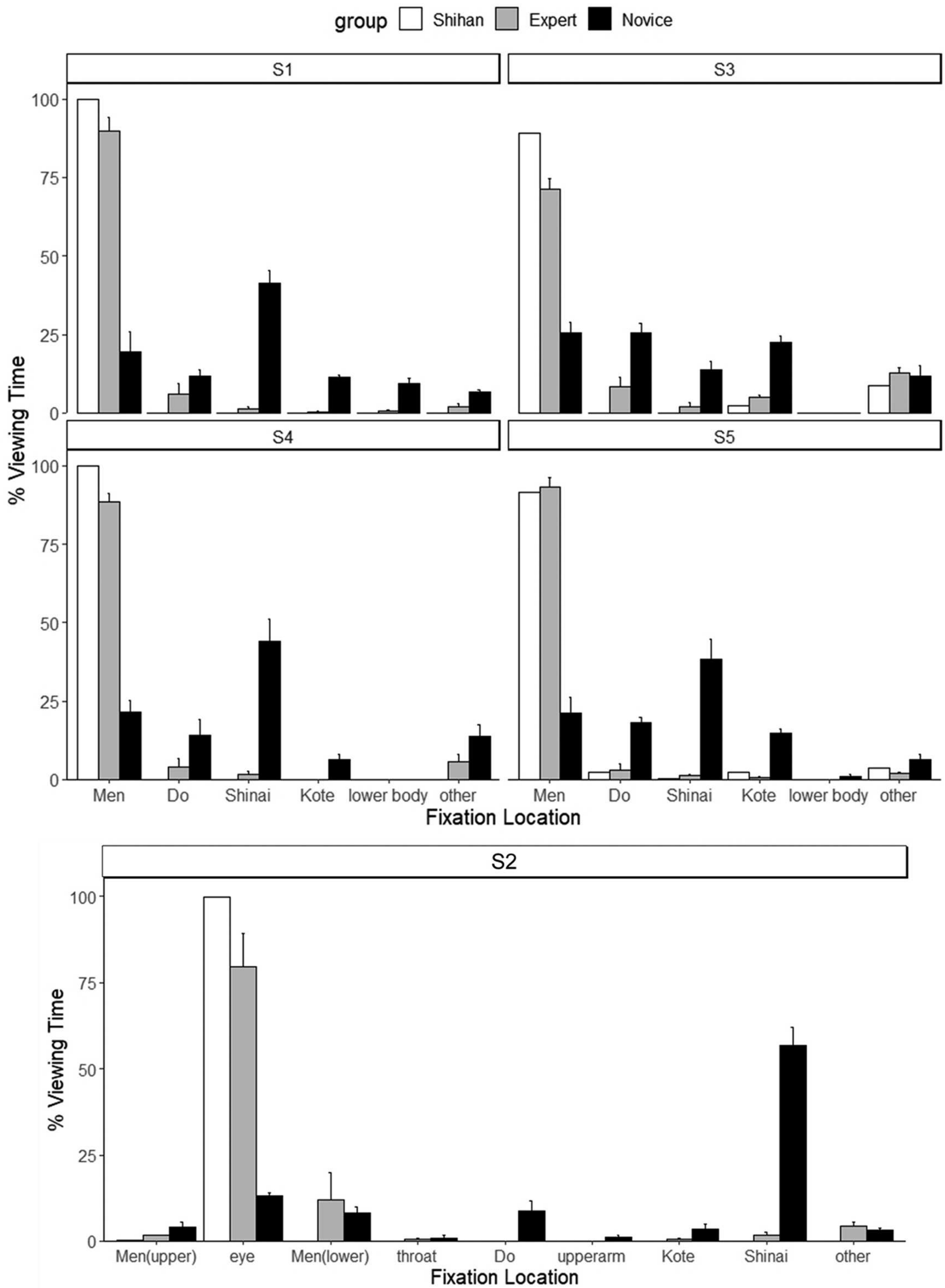

FIGURE 4 | Mean (SD) percentage viewing time per fixation location which is categorized in **Figure 3**.

quickly and accurately with a high success rate (**Table 1**). It is assumed that experts could utilize peripheral vision properties "focusing" on the body as a whole while setting their line of sight on the opponent's eye; therefore, they made a better prediction by picking up relevant cues from distal body areas such as an opponent's sword, arm, and even foot.

The present findings agree with those reported by Piras et al. (2014), who revealed that expert judo fighters spent a great percentage of their time fixating their gaze on the central regions of their opponent's upper body, primarily the lapel and the face. Williams and Elliott (1999) and Milazzo et al. (2016b) indicated that expert karate fighters "visually anchored" their attention on the head and torso, while Ripoll et al. (1995) showed that expert French boxers maintained foveal fixation mainly on the central regions of their opponent's body as a "visual pivot," while using their peripheral vision to monitor their opponent's limb movements. Such "visual pivot" or "visual anchor" strategies have been reported in other sports like baseball batting (Kato and Fukuda, 2002), soccer penalty kicking (Savelsbergh et al., 2002; Piras and Vickers, 2011), one-on-one defense in soccer (Nagano et al., 2004), golf putting (Naito et al., 2004), and volleyball reception (Vansteenkiste et al., 2014), which indicates that these strategies are not only confined to combat sports. More recently, Vater et al. (2019) proposed the definition and operationalization possibilities of three different gaze strategies: the "foveal spot," the "gaze anchor," and the "visual pivot." While the concepts of pivots or anchors have been newly defined, it is beneficial to discuss these suggestions, and further evidence to support these concepts should be collected.

When comparing the results of this study to previous studies, it must be noted that the visual search strategies of experts may depend on the subjective task demand required of each player relative to his or her particular skills. Hagemann et al. (2010) examined expert épée fencers' eye movements under laboratory settings with filmed video stimuli incorporating temporal and spatial occlusion. The study revealed that experts fixated particularly on the upper trunk but shifted their eye movements to neighboring body regions when the upper trunk was occluded. Furthermore, the viewing percentage distribution results showed that experts fixated more on their opponent's weapon (26%) in the lower trunk region (30%) than the upper trunk region (about 15%) and head (1%). It is significant to note that the entire body is a valid target in épée fencing, and it is therefore inferred that experts needed to attend not only to the proximal region of their opponents' bodies but also to the distal region as well. Similarly to that study, Hausegger et al. (2019) reported that expert kung fu (Qwan Ki Do) athletes focused more on their opponent's head, whereas Tae Kwon Do athletes mainly attacked their legs and anchored their gaze on their opponent's lower region to monitor the relevant cues if kicking attacks were solely expected. In contrast, Kendo fighters are only allowed to attack their opponent's *Men*, *Do*, and *Kote*, which are all above the hip; hence, it is assumed that they focus their gaze on the eyes of their opponent. Again, it is said that "Enzan no Metsuke" is the *Waza* whereby fighters look at their opponent's eyes with a gaze toward the mountains in the distance, taking in not only their opponent's face but their whole body as well. A recent study has demonstrated that fixating at a far target would contribute to faster reaction and that the effect is specific to the focus location in the peripheral visual field (Kokubu et al., 2018). Although the distance of expert Kendo fighters' focus location was not measured in this study, it is considered that they tried to focus on a distant place through the opponent's eye and utilize peripheral vision with "Enzan no Metsuke," so that they showed better performance with a high success rate during all sessions.

Notable findings indicate that expert Kendo fighters adopt a visual search strategy involving fewer fixations of longer duration than novices who make a greater number of short fixations. These results are consistent with what has been found in previous research in judo (Piras et al., 2014) and karate (Williams and Elliott, 1999; Milazzo et al., 2016b). Furthermore, Milazzo et al. (2016a) showed that karate fighters changed their visual search behavior by focusing on fewer locations for a longer duration, and experienced fighters improved decision-making accuracy if they received video-based implicit perceptual-motor training. When analyzing mean fixation duration (**Table 2**), this study revealed that Kendo experts fixated for an average of 1,678–4,459 ms on each location in all the sessions, which is much longer than the 328 ms recorded for karate (Williams and Elliott, 1999), 760 ms for judo (Piras et al., 2014), 1,026 ms in karate (Milazzo et al., 2016b), and 2,423 ms in French boxing (Ripoll et al., 1995). Ultimately, the *Shihan* showed a much longer fixation duration than the experts in most of the sessions. A possible explanation for this might be that Kendo fighters tend to keep their fighting distance while waiting for the right opportunity to attack without any dynamic movements, which is referred to as *Maai*. The state of that behavior sometimes looks like freezing; therefore, their eyes also seemed to move quietly. Conversely, during open ball-play sports like soccer, experts typically employed a visual search strategy involving more fixations of shorter duration in the display (e.g., not only fixating on the ball but the positions and movements of the other players as well) because their environment changes dynamically (e.g., Ward et al., 2002; Roca et al., 2011). These exhaustive and dynamic visual search behaviors are thought to underpin the superior anticipation and decision-making skills of experts (Williams et al., 1999).

In target tasks such as a basketball free throw or darts, the "quiet eye" (QE) is utilized. The QE is defined as the final fixation, or tracking gaze, on a specific object or location in the period before the unfolding of the final movement that is critical for a successful performance. It has been argued that an earlier and longer QE duration is a characteristic of elite performers (Vickers, 2007, 2016). In this study, sessions were not terminated by each attack; rather, they lasted till a specific ending time (see *Procedure* section). Therefore, expert Kendo fighters spontaneously kept their eyes on the eyes of their opponent to utilize their peripheral vision to pick up relevant cues from the distal body regions, even after their own attack movement had unfolded. Their eyes moved "quietly" but fixated on a specific target only before the unfolding of the final movement.

One limitation of this study is the lack of records of any additional responses, such as pushing keys or verbal reports. For example, it is not clear how widely they could pick up information from peripheral visual areas, how far they focused, or what they thought during tasks. The ultimate goal of the study was considered to be the examination of the natural, visual behaviors of Kendo fighters during *in situ* conditions from an ecological validity viewpoint. Thus, we decided not to include any additional responses during the sessions, because gaze and movement behaviors function differently depending on the experimental task constraints selected for empirical investigations (Dicks et al., 2010). Moreover, the natural motor response of the participants should be favored over verbal or button-press responses (Kredel et al., 2017).

The *Shihan*, aged 65 years, displayed ultimate visual behaviors by employing effective and stable visual search activities, and it is assumed that he utilized his peripheral vision to pick up relevant cues from the opponent's distal body areas Vater et al. (2019). Any additional tests for functional abilities were not conducted at this time, so it is unclear what specific abilities the *Shihan* possesses. Nevertheless, he performed very well, with a high success rate (**Table 1**) during all sessions. In this study, he participated as a special reference and was not examined using statistical analysis. Recent research has demonstrated that older martial arts athletes (judo and karate) perform better than non-athletes of the same age in the investigation of peripheral vision and perceptual asymmetry tasks (Muiños and Ballesteros, 2014), and physical activities including martial arts can improve peripheral vision properties in older individuals [for a review, see (Muiños and Ballesteros, 2018)]. It was invaluable that *Shihan* who are awarded the eighth *Dan* and *Hanshi* title, which is the highest attainable rank in Japan (with over 40 years prior kendo experience, but acceptant rate is below 1%), participated in this study, and the data regarding his visual behavior is extremely valuable, not only for science but also in the practical domain.

CONCLUSION

The purpose of the present study was to clarify the visual search strategies of expert Kendo fighters through sparring practices to analyze the application of the concept of "Enzan no Metsuke" under *in situ* experimental conditions. Results revealed that experts, especially *Shihan*, set their eyes on their opponent's eyes with a gaze toward the mountains in the distance to utilize their peripheral vision. Additionally, they adopted a visual search strategy that involves fewer fixations of longer duration. These results reveal that the "visual pivot" strategy can be regarded as a behavior of "Enzan no Metsuke"; however, further research should be conducted to investigate the relationships between peripheral vision and motor control in more detail.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Ethics Committee of Keio University SFC. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TK contributed the conception, design, and conduct of the study, and also wrote the whole manuscript.

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Temporally Coupled Coordination of Eye and Body Movements in Baseball Batting for a Wide Range of Ball Speeds

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We investigated the visuomotor strategies of baseball batting, in particular, the relationship between eye and body (head and hip) movements during batting for a wide range of ball speeds. Nine college baseball players participated in the experiment and hit balls projected by a pitching machine operating at four different ball speeds (80, 100, 120, 140 km/h). Eye movements were measured with a wearable eye tracker, and body movements were measured with an optical motion capture system. In the early period of the ball's flight, batters foveated the ball with overshooting head movements in the direction of the ball's flight while compensating for the overshooting head movements with eye movements for the two slower ball speeds (80 and 100 km/h) and only head rotations for the two faster ball speeds (120 and 140 km/h). After that, batters made a predictive saccade and a quick head rotation to the future ball position before the angular velocity of the ball drastically increased. We also found that regardless of the ball speed, the onsets of the predictive saccade and the quick head movement were temporally aligned with the bat-ball contact and rotation of the hip (swing motion), but were not correlated with the elapsed time from the ball's release or the ball's location. These results indicate that the gaze movements in baseball batting are not solely driven by external visual information (ball position or velocity) but are determined in relation to other body movements.

Keywords: baseball batting, eye movements, head movements, hand-eye coordination, predictive saccades

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INTRODUCTION

In hitting sports such as baseball, cricket, and tennis, players must make very accurate predictions about where and when the ball will come. Table tennis players, for example, demonstrate timing accuracies as precise as 2–5 ms (Bootsma and van Wieringen, 1990). Baseball batters also require accurate spatial bat control, to centimeter order precision considering the diameter of the bat. To make an accurate estimation of the ball trajectory, the gaze movement strategy is considered to be a critical factor because it affects the quality of the visual information gathered by the eye. Moreover, the gaze movement strategy tells us which visual information during a ball flight is important (Land and McLeod, 2000). In fact, many studies have indicated that visual strategies differ depending on the player's skill level (Land and McLeod, 2000; Rodrigues et al., 2002; Mann et al., 2013; Kishita et al., 2020).

Most of the studies on visual strategies of sports players have focused on what kind of visual information the players obtain and how they obtain it. The previous studies have revealed locations and events that are important for a good performance and how good players obtain such visual information. One visual strategy is predictive eye movements, wherein the eyes move to the locations where critical events will happen. In some hitting sports, players often make saccades to the locations where the ball will bounce in the future; e.g., this has shown to be the case in cricket (Land and McLeod, 2000; Croft et al., 2010; Mann et al., 2013), tennis (Williams et al., 1998), squash (Hayhoe et al., 2012), and table tennis (Land and Furneaux, 1997). The visual information from the place that the ball will bounce is considered to be useful for estimating the ball trajectory after the bounce. As well, other distinctive strategies, such as head tracking in cricket (Mann et al., 2013) and quiet eye in table tennis (Rodrigues et al., 2002), are considered to be effective ways of obtaining visual information.

However, gaze movements are sometimes affected by body movements and cannot be just for obtaining visual information. Laboratory studies suggest that body movements suppress gaze behavior. Neggers and Bekkering (2001) showed that gaze is anchored during reaching tasks, and such anchoring is not due to visual information being gathered. Furthermore, close temporal correlations between eye and hand movements have been demonstrated in several different visuomotor tasks (Sailer et al., 2000). In addition, the visual strategy may vary between hitting/intercepting the ball and just looking at the ball. It was shown that baseball players track the ball with smooth-pursuit eye movements when they watch it in flight but do not try to hit it (Bahill and LaRitz, 1984). In contrast, they use a saccade toward the impact position just before the bat-ball contact when they try to hit it (Kishita et al., 2020). This discrepancy in gaze movements indicates that the swing motion affects the visual tracking strategy.

Predictive eye movements toward the impact position such as what occurs in baseball batting (Kishita et al., 2020) are also observed in other hitting sports, including tennis (Williams et al., 1998), table tennis (Rodrigues et al., 2002), and cricket (Mann et al., 2013). What is interesting here is that the time from the landing of saccades to the bat-ball contact is too short for the swing motion to reflect the visual information due to the delay of visuomotor processes (Kishita et al., 2020). This fact leads us to consider other functional significances of this gaze shifting behavior besides obtaining visual information. Eye movements are known to convey position information on objects in the eye-centered coordinates used for motor planning (Buneo and Andersen, 2006). The same mechanism may be at work when catching and hitting in interactive ball sports. Thus, for a comprehensive understanding of gaze behavior during sports, not only is the strategy of acquiring visual information important, so is its relationship with body movements. In the case of baseball batting, the torso starts rotating first, and then a bat is accelerated. Since the order of these sequential movements is maintained in most cases, the timing of the torso rotation seems to reflect the expected time of ball arrival.

In this study, we investigated how differences in ball speed affect the visual strategies of baseball batters. Specifically, we measured eye, head, and hip movements of nine college baseball players during a batting task conducted under four different ball-speed conditions (80, 100, 120, and 140 km/h). The data collected on the eye and head movements were used to investigate the visual strategies. By measuring both eye and head movements, the contributions of the eye and head movements to the overall gaze movements can be calculated. The data collected on the hip rotation was used to clarify the relationship between the visual strategy and swing motion. These data reveal how the batters moved their gaze for different ball speeds and how eye and head movements each contributed to gaze shift changes. Moreover, the results provide a better understanding of the mechanism of gaze control in hitting tasks, such as whether the visual strategy is determined only by external factors (visual information: e.g., ball position and velocity) or by internal factors (body movements).

METHODS

Participants

Nine college baseball field players (five right-handed batters and four left-handed batters, aged 20–22 years: $M = 20.78$, $SD = 0.83$) participated in this experiment. The participants play in the Tokyo Big6 Baseball League, which is one of the best college baseball leagues in Japan. All the participants provided written informed consent before the experiments. This study was approved by the Ethics and Safety Committees of NTT Communication Science Laboratories and was under the Declaration of Helsinki.

Apparatus

Eye and head movements were measured with the same apparatus used in Kishita et al. (2020). Eye movements were recorded monocularly with a wearable eye tracker (Pupil headset, Pupil Labs GmbH, Germany). Left-handed batters' right eyes and right-handed batters' left eyes were recorded to reduce asymmetry. The sampling frequency of the eye camera and scene camera (which recorded the view from in front of the batter's head) were 200 and 120 Hz, respectively. Consequently, the eye position data were recorded at a sampling frequency of 200 Hz. The ball positions were manually digitized from thinned-out scene camera images and resampled to match the sampling frequency of the eye position data. Head and hip movements were measured at a sampling frequency of 240 Hz with an optical motion capture system (Optitrack, NaturalPoint, Inc., the U.S.). Participants wore a helmet that was tightly fixed to their heads with a headband and chin strap. Reflective markers were attached to the helmet for the optical motion capture system to measure the head movements. A waistband with reflective markers attached to it was worn to measure the hip movements. The participants hit balls projected by a three-wheel pitching machine (Pitch 18, Nishino-Machinery Corporation, Japan). The distance between the ball acceleration point of the pitching machine and the bottom of home plate was 16.7 m. The pitching machine was adjusted so that the ball would pass the center of home plate at the level of the participants' waist (i.e., the center of the strike zone). The time of bat-ball contact was detected from videos recorded with a high-speed camera at a sampling frequency of 300 Hz. The ball-release timing was obtained from a photosensor attached to the pitching machine. The devices were synchronized using LED lights that flashed at the start of motion-capture recording. The LED lights were captured by the high-speed camera recording the bat-ball contact and the scene camera of the eye tracker.

Procedure and Design

The experiment began with the calibration of the eye tracker using the manual marker calibration provided by the operating software. The eye camera and the scene camera images were monitored in real time, and recalibration was performed whenever it was needed.

Participants were instructed to hit the ball strongly toward the center of the field. The pitch type was fastball only. The ball speed was set to 80, 100, 120, or 140 km/h. The mean ball speeds for each condition, obtained from two photosensors on the pitching machine, were 78.8 ($SD = 0.85$), 102.5 ($SD = 1.64$), 123.3 ($SD = 2.02$), and 142.5 ($SD = 2.33$) km/h. Each ball-speed condition was tested in a separate block of trials. In each block, five participants started with the slowest ball condition and proceeded to the faster conditions, while the other four participants started with the fastest condition and proceeded to the slower conditions. Before starting each block, participants practiced several times to get used to the ball speed of the new block. In each block, the trials were repeated until the number of the bat-ball contacts reached 11–13 times.

Data Analysis

The eye and head movement parameters were processed and expressed using the same methods as in the previous study (Kishita et al., 2020). The parameters and the coordinate system are illustrated in **Figure 1**. The Y_{field} axis was parallel to the pitcher-catcher direction and the X_{field} axis was perpendicular to the Y_{field} axis. The origin of the coordinate system was the center of the head. Thus, the position of the origin moved with the translational motion of the head. The data of the left-handed batters were inverted to fit this coordinate system.

The head direction (θ_{head}) was defined as the angle between the X_{field} axis and the median plane of the head. The head direction was calculated from the reflective markers on the helmet. The eye position (θ_{eye}) was represented as the angle between the head direction and the gaze direction, and the ball direction (θ_{ball}) was represented as the angle between the head direction and the ball direction in the horizontal plane. Here, we call the direction of gaze relative to the X_{field}-Y_{field} coordinates the gaze direction ($\theta_{head} + \theta_{eye}$) to distinguish it from the eye position (θ_{eye}), which is the direction of the gaze relative to the head direction. The eye and ball position data were corrected for the effects of lens distortion and head tilt. The eye position data were smoothed with a second-order Savitzky-Golay filter with a window size of nine points. The hip direction (θ_{hip}) was defined as the angle between the median plane at the height of the waistband and the X_{field}-axis. The hip movements obtained

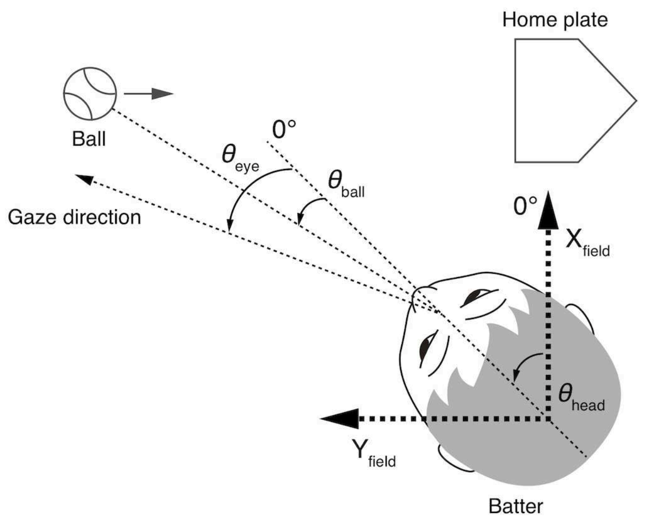

FIGURE 1 | Geometry of parameters used in the analyses from Kishita et al. (2020). The Y_{field} axis is parallel to the pitcher-home plate direction, and the X_{field} axis is orthogonal to the Y_{field} axis. The origin of the X_{field}-Y_{field} coordinates is at the center of the head. The head directions (θ_{head}) is expressed in the X_{field}-Y_{field} coordinates, and the eye direction (θ_{eye}) and the ball direction (θ_{ball}) are relative to the head direction.

from the motion capture data were smoothed by with a second-order Savitzky-Golay filter with a window size of fifty points. All movement data were resampled to match the sampling frequency of the eye position data (200 Hz).

Data from the trials in which the head direction or the eye position at the time of ball release deviated by more than 3 *SD* compared with the other trials conducted under the same conditions were excluded from the data sets. The number of data for each speed condition used for analysis was from 8 to 13 trials. To elucidate the general characteristics of baseball batters, we analyzed the mean data of all participants obtained from the mean data of each player.

Statistical Analyses

For each condition, the contributions of eye and head movements to the ball tracking were assessed by two-tailed one-sample t-tests applied to the amount of eye and head movements from the ball release to each 10% of the ball's flight duration (**Figure 2C**) and to the mean angular velocities of the eye and head movements during each 10 equally divided time interval (**Figure 2D**). The sample size for each test was nine, corresponding to the number of participants.

For each participant and condition, we expressed the time and the ball position when the eye movements reached the peak velocity (representing the saccadic eye movement) by (1) the time from ball release, (2) the time before the bat-ball contact, and (3) the ball's distance from home plate (**Table 1**). These values were obtained from the mean data of each participant. To examine which events are in a temporally coupled relationship with the eye movements, we performed a one-way repeated-measurements ANOVA on each data set aligned at the different events. Ryan's method was used as a *post-hoc* test with an alpha level of 0.05.

RESULTS

Strategies for Tracking at Different Ball Speeds: Different Amounts of Eye and Head Movement

Figure 2A shows the mean gaze direction ($\theta_{head} + \theta_{eye}$: red lines), mean ball direction ($\theta_{head} + \theta_{ball}$: black dotted lines), and their difference (i.e., the mean error, $|\theta_{ball} - \theta_{eye}|$: purple lines) in the X_{field}-Y_{field} coordinates. As can be seen from the magnitude of the error, for all ball-speed conditions, batters were able to track the ball accurately for a while after the ball was released. However, the amounts of eye and head movement (blue and green lines in **Figure 2B**, respectively) varied during the tracking period and depending on the ball-speed conditions. To illustrate these differences, we plot the amount of eye and head movements from ball release to each 10% of the ball's flight duration (**Figure 2C**) and their mean angular velocities during each time interval (**Figure 2D**). The percentage on the x-axis shows time (% of the ball's flight duration), and a positive value on the y-axis indicates the direction of the ball's flight.

First, although the final displacement of the eye position and head direction were almost the same for all ball-speed conditions (range of 12–14° at 100% in **Figure 2C**), the amounts of eye and head movement differed greatly between the early and late stages of tracking. In the early period (**Figures 2C,D**), when the ball moved through a smaller visual angle, batters mainly rotated their head in the direction of the ball's flight. On the other hand, eye movements increased in the later period (**Figures 2C,D**), when the angular velocity of the ball dramatically increased (**Figure 2A**). As can be seen from the velocity profile in **Figure 2D**, the eye movements exceeded 100°/s at some time in the latter half of the flight, which indicates that saccadic eye movements took place. In addition, **Figure 2A** shows that these saccades were predictive because they landed on the future location of the ball, and that the error between the eye positions and ball directions ($|\theta_{ball}$-$\theta_{eye}|$) became large during this saccade period.

The amounts of eye and head movement depended not only on the phases of tracking but also on the speed conditions. During the first half of the two lower speed conditions (80 and 100 km/h in **Figure 2D**), we observed that the head and eyes rotated in opposite directions; the head overshot the ball in the direction of the ball's flight, while the eyes moved in the opposite direction to compensate for the overshoot component. In contrast, under the faster ball-speed conditions (120 and 140 km/h in **Figure 2D**), the compensatory eye movements appeared only in the early (0–20%) period. For all speed conditions, the amount of eye movement in the direction of the ball's flight became significant when the angular velocity of the ball abruptly increased (about 60–90% in **Figure 2D**).

Temporal Relationship Between Eye and Body Movements

To examine what triggered the eye movements, especially the predictive saccades, we plotted the mean angle of the eye position and the mean angular velocity of the eye movements against the time after ball release (**Figures 3A,D**), time before bat-ball contact (**Figures 3B,E**), and against the ball's distance from home plate (**Figures 3C,F**). As is obvious from the figures, the saccade onsets were aligned with the time of the bat-ball contact at all ball speeds. To statistically assess this, we obtained the times and the ball positions when the eye movements reached the peak velocity aligned with different events (ball release, bat-ball contact, distance of the ball from home plate: **Table 1**), and applied a one-way repeated-measures ANOVA to each data set. A significant main effect was found for the time of the peak eye velocity aligned with ball release [ANOVA: $F_{(3,24)} = 827$, $p < 0.01$; *post hoc t*-tests: $p < 0.01$ for all pairs] and for the ball position at the time of peak eye velocity [ANOVA: $F_{(3,24)} = 15.65$, $p < 0.01$; *post hoc t*-tests: $p < 0.01$ for all pairs except for 100 vs. 120 km/h ($p < 0.1$) and 120 vs. 140 ($p < 0.1$)] but not for the time of the peak eye velocity aligned with bat-ball contact [$F_{(3,24)} = 0.171$, $p = 0.915$]. This indicates that the predictive saccades were not triggered by some event in time or space after the ball was released, but by prediction of the time of bat-ball contact, which indicates a temporal relationship between eye and other body movements.

Similar results can be seen in the plots of head and hip positions and movements aligning at the time of bat-ball contact (**Figure 4**). The bat-ball contact and hip movement were temporally aligned for all ball-speed conditions. In addition, the hip movement and the eyes and head movements were also neatly aligned. These results provide evidence of a very close temporal connection between eye and body movements in baseball batting.

DISCUSSION

In the present study, we investigated baseball batters' visuomotor strategies for different ball speeds. The common characteristics for all ball-speed conditions were that batters foveate the ball for a while after it is released, mainly by using head rotations, and then use a saccade and a quick head rotation toward the future position of the ball. These characteristics are consistent with our previous study on professional baseball players (Kishita et al., 2020). In addition, by using conditions with different ball speeds, we revealed two interesting characteristics that (1) overshooting head movements in the direction of the ball's flight and compensatory eye movements in the opposite direction were observed for slower than familiar ball speeds and (2) eye movements were controlled in a temporal connection with bat-ball contact.

Eye and Head Movements in Relation to the Speed of the Ball

The batters who participated in the current study usually bat against pitches corresponding to the two faster ball conditions (120 and 140 km/h). Therefore, it is plausible that they usually

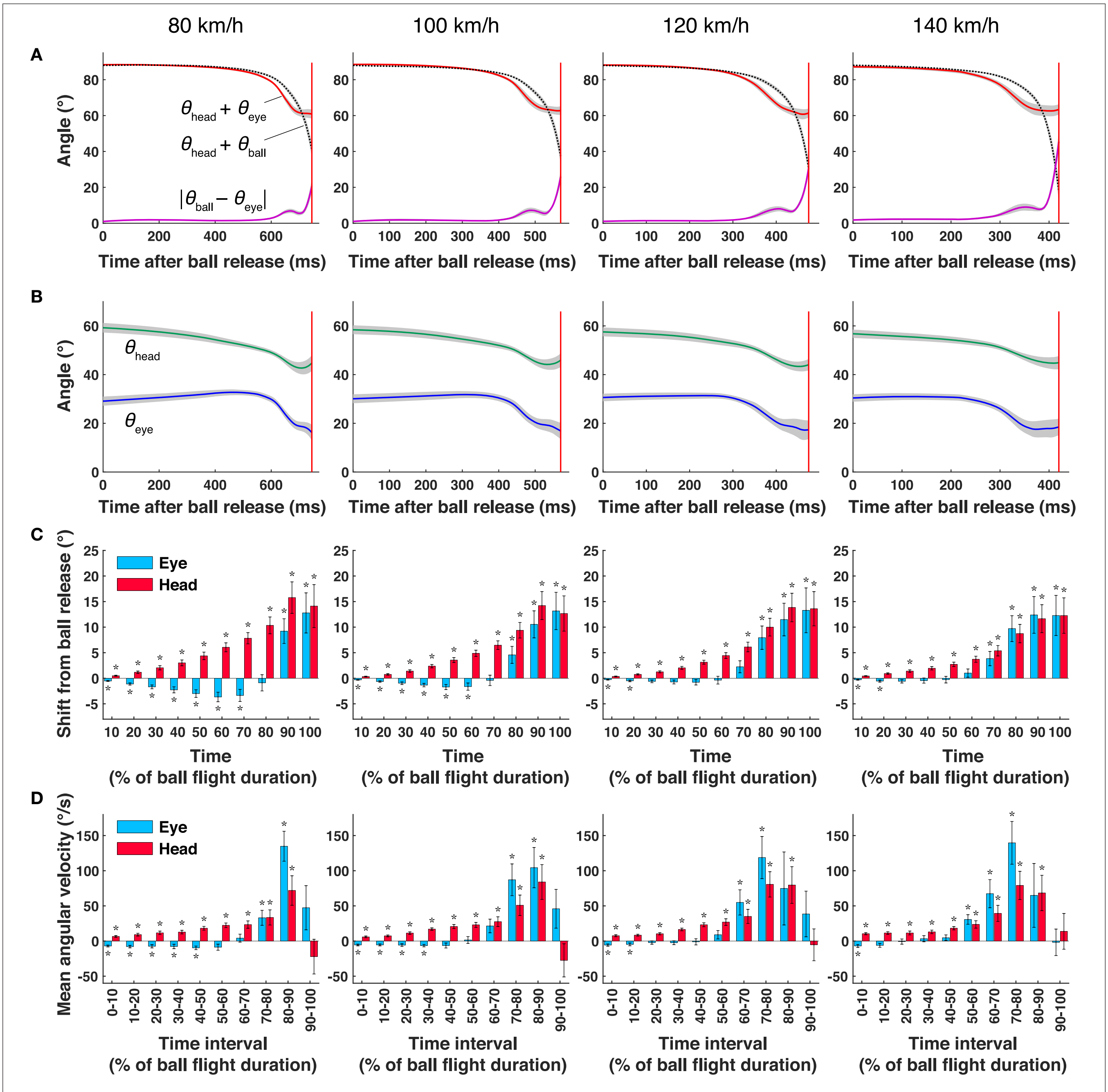

FIGURE 2 | Mean gaze direction, eye position, and head direction at different ball speeds. **(A)** Gaze direction ($\theta_{head} + \theta_{eye}$: red line), ball direction in field coordinates ($\theta_{head} + \theta_{ball}$: black dashed lines), and difference between gaze direction and ball direction ($|\theta_{eye} - \theta_{ball}|$; purple lines). **(B)** Mean head direction (θ_{head}: green lines) and eye direction (θ_{eye}: blue lines). The shaded areas represent the standard error. **(C)** The amount of eye and head movements from ball release to each 10% of the ball's flight duration. **(D)** Mean angular velocity of eye position and head direction within each time interval. Each interval (%) was obtained by dividing the total time from ball release to bat-ball contact into 10 equally spaced bins. The error bars represent the standard error, and the asterisks represent the results of *t*-tests ($p < 0.05$); the mean values are significantly larger or smaller than zero. The red vertical lines show the mean bat-ball contact time.

adopt the strategy of tracking the ball using head rotations without eye movements for the initial ball trajectory (or for small visual changes), as was observed in the faster ball conditions. Head tracking has been used in many ball sports and similar situations, and its benefits have been discussed in relation to, e.g., catching the ball (Oudejans et al., 1999; Zaal and Michaels, 2003), basketball jump shooting (Ripoll et al., 1986), cricket batting (Mann et al., 2013), and baseball batting (Fogt and Zimmerman, 2014; Higuchi et al., 2018; Kishita et al., 2020). Studies on the visual-motor system have also suggested the benefits of head

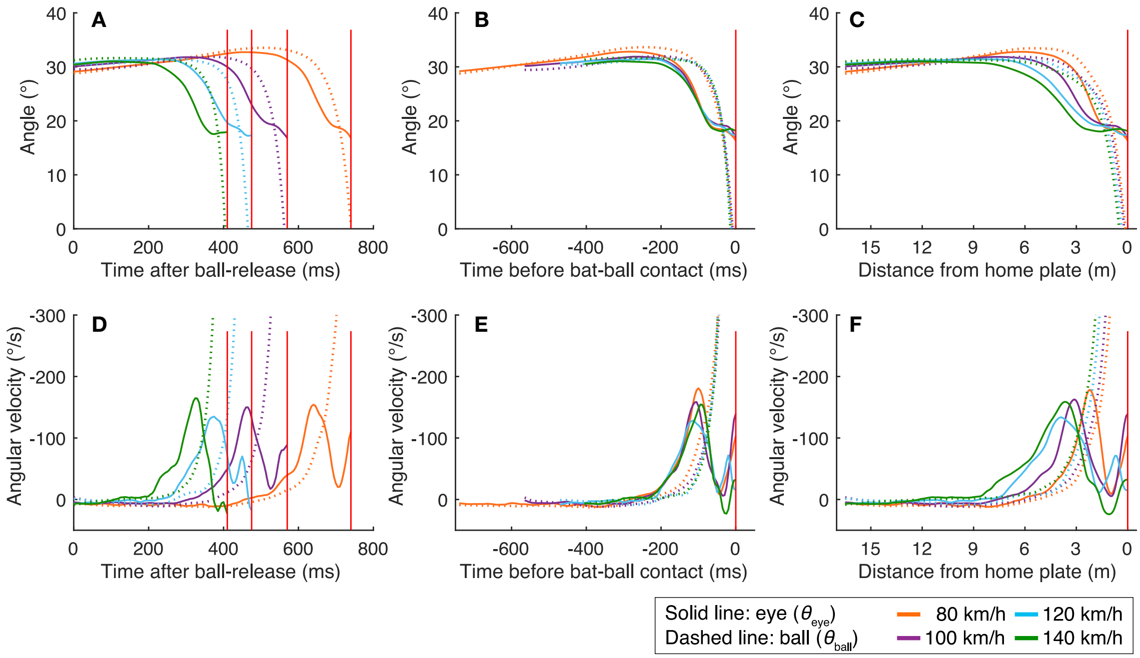

FIGURE 3 | Mean eye positions and eye velocities aligned to three different events. The eye positions are plotted as a function of time after ball release **(A)**, time before bat-ball contact **(B)**, and distance of the ball from home plate **(C)**. The angular velocities are shown in the same way: as a function of time after ball release **(D)**, time before bat-ball contact **(E)**, and distance of the ball from home plate **(F)**. The red vertical lines show the mean time or location of the bat-ball contacts. The colors of the line indicate ball speed. The dotted lines show the ball's angular position or velocity.

TABLE 1 | The time when the velocity of eye movements peaked and the ball position at that time.

	Release aligned time (ms)		Impact aligned time (ms)		Ball position (m)	
Ball speed	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
80	642	23.3	−108	26.6	2.38	0.57
100	465	37.5	−107	37.5	3.09	1.08
120	373	38.0	−105	38.8	3.62	1.33
140	316	32.8	−104	35.3	4.08	1.35

The mean values and the standard deviations were calculated from the mean values of each participant. The release aligned time represents the time after ball release, and the impact aligned time represents the time before the bat-ball contact. The ball position shows the distance between the ball and home plate at the time when the eye movement velocity is at its peak.

tracking. It has been pointed out that motor planning in visual-motor tasks is performed in the egocentric coordinate system, which is crucial for the visuomotor system (see e.g., De Wit et al., 2012). Mann et al. (2013) mentioned that keeping the direction from the head to the target constant may be advantageous for representing the target position in an egocentric coordinate system. Therefore, baseball batters may try to track the ball with head movements as much as possible while maintaining the ball's direction relative to the head in order to represent the ball in a head-centered coordinate system and to facilitate accurate motor planning.

In the two slow-speed conditions (80 and 100 km/h), overshooting head movements in the direction of the ball's flight and compensatory eye movements in the opposite direction were observed during the first half period (0–50%, in **Figure 2D**). However, it seems that different functions work in the early (0–20%) and late (20–50%) stages. Shortly after the ball is released (0–20%), the function appears to be a typical vestibular eye reflex (VOR), where the eyes and head move in opposite directions at approximately the same speed. This was seen under all speed conditions. In contrast, in the next period (20–50%), the speed of the head movement gradually increases compared to the speed of the eye movement while tracking the ball. In this period, the position of the ball acquired on the retina is thought to be reflected in the eye movements. This gaze strategy that tracks moving objects using a combination of eye and head movements is called combined eye-head tracking (CEHT). CEHT is considered to be realized by adjusting both smooth pursuit and VOR signals (Lanman et al., 1978; Huebner et al., 1992). In this sense, the head tracking seen under the faster ball-speed conditions (120 and 140 km/h) can also be regarded as a type of CEHT (Huebner et al., 1993).

Why did the batters produce almost the same head movements regardless of the speed of the ball and adjust their gaze direction by using eye movements? This is probably because their head movements for tracking the ball thrown by the pitcher were acquired during the course of a long period of training and are difficult to change. In other words, eye movements are more agile and more accurate for making small gaze adjustments.

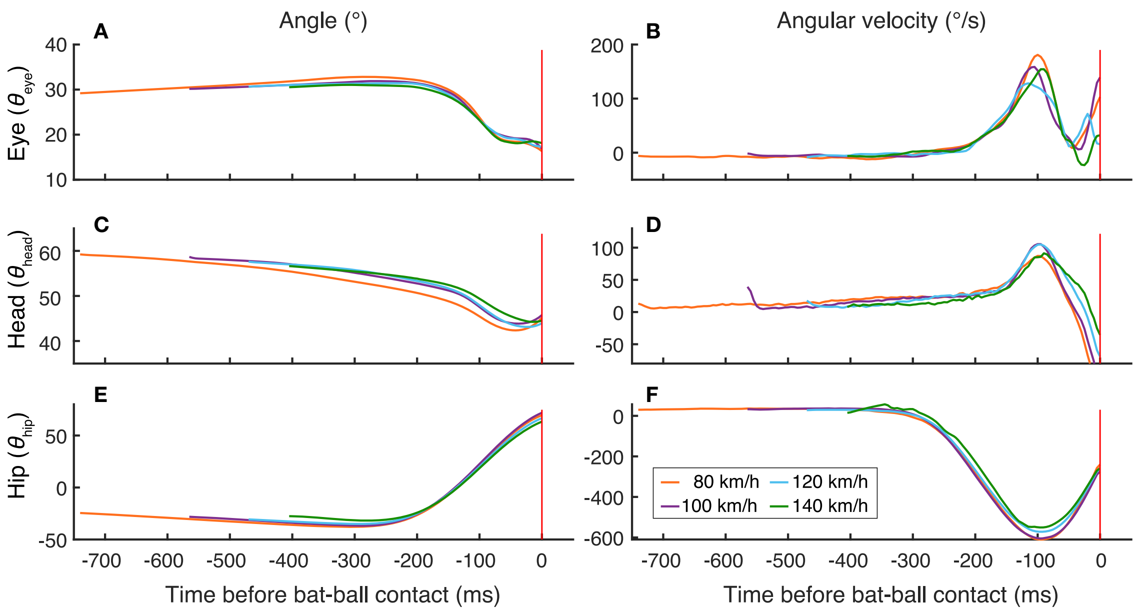

FIGURE 4 | Temporal changes of the mean positions of the eye **(A)**, head **(C)**, and hip **(E)** and the mean velocities of the eye **(B)**, head **(D)**, and hip **(F)**. All the data are aligned at the time of bat-ball contact. The colors of the lines indicate the ball-speed condition. The red vertical lines show the bat-ball contact time.

Our findings suggest that for sudden (unexpected or unfamiliar) changes in target positions, it is easier and more accurate to adjust the gaze position by using eye movements than by using head movements.

What Determines the Visual Tracking Strategy in Baseball Batting?

Our results indicate that batters' visual tracking strategy is constrained not only by the ball's trajectory, but also by other body movements that affect the batting action. First, the visual tracking behaviors (i.e., eye and head movements) have strong temporal coupling with the swing motion, regardless of the ball's speed. The onset of the predictive saccade and quick head rotation was precisely aligned with the time of bat-ball contact and hip rotation. The same temporal alignment would not occur if the specific ball speed or position were used as a reference for the eye and head movements. Second, the fact that the saccade was predictive also indicates that eye movements were not solely determined by the visual information about the ball. When tracking a moving object, saccades are often triggered by retinal slips due to the speed limitation of smooth-pursuit eye movements (de Brouwer et al., 2002). However, here, the saccades started when the ball was much slower than the maximum speed of smooth-pursuit eye movements (**Figures 3D–F**). This also implies that the batters' made the saccades actively in response to the ball's movement and predicted when the bat-ball contact would take place.

One possible reason why visual tracking behavior is determined by the temporal relationship with movements of other body parts is that the maximum time available for gathering visual information for hitting depends on the timing of the bat swing. Since the goal of batting is to bring the bat into contact with the ball, the batter needs to adjust his/her swing to the movement of the ball. However, once the swing starts, the delay of the visuomotor processes restricts the amount of visual information that can be reflected in the swing motion, so it is not surprising that the visual strategy depends on the swing motion. However, this does not answer the question of why batters shift their gaze position to the future ball position by using the predictive saccades and quick head rotation.

Why Shift the Gaze to the Impact Position in Time With the Swing Motion?

One simple interpretation for shifting the gaze position in advance is to obtain visual information at the impact position. Rodrigues et al. (2002) mentioned that table tennis players stabilize their head and eyes just before the racket makes contact with the ball in a forehand stroke. However, from the viewpoint of how long it takes the brain to process visual information, it has also been pointed out that even if visual information at the time of bat-ball contact can be obtained, it is difficult for the swing motion to reflect that information quickly enough in movements online (Bahill and LaRitz, 1984; Kishita et al., 2020). In the present study, the gaze and ball positions overlapped about 50 ms before the bat-ball contact (**Figure 2A**), which also seems too short for the ball position information to be reflected in the swing motion. Furthermore, visual occlusion experiments on baseball batting have confirmed that visual occlusion occurring 150 ms before arrival of the ball has no significant effect on batting performance (Higuchi et al., 2016). For these reasons, if the gaze moves to the impact position in order to obtain visual information, the information gained there is likely used for learning in the future, not for online visuomotor responses.

Another possible reason for gaze shifting before the ball comes is that batters utilize gaze to build a representation of predicted impact positions for motor planning. The look-ahead fixation not only gets visual information but also passes the location of the target of motor planning (Land and Tatler, 2009). In this process, an efference copy of eye movements provides the eye position information for motor planning, which is critical for calculating the distance between the target and limb (Lewis et al., 1998). Importantly, the efference copy signal can be used immediately, i.e., without delay, which ensures that it can be used in the current motion. Exact temporal coupling of eye and body movements has also been observed in simple reaching tasks, which are thought to result from sharing of the nervous system between eye and body movements (see, e.g., Sailer et al., 2000). We suggest that the same may occur in baseball batting.

CONCLUSION

We investigated the eye and body movements of baseball players batting against a wide range of ball speeds. We found that their visual strategies exhibited two characteristics: first, in the early period of the ball's flight (when the change in the visual angle is small), batters adopt different visual strategies, i.e., tracking the ball by overshooting head movements with compensatory eye movements in the opposite direction when it's slow (80 and 100 km/h) or by using head movements when it's fast (120 and 140 km/h). These different strategies are probably the result of a long period of training involving tracking balls with head movements and responding to other sudden speed changes with eye movements. These results provide insights into how players use their eye and head movements depending on the ball's trajectory and body movements in many ball sports. In addition, they suggest the possibility of developing new vision training that also uses head tracking, rather than conventional vision training that aims to accurately track the target only by eye movements, as represented by dynamic visual acuity training. The second finding is that the timing of the major gaze shifts (predictive saccade and rapid head movement) is determined by the timing of the bat-ball contact, regardless of the ball's speed. This means that the visual strategy is determined not only by the visual information associated with the movement of the target, but in some situations, it is also determined in relationship with body movements. Since the focus here was on clarifying general visuomotor strategies of baseball batters, the batter's level- or type-specific characteristics may not have been fully captured. However, our findings may reveal not only the characteristics of baseball batters but also the basic characteristics of human visuomotor coordination under such extreme conditions: interaction with an object moving at a very high speed by using unconstrained eye and head movements.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by NTT communication science laboratories. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YK, HU, and MK conceived, designed the experiments, and interpreted the data. YK and HU performed the experiment. YK conducted the data analysis and drafted the manuscript. HU and MK edited and revised the manuscript, and approved the final version.

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Looking to Learn Better - Training of Perception-Specific Focus of Attention Influences Quiet Eye Duration but Not Throwing Accuracy in Darts

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Investigations of the association of focus of attention and quiet eye duration have shown mixed results. It is possible that when focusing on visuo-motor learning a more sensitive category system of instructions might be useful. The aim of this study was to investigate the interaction of focus of attention and quiet eye duration in darts. In addition to locus-directed foci (external, internal), perception-directed (visual, kinesthetic) foci of attention were considered. Participants were divided into four groups and had to perform a pre- and post-test with a 1-week training intervention in between. Throwing accuracy (TA) and quiet eye duration (QED) were measured using the SMI eye tracking glasses. An analysis of covariance (2x2) showed no significant group differences or interactions for TA. For QED, an analysis of variance (2x2x2) showed quiet eye duration was increased with the intervention but there were significant differences between the tests. A significant interaction of test and perception-directed focus was observed. Visually instructed groups increased QED whereas the kinesthetic group decreased the QED, suggesting perceptual and motor learning may be asynchronous. One possible explanation for the trends might be the common-coding theory of perception and action.

Keywords: quiet eye, focus of attention, motor learning, vision, instructions

INTRODUCTION

Sport research has shown that perceptual and motor performance are strongly linked (Janelle et al., 2000; Martell and Vickers, 2004; Vickers and Williams, 2007; Lohse et al., 2010; Wulf, 2013). For example, the "quiet eye" is a perceptual phenomenon that considers the influence of final fixation duration on motor learning and performance processes (for an overview, Vickers, 2007; Lebeau et al., 2016). Similarly, a performer's "focus of attention" in the context of motor learning and motor performance has received considerable attention in the last two decades (for a review, Wulf, 2013). In the past few years, several studies have considered the relationship between quiet eye and focus of attention, showing mixed results (Moore et al., 2012; Klostermann et al., 2014; Rienhoff et al., 2015). The main objective of the present study was to gain deeper insight into the relationship between focus of attention and quiet eye, particularly the interdependency of motor and perceptual learning, by considering the influence of different instructions on quiet eye duration and motor performance in a learning task.

Based on the ground-breaking work by Wulf et al. (1998), a range of researchers have considered the influence of external (i.e., attention to one's movement effect) and internal (attention to one's own movement) foci of attention in sport situations (Perkins-Ceccato et al., 2003; Wulf, 2013). Most of these studies have shown a benefit for an external focus of attention in the context of motor learning (Carpenter et al., 2013; Wulf, 2013), although some studies have shown inconsistent results (Rienhoff et al., 2015).

A few studies have considered the influence of focus of attention instructions in aiming tasks (Zachry et al., 2005; Castaneda and Gray, 2007; Wulf and Su, 2007; Lohse et al., 2010; Schorer et al., 2012; Querfurth et al., 2016). Schorer et al. (2012), for example, compared the influence of different instructions on dart throwing performance of experts and novices, finding mixed results. In doing so, they used two internal and one external focus of attention conditions. Castaneda and Gray (2007) compared skill/external, skill/internal, environmental/irrelevant and environmental/external instructions in less-skilled and highly skilled baseball players. For highly-skilled athletes, they noted a benefit for an environmental/external instruction; for the less-skilled athletes they found best performances in the two skill conditions. Wulf and Su (2007) investigated the influence of external and internal instructions on golf shooting accuracy in novices in a learning task. The novices were divided into three groups (internal, external, control) and performed 60 practice and 10 set trails. Results indicated a benefit of an external focus of attention. Finally, Lohse et al. (2010) investigated participants in a dart throwing task and compared internal and external instructions. Equally, benefits for an external focus on dart throwing performance were identified. As noted earlier, the results of these studies have been mixed, which may have been due to the inconsistency in the instructions used (see **Table 1**).

When focusing on understanding peak performance in the context of perception-action coupling, particularly in aiming sports, the quiet eye phenomenon has received considerable attention in the context of sport science. This perceptual criterion, which focuses on visual information processing, is also seen as a strong predictor of motor outcomes (Vickers, 2007; Rienhoff et al., 2016). The quiet eye reflects the final fixation on a target prior to the initiation of the critical movement phase and has been examined in the context of tactical tasks, interceptive timing tasks, and targeting tasks (Vickers, 2007). The quiet eye has a minimal duration of 100 ms and a maximum gaze vector deviation of 3° (Vickers, 2009). Previous research has linked expertise differences to quiet eye duration with experts showing longer durations (Vickers, 1996). Furthermore, studies have shown that longer quiet eye durations are associated with better motor results (Moore et al., 2012; Vine et al., 2014), especially in aiming tasks (Vickers et al., 2000; Harle and Vickers, 2001).

According to Lebeau et al. (2016), only nine investigations have focused on the influence of quiet eye duration in the context of perceptual-motor learning. In these studies, different instructions and feedback were used to influence perceptual performance (i.e., quiet eye) (Adolphe et al., 1997; Wilson et al., 2009). One of the first studies to investigate the trainability of quiet eye duration was done by Adolphe et al. (1997). They examined changes in quiet eye duration over a 6-week training intervention in volleyball players. Players were given video feedback about their gaze behavior that led to longer durations and earlier onsets of the final fixation. In a subsequent study, Harle and Vickers (2001) considered the influence of a quiet eye training intervention using video feedback over a two season period in basketball players compared with elite models. This training resulted in the basketball players improving their throwing average and demonstrating longer and more stable quiet eye durations. Learning studies have also investigated quiet eye in the context of anxiety, with results showing a positive influence of learning on quiet eye duration (Vine and Wilson, 2011; Wood and Wilson, 2011, 2012). Wilson et al. (2009) investigated basketball free throws under three different conditions (control condition, high, and low pressure) and showed that quiet eye durations were longer for hits compared to misses. Moreover, they showed that quiet eye durations decreased in high pressure situations, whereas the number of fixations increased.

Combining these two phenomena, recent studies have begun explore the influence of focus of attention instructions on quiet eye duration. The existing examinations in this area (Klostermann et al., 2014; Ziv and Lidor, 2014; Rienhoff et al., 2015) have shown mixed results, again perhaps due to the use of varying instructions (see **Table 2**). Ziv and Lidor (2014) asked participants to perform golf putts after receiving internal and external focus of attention instructions. Additionally, they had participants perform the task under distracted and non-distracted conditions, with results showing a benefit for external instructions on quiet eye duration but not putting performance in non-distracted situations. Rienhoff et al. (2015) investigated differences between external and internal foci of attention, which were spatially relatively close together (external: hand, internal: hand). The results indicated internal focus was beneficial for extending quiet eye durations, but the external focus resulted in better throwing accuracy. Querfurth et al. (2016) showed a benefit for internal instructions in novices by investigating the QE duration and the motor outcome in a dart throwing task resulting in earlier QE-onset and later QE-offset in internal instructions. Last, Klostermann et al. (2014) investigated the influence of movement-related and effect-related focus of attention and demonstrated better putting performance for effect-related instructions and a later quiet eye offset with movement-related quiet eye duration. As noted in **Table 2**, there were considerable differences in the instructions used across these studies. When considering the instructions in recent studies concerning quiet eye training, it is notable that all instructions focused on kinesthetic parameters, compared with studies on focus of attention (see **Table 1**), where instructions in both visual and kinesthetic categories were used.

Moore et al. (2012) considered the influence of a training intervention on quiet eye duration and putting performance in golf novices and used focus of attention instructions as an explanation for their results. Two different groups took part in the study (quiet-eye training group, technical training group) with the quiet eye training group receiving instructions on the

TABLE 1 | Varying used focus of attention instructions in aiming tasks.

Study	External instruction	Internal instruction	Supplementary instruction
Castaneda and Gray (2007) Participants: less-skilled vs. highly skilled	Skill/external: movement of the bat (kinesthetic) Environmental/external: the ball leaving the bat (kinesthetic)	Skill/internal: movement of the hand (kinesthetic)	Environmental/irrelevant: auditory tones
Wulf and Su (2007) Participants: Novices	Pendulum motion of the clubhead (kinesthetic)	Swinging motion of the arms(kinesthetic)	
(Lohse et al., 2010) Participants: Novices	Visually focus on the bulls-eye…mentally focus on the movement of your arm. When you're off target think about how you can correct the mistake by changing the motion of your arm. Each time you throw, focus on your arm and think about how you are moving (visual and kinesthetic).	Visually focus on the bulls-eye…mentally focus on the flight of the dart. When you're off target think about how you can correct the mistake by changing the flight of the dart. Each time you throw, focus on your dart and think about how it should fly (visual and kinesthetic).	
Schorer et al. (2012) Participants: Experts and novices	Concentrate on the bullseye (visual)	Internal 1: concentrate on the return point of the dart (kinesthetic) Internal 2: concentrate on the release of the dart (kinesthetic)	

An exploratory representation of varying focus of attention instructions used in different studies within the context of aiming tasks.

TABLE 2 | Varying used focus of attention instructions in the context of quiet eye.

Study	Instruction 1	Instruction 2
Klostermann et al. (2014)	Effect-related: Hit the target cross as accurately as possible and, in particular, mentally pay attention to the feeling when the ball leaves the head of the putter. By this, I mean the first feedback on putting success (feeling virtually no collision between the ball and putter head) or failure (feeling a noticeable collision between the ball and putter head) (kinesthetic).	Movement-related: Hit the target cross as accurately as possible and, in particular, mentally pay attention to the feeling at the rear reversal point of the swing. By this, I mean the rhythm and speed of the swing between backswing and forward swing (kinesthetic).
Rienhoff et al. (2015)	Exernal: focus on the ball (kinesthetic)	Internal: focus on the hand (kinesthetic)
Ziv and Lidor (2014)	External: focus on the pendulum motion of the club head (kinesthetic)	Internal: focus on the swinging motion of their arms (kinesthetic)

Recently used focus of attention instructions in studies within the context of quiet eye duration and motor performance.

direction of their gaze behavior, while the technical training group's instructions related to the technical execution of a golf putt. All participants had to perform baseline, retention and "pressure" tests. In addition to results on physiological parameters, results showed that the quiet eye trained group had longer quiet eye durations and a more expert-like putting performance (kinematic) in retention and pressure tests. Moore et al. (2012) argued that their results may be associated with a better external focus of attention and that longer quiet eye durations lead to a more effective external focus of attention.

Studies to date demonstrate interactions between perceptual phenomena (quiet eye) and cognitive processes (focus of attention) (Klostermann et al., 2014; Ziv and Lidor, 2014; Rienhoff et al., 2015). Rienhoff et al. (2015) postulated that this research area needs greater attention to gain deeper insight into the processes of perception-action coupling, especially regarding the mechanisms that explain the influence of different instructions on the quiet eye and motor performance. Unfortunately, the instructions used across studies have been inconsistent, making it difficult to compare results. As Wulf (2013) postulated, a change of a single word might influence the performance outcome.

The first aim of this study was to replicate findings concerning the trainability of quiet eye duration (Adolphe et al., 1997; Harle and Vickers, 2001; Causer et al., 2011; Vine et al., 2011, 2014) and the association of this duration with motor performance in darts (Vickers et al., 2000). We hypothesized a general improvement in quiet eye duration and throwing accuracy from pre- to post-test. More precisely, we assumed that practice would increase the outcome which is related to participant's performance in both motor and visual behavior using a training intervention with attentional instructions.

Our second aim was to investigate the association between quiet eye duration and focus of attention by classifying focus of attention instructions to allow a better comparison between different studies. To this end, we developed a category system that is more sensitive in order to gain more precision into the association between the phenomena and their influence on the motor result. The similarities and differences in the instructions used in prior work informed the development of two different categories, locus-specific instructions [external vs. internal, such as used by Wulf (2013)], and perceptionspecific instructions [kinesthetic vs. visual such as the movement-related or vision-related foci as used by Lohse et al. (2010), Schorer et al. (2012), Klostermann et al. (2014)]. In the first category, all instructions relate to vision, directing the visual system either directly or indirectly. Conversely, kinesthetic instructions focus on the movement itself (e.g., movement execution, movement of a subject like a ball). The foundation for this approach was the assumption that visual instructions might influence perceptual performance while kinesthetic instructions might influence motor performance, detached from the locus of attention (external vs. internal). Therefore, we investigated the influence of four different focus of attention instructions (internal vs. external x visual vs. kinesthetic) on quiet eye duration and motor performance in the context of visuo-motor learning. Keeping in mind that a single word might change the performance outcome, we tried to use instructions that were very similar. On the one hand, referring to Wulf (2013) we focused on the difference between external and internal focus of attention, while on the other hand we tried to generate two new categories (visual and kinesthetic) which consider the possibility of perception-specific focus of attention. To gain deeper insight, we categorized the examples in **Tables 1**, **2** to the visual and kinesthetic approach used in this study. In addition, no studies have focused on the association of focus of attention and quiet eye using a focus of attention based on the visual category.

For throwing performance, we hypothesized better throwing results for external instructions compared with internal instructions (locus of attention) based on Wulf (2013). Second, we assumed a higher improvement in throwing accuracy via kinesthetic instructions because of the possible link between motor performance and the kinesthetic sense. As noted, instructions given in previous studies differ a lot from each other, Schorer et al. (2012) focused on kinesthetic instructions (movement), whereas Lohse et al. (2010) used a visual instruction on the bullseye (cf. **Table 1**). Finally, we hypothesized a benefit (throwing performance) in perception-directed instructions compared to locus-directed instructions.

For quiet eye duration, we hypothesized longer quiet eye durations for the external instructed compared with the internal instructed group (locus-directed focus of attention), based on the assumption that external instructions lead to superior results (Wulf, 2013; Ziv and Lidor, 2014). In addition, we hypothesized a benefit for visually-directed instructions compared with kinesthetic instructions because the perceptual phenomenon of quiet eye might be more affected by a focus of attention related to directing the visual sense. Finally, we hypothesized an improvement (longer quiet eye duration) in perception-directed instructions compared to locus-directed instructions. These instructions might influence visual perception (quiet eye duration) more than locus of instruction, with the greatest benefit expected for external visual instructions. As mentioned, recently used instructions mixed locus-specific (internal vs. external) and perception-specific (visual vs., kinesthetic) instructions, without differentiating between these categories. This differentiation might be fruitful for perceptual-motor learning.

In summary, our differentiation of instructions should facilitate a more detailed investigation of the interaction of locus-specific and perception-specific focus of attention. This might be a first step toward better comparability between studies using different instructions.

METHODS

Participants

A total of 36 dart novices completed this study and were divided into four groups [internal visual ($n = 10$), external visual ($n = 9$), internal kinesthetic ($n = 7$) and external kinesthetic ($n = 10$)][1]. Participants had no experience in dart training and had normal or corrected-to-normal vision. At the beginning of this study all participants provided informed consent and completed a questionnaire detailing their age, dart experience and any eye or visual diseases. This study was approved by the University of Oldenburg ethics committee.

Task and Procedure

The main task in the experiment was to perform dart throws toward the bullseye as accurately as possible. The dartboard was in line with the standards of the World Darts Federation (WDF). The dartboard had a total diameter of 34 cm and the bullseye was adjusted to a height of 1.73 m with a throwing distance of 2.37 m. All participants used regular darts with a weight of 24 g per arrow. The study design was divided into three phases, pretest, training and posttest. First, participants were asked to perform 30 dart throws, aiming to hit the bullseye or get as close as possible. After the pretest, participants were divided randomly into four different groups for the training phase. Participants conducted three training days with 50 throws in each session. Each group was instructed differently in the training phase:

(a) visual internal (*concentrate on your eye*)
(b) visual external (*concentrate on the bullseye*)
(c) kinesthetic internal (*concentrate on your hand*)
(d) kinesthetic external (*concentrate on the dart*)

The instructions were given exactly as reported above. The word "concentrate" was used to direct each participant's focus of attention. When considering the attentional focus "performer's focus of attention or concentration during the planning or execution of a motor skill has a significant influence on movement quality." (Wulf, 2013) The whole procedure, including the training interval (pretest, training, posttest), was done in ∼7 days per participant.

Apparatus and Measurement

In the pre- and post-test, quiet eye duration (in ms) and throwing accuracy as radial distance from the bullseye (in cm) were analyzed as dependent variables. For measuring throwing accuracy, an external digital camera (Sony, HDR-CX320, 8.9 megapixels) was used to capture videos from the dartboard. From the recorded videos, screenshots were produced to allow for the analysis of the radial distance from the bullseye in pixels, which were converted into cm. Gaze behavior was recorded using SMI eye tracking glasses 2.0. This head mounted eye tracking system enables binocular eye tracking with a frequency of 60 Hz and facilitates mobile eye tracking by a linked smartphone via USB stored in a belt bag. Thus, participants were able to move freely and carry out dart throws in an almost natural

[1]The differences in the sample sizes for each group were due to four participants dropping out during the training phase of this study.

TABLE 3 | Mean scores (M) and standard deviation (SD) for the different groups in throwing accuracy (TA) and quiet eye duration (QED).

Instruction	TA Pretest		TA Posttest		QED Pretest		QED Posttest	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Internal-visual	6.8	1.2	6.1	1.2	498	322	867	392
External-visual	6.6	1.8	6.7	2	499	347	946	442
Internal-kinesthetic	11	4.4	11.3	2.8	618	380	579	293
External-kinesthetic	10.8	2.9	9.6	3.6	686	482	565	384

environment. After the eye tracking system was adjusted, a three-point calibration was done to ensure an optimal tracking ratio for each participant. For defining the quiet eye period, the integrated scene camera from the eye tracking glasses was used. This camera recorded the field of vision from the participant. Based on these videos, quiet eye duration was analyzed with BeGaze, a gaze analysis software. In doing so, the returning point (flexion to extension) of the throwing motion was determined from the scene camera. Then, the quiet eye period was extracted by analyzing the last fixation that began prior to the returning point. The duration of this fixation was manually extracted and defined as the quiet eye duration. Therefore, BeGaze also considered the duration the duration as the gaze vector deviation in the automatic analysis as requested by the definition of quiet eye. Random frame-by-frame video analysis was done to check data accuracy. The quiet eye period was defined as being prior to the critical movement phase. In the targeting task of dart throwing the critical movement phase is the start of the extension phase (Vickers et al., 2000).

Statistical Analyses

To check for baseline differences, an analysis of variance was performed for quiet eye duration and throwing accuracy. If pretest differences were found, an ANCOVA (2x2x2: test × locus-directed focus vs. perception-directed focus) was calculated. If no baseline differences were measured, an ANOVA (2x2x2: test × locus-directed focus vs. perception-directed focus) was conducted. In addition, a Kolmogorov Smirnov Test was calculated to check the normality of the data.The alpha level was set to 0.05 and all data analyses were conducted with SPSS 22.0, Effect size generator 2.3 (Devilly, 2004) and G*power 3.1.9.2 (Faul et al., 2007).

RESULTS

In the following section, the influence of different instructions on perceptual-motor results are described, beginning with the influence on the perceptual performances (e.g., quiet eye) followed by the results for throwing accuracy.

Results Concerning Quiet Eye Duration

First, we investigated differences in quiet eye duration with a baseline check. No significant differences between locus specific focus of attention, $F_{(1,32)} = 0.07$, $p = 0.79$, $f = 0.04$, $CI = -0.52$ to 0.79, $1 - \beta = 0.95$, and perception specific focus of attention, $F_{(1,32)} = 1.37$, $p = 0.25$, $f = 0.40$, $CI = -0.26$ to 1.06, $1 - \beta = 0.96$, were demonstrated. Additionally, no significant interaction was revealed, $F_{(1,32)} = 0.07$, $p = 0.79$, $f = 0.04$, $1 - \beta = 0.95$ (cf. **Table 3**).

To investigate differences in quiet eye duration between tests, we conducted an analysis of variance (2x2x2) (tests × locus-directed focus vs. perception-directed focus), which revealed significant differences between pre- and post-tests, $F_{(1,32)} = 6.93$, $p = 0.01$, $f = 0.43$, *CI*: -0.03 to 0.90, showing a strong effect size. Quiet eye duration was extended from pretest (*M:* 574 ms, *SD*: 382 ms) to posttest (*M:* 747 ms, *SD*: 408 ms), the Δ of the alteration of the quiet eye duration is presented in **Figure 1**. No significant differences for perception-specific focus of attention were found, $F_{(1,32)} = 0.62$, $p = 0.44$, $f = 0.24$, *CI*: -0.42 to 0.90, but there was a significant interaction of test and perception-specific focus of attention, $F_{(1,32)} = 15.31$, $p < 0.01$, $f = 0.69$. Visually instructed groups increased their quiet eye duration while the kinesthetically instructed group reduced their quiet eye duration. For locus-specific focus of attention no significant differences were revealed, $F_{(1,32)} = 0.09$, $p = 0.77$, $f = 0.08$, *CI*: -0.57 to 0.74, $1 - \beta = 0.95$. As well, no significant interaction of test and locus-specific focus of attention, $F_{(1,32)} < 0.01$, $p = 0.97$, $f = 0.05$, $1 - \beta = 0.95$ was found. Both the externally instructed groups and the internally instructed groups increased their quiet eye duration between tests (c.f. **Figure 1**). The three way interaction (test × visual vs. kinesthetic × internal vs. external) was also not significant, $F_{(1,32)} = 0.43$, $p = 0.52$, $f = 0.11$, $1 - \beta = 0.10$.

Results Concerning Throwing Accuracy

To test for baseline differences, we conducted an analysis of variance (2x2x2) (test × internal vs. external × visual vs. kinesthetic). Pretest differences between the two perception specific foci of attention, $F_{(1,32)} = 20.75$, $p < 0.01$, $f = 1.47$, $CI = 0.74$–2.20, were revealed. The visually instructed group demonstrated better throwing accuracy compared to the kinesthetically instructed group. No significant differences were found for the locus specific focus of attention, $F_{(1,32)} = 0.05$, $p = 0.83$, $f = 0.03$, $CI = -0.65$ to 0.56, $1 - \beta = 0.95$. Additionally, no significant interaction was found, $F_{(1,32)} < 0.01$, $p = 0.99$, $f < 0.01$, $1 - \beta = 0.95$.

Due to the pretest differences in the perception specific focus of attention, an analysis of covariance (2x2: internal/external vs. visual/kinesthetic) was done for group differences. The ANCOVA showed no significant interaction for the groups, $F_{(1,31)} = 3.35$,

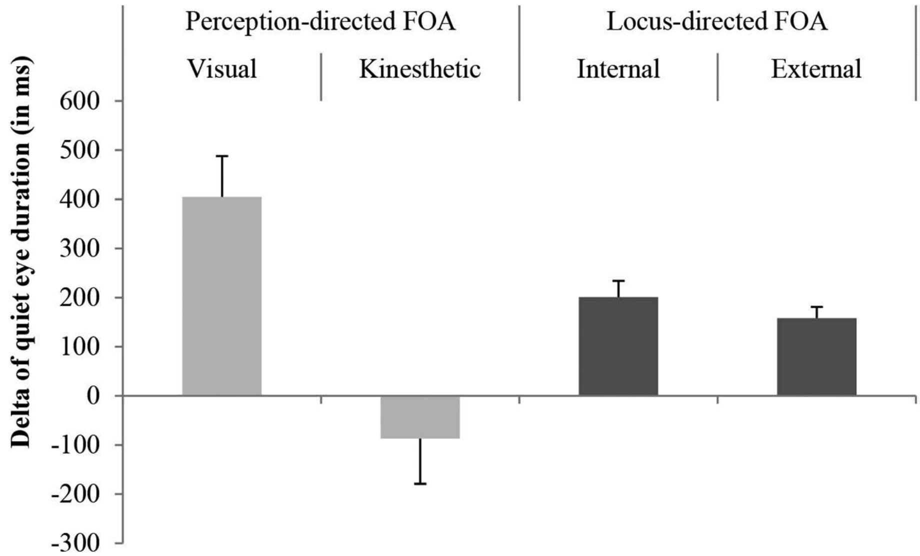

FIGURE 1 | Mean values of the variation of the quiet eye duration between pre- and posttest (Δ) with error bars representing the standard deviation.

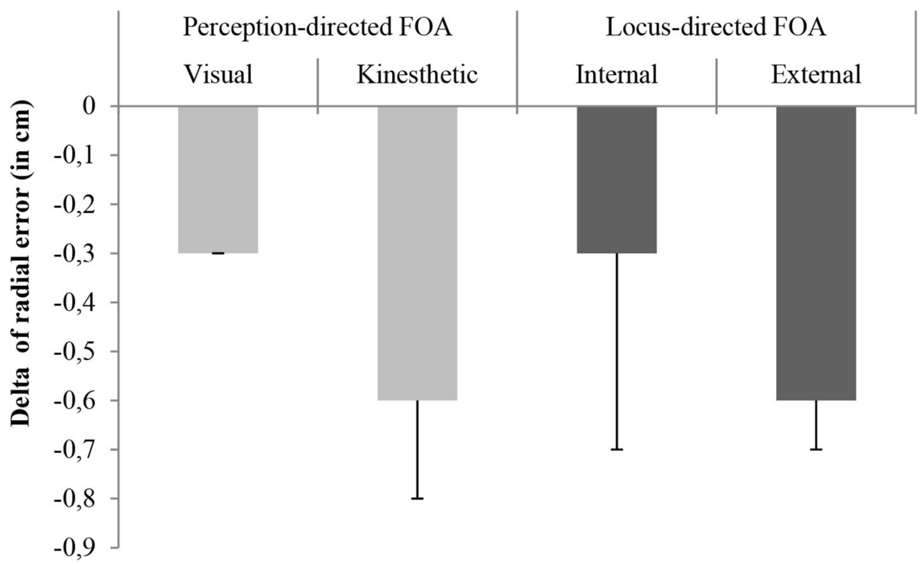

FIGURE 2 | Mean values representing the reduction of radial error in throwing accuracy between pre- and posttest (Δ) with error bars representing the standard deviation.

$p = 0.08, f = 0.33, 1 - \beta = 0.97$. Also, no significant differences between the locus-foci of attention $F_{(1,31)} = 0.40, p = 0.53, f = 0.11, 1 - \beta = 0.95$, or the perception-specific focus of attention, $F_{(1,31)} = 2.76, p = 0.11, f = 0.30, 1 - \beta = 0.96$, were found. To investigate differences for throwing accuracy from pre-to post-test, an ANOVA was conducted but showed no significant effects, $F_{(1,32)} = 1.13, p = 0.30, f = 0.13, CI = -0.33$ to 0.59, $1 - \beta = 0.95$. All groups improved throwing accuracy slightly with lower values representing a better accuracy (Pretest: *M*, 8.7 cm; *SD*, 3.3 cm/ Posttest: *M*, 8.2 cm; *SD*, 3.2 cm). The Δ of the radial error reduction is presented in **Figure 2**.

DISCUSSION

The first aim of this investigation was to replicate findings concerning the trainability of quiet eye duration and its association with motor results. As expected, we were able to replicate findings regarding the trainability of quiet eye; the 1-week training intervention led to significantly longer quiet eye durations overall. However, this effect was different across the training groups. Quiet eye durations increased in the visually instructed groups, but the kinesthetically instructed groups showed reduced quiet eye durations.

Interestingly, there were descriptive results showing that the groups improved their throwing results by reducing radial error, and although these results did not reach significance they showed a reasonable effect size ($f = 0.13$) given the length of the intervention. The non-significant improvement of throwing accuracy from pre to post-test might be best explained with the measuring unit. When having a look at the dartboard, millimeters are crucial for a hit or a miss. It might be that a longer training intervention would lead to greater reductions in the radial error but we believe this positive trend is notable. Pre-/post-test differences showed longer quiet eye durations with a reduction in radial error and therefore better motor results. These results are in line with prior work (Harle and Vickers, 2001; Vine and Wilson, 2010; Vine et al., 2013; Miles et al., 2014). In summary, these trends suggest an improvement in quiet eye duration is associated with better throwing results.

Our second aim of this study was to evaluate the different focus of attention instructions, particularly the value of more sensitive instructions for gaining deeper insight into the association between quiet eye duration and throwing results in darts. When considering the locus of focus of attention (external vs. internal, Hypothesis 1), no significant group differences were revealed for throwing accuracy but there was a medium sized effect ($f = 0.33$). It is notable that the trend suggests a higher improvement for the external compared to the internal instructed groups, which is descriptively in line to our hypothesis and prior work (Carpenter et al., 2013; Wulf, 2013). When considering the results on quiet eye duration, no significant group differences were found. Both locus-directed groups increased their quiet eye duration.

Our second hypothesis considered differences in the perception-specific focus of attention (visual vs. kinesthetic). No significant group differences were found for throwing accuracy. However, besides the externally instructed groups, the kinesthetically instructed groups showed a lot higher improvement in throwing accuracy compared with visual or internal instructions. For quiet eye duration, a significant interaction between perception-specific groups and test was revealed. The visually instructed group increased their quiet eye duration whereas the kinesthetically instructed group decreased their quiet eye duration. This is in line with our hypothesis that in addition to locus of instruction, the sense that is being targeted in the instruction can influence the perceptual and motor result.

For the comparison between locus- and perception-specific focus of attention, no significant interaction of groups was revealed for throwing accuracy: all groups improved throwing accuracy slightly. Similarly, the interaction for quiet eye duration was also not significant. Surprisingly, we were not able to replicate the significant group differences between the locus-directed instructions (internal vs. external) in novices; whenever the trend showed the correct direction in throwing accuracy, the results for quiet eye duration were very similar. These results are in line with prior research (e.g., Wulf, 2013) suggesting novices profit from an external focus of attention.

As Castaneda and Gray (2007) postulated, a focus on skill execution improves motor performance in novices, we would argue that in perceptual-motor learning it is necessary to consider the skill under examination (perceptual or motor), because the specificity of instruction (i.e., kinesthetically vs. visually-directed) may be important. Results concerning our second hypothesis are in line with prior research showing that a focus on the movement effect (external) results in better motor performance then attending to the movement itself (internal) in novices (Wulf and Prinz, 2001). Similarly, Castaneda and Gray (2007) showed that an external focus on skill execution led to better batting performances. With regard to our aims (i.e., benefit for perception-specific focus of attention and its specificity in perceptual-motor learning), one needs to consider that perceptual and motor performance might be differentially influenced by different foci of attention. Concerning the motor results (throwing accuracy), the kinesthetic-external group showed the highest improvement in throwing accuracy, which is in line with results from (Castaneda and Gray, 2007). One possible explanation for this pattern of results is the common-coding theory of perception and action, first discussed in this area by Wulf and Prinz (2001). This theory proposes that actions are controlled by their intended effect. These effects should be as remote as possible and relatively close to the action that produces it. To focus on the dart (external kinesthetic) is less remote as a focus on the hand; moreover, the dart is relatively close to the produced action. Based on this theory, a focus on the dart is directly associated with the movement of the dart throw; however, a focus on the trajectory of the dart, for example, would have led to worse performance because this focus cannot be associated with the movement itself.

Bringing these approaches (Wulf and Prinz, 2001; Castaneda and Gray, 2007) together, it is reasonable that the focus on the dart (kinesthetic external) led to the highest improvement on the motor result in the context of motor learning. When focusing on perceptual performance, one could argue that the visual-external focus of attention should show the highest improvement in quiet eye duration, which is supported by the results of this study. Additionally, the common coding theory of perception and action might explain the pattern for the quiet eye results. Wulf and Prinz (2001) noted that actions might be more fruitful when they are planned with a focus on the intendent effect instead of the movement itself. This approach might explain the highest benefit of quiet eye duration for visual-external instruction. In particular, the significant interaction of perception-specific focus of attention and test suggests that in addition to locus, the sense being targeted (visual, kinesthetic) influences both motor and perceptual performance. Interestingly it seems that the visual system is affected by both visual foci of attention instructions.

In conclusion, our results indicate that small changes in instructions influence their effects on perceptual and motor results. It is notable that visually-directed instructions showed greater effects on perceptual performance (e.g., quiet eye), and that kinesthetically-directed instructions seemed to influence the motor result (radial error) as strongly as the external instructions. Results of this 1-week training intervention suggest perceptual and motor learning in novices could be asynchronous. With this in mind, it would be interesting to have a closer look at the synchrony of perceptual and motor learning; a learning intervention of 1 week might be not long enough to show the assimilation of these two factors. Further research should focus on longer training interventions for getting deeper insight into the influence of instructions in the learning of perceptual-motor skills and on perception and action coupling in motor learning processes. Ziv and Lidor (2014) argued that the influence of different focus of attention instructions might be task specific and dependent on the skill level of the learner. Moreover, they argued that more work on specific foci is necessary for getting a deeper understanding of the phenomenon, especially with different levels of expertise and specific tasks. Given our results, the necessity of a standardized and well categorized instruction system is obvious; unfortunately this has not been done in prior work. So far, many studies have used inconsistent instructions making it difficult to compare across studies. This study is a first step to categorizing instructions (possibly only relevant for aiming tasks) that developed two more sensitive categories (locus specific: external vs. internal, perception-specific: visual vs. kinesthetic), which seem to be useful in the context of perceptual-motor learning.

Despite these interesting results, it is possible there were limitations in the methodological design (e.g., difficulty for the participants to interpret the instruction *focus on your eye and the sample size*) suggesting our approach needs to be validated in further research. Additionally, the low sampling rate of the eye tracker (60 Hz) may have influenced the results, higher sampling rates might show a better resolution of fixation duration and should be used in next studies. It is also possible our category system does not consider all categories; as noted earlier, the influence of focus of attention instructions seems to be task specific and there might be additional categories, as previous research pointed out (Hänsel and Seelig, 2003; Hossner et al., 2006). However, the categories used in this study provide a good basis to develop a system that promotes better comparability between the instructions used across studies. Our study showed that besides the locus of attentional focus, the perception-directed focus seems to influence perceptual-motor learning in novices. It will be important to determine the extent to which the effect of perception-directed focus of attention applies beyond aiming tasks. While our study provides new insight on the association of focus of attention and the quiet eye, additional work will be necessary to gain further understanding of other perceptual-motor tasks, different expertise levels and the associations between these factors with perceptual, cognitive and motor performance.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical committee of the University of Oldenburg. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JN and JS planned and conducted the study. All authors contributed to the article and approved the submitted version.

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Saccadic Eye Movements Attenuate Postural Sway but Less in Sleep-Deprived Young Adults

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Sleep deprivation affects the performance of postural control and several other aspects related to attentional mechanisms that may alter sensory cue acquisition strategies. This study aimed to examine the possible effects of horizontal saccades and ocular fixation on a target in the performance of postural control in young adults with sleep deprivation. Twenty-six adults formed two groups, tested in two evaluations. In the first evaluation, participants slept normally on the night before. In the second evaluation, 13 participants were sleep deprived (SD) and 13 slept normally (control group [CG]) on the night before. In both evaluations, each participant stood upright as still as possible, in two experimental conditions: fixating the eye on a target and performing saccadic movement toward a target presented in two different locations (0.5 Hz). Each participant performed 3 trials in each condition, lasting 62 s each. Body oscillation was obtained in both anterior–posterior and medial–lateral directions. Results showed that SD participants swayed with a larger magnitude and higher velocity after sleep deprivation in the fixation condition. In the saccadic condition, body sway magnitude and velocity were reduced but were still larger/higher in the SD participants. Sleep deprivation deteriorates the performance of postural control. Saccadic eye movements improve postural control performance even in sleep-deprived participants but are still not sufficient to avoid postural control deterioration due to sleep deprivation.

Keywords: postural balance, saccades, sleepiness, visual fixation, adults

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INTRODUCTION

Sleep conditions have become a recent and relevant problem in modern societies because of the considerable decrease in hours that had been used for resting in the previous decades (Schoenborn and Adams, 2010). Moreover, about one third of adults sleep <6 h per night (Tobaldini et al., 2017), leading to sleep restriction and even sleep deprivation.

Sleep deprivation or restriction affects performance in many of our daily activities. For instance, several studies have shown deleterious effects on postural control performance (Liu et al., 2001; Nakano et al., 2001; Fabbri et al., 2006), with sleep-deprived young adults swaying with larger magnitude (Gribble and Hertel, 2004; Gomez et al., 2008; Patel et al., 2008; Ma et al., 2009; Robillard et al., 2011; Aguiar and Barela, 2014) and higher velocity (Liu et al., 2001; Gribble and Hertel, 2004; Robillard et al., 2011; Aguiar and Barela, 2014) during maintenance of upright stance.

The detrimental effects on postural control performance after sleep deprivation have been attributed to the deterioration of visual-spatial performance (Roge et al., 2002; Kendall et al., 2006; Chee et al., 2010), reduced sensitivity of visual perception (De Gennaro et al., 2000; Fransson et al., 2008), and reduced attention capacity (Lim and Dinges, 2008; Martella et al., 2011; Roca et al., 2012; Vargas et al., 2017). It has also been suggested that sleep deprivation would affect the acquisition of sensory cues and its integration into motor action in maintaining and controlling postural orientation (Fabbri et al., 2006; Gomez et al., 2008; Bougard et al., 2011; Aguiar and Barela, 2014, 2015).

Although postural control functioning is based on sensory cues coming from multiple sources, the role and the use of visual information in postural control functioning and performance have motivated many studies. For instance, a common finding is that the magnitude of oscillation during an upright stance more than doubles when visual cues are absent (Liu et al., 2001; Fabbri et al., 2006; Morad et al., 2007; Ma et al., 2009; Robillard et al., 2011). It has been suggested that the stabilizing effect when fixating a target in the upright stance is due to minimization of the retinal slip of the target projected onto the retina (Paulus et al., 1989) and in doing so, all body sway also would be reduced.

More interesting, however, it is that several studies have shown that postural control performance is even further improved when one performers saccadic eye movements, fixating a target presented in different locations (Rougier and Garin, 2007; Stoffregen et al., 2007; Rey et al., 2008; Legrand et al., 2013; Rodrigues et al., 2013, 2015; Aguiar et al., 2015; Bonnet and Baudry, 2016a,b). Two explanations have been forwarded to account for such postural control improvement due to different visual cues. One explanation suggests that the stabilizing effect of saccadic movements on postural control is due to a possible "efferent copy" of eye movements made available to the central nervous system, which would lead to improvement of postural stabilization (Guerraz and Bronstein, 2008).

The second explanation is that possible reduction of body oscillation would be related to the use of a different goal during the saccadic movement. In this case, to achieve the goal of visual fixation in different targets, one would need to reduce body sway, and thus further postural stabilization would be due to the suprapostural goal of the upright stance task (Stoffregen et al., 1999). In this case, improvement in stability would be achieved, at least in part, to facilitate the performance of the suprapostural task (Oullier et al., 2002).

In both explanations, the postural control system has available extra resources (e.g., sensory cues, attentional efforts, and cognitive enrolment) that lead to performance improvement and more stable upright stance control. Considering that young sleep-deprived adults show less efficient postural control functioning, we question the use of saccade eye movement to improve postural control functioning in sleep-deprived adults. Such questioning is relevant considering that the use of vision in eye-guided movement conditions might be considered an active visual task, involving synergistic relations between the postural and visual systems (Bonnet and Baudry, 2016a,b). Moreover, in such condition the central nervous system needs to cognitively involve both the control of both eye movements and postural sway. Because sleep deprivation or restriction impacts negatively postural control performance that might be due to the acquisition of vision cues (Cheng et al., 2018) and attentional capacity (Caldwell et al., 2003), sleep-deprived adults might prevent the use of additional sensory cues in the eye-guided task or even not be able to synergistically couple eye movements and postural sway, resulting in overall postural control performance improvement. Therefore, the aim of this study was to examine postural control performance of young sleep-deprived adults in fixating and performing horizontal saccades during an upright stance. Our hypothesis was that sleep deprivation would deteriorate postural control performance and also would impair the usage of additional cues from eye-guided movements to improve postural control performance.

METHODS

Subjects

Twenty-six healthy young adults composed two groups: 13 volunteers constituted the sleep-deprived (SD) group (8 males and 5 females, 24.8 ± 5.8 years) and 13 constituted the control group (CG) (8 males and 5 females, 24.9 ± 5.9 years). Participants were undergraduate students, had normal or corrected-to-normal vision, and reported no diagnosed sleep disturbances or motor commitments. Prior to participation, all volunteers signed a written consent form according to the procedures approved by the Institutional Ethics Committee.

Procedures

Participants were initially contacted when the experimental procedures were explained. They also were instructed to maintain regular sleep schedules, in the 3 day period before the experimental testing, which were monitored by sleep diaries.

When scheduled, participants from both groups arrived at the laboratory between 8 and 10 a.m., after a normal night of sleep. Each participant was asked to turn in the sleep diaries from the previous days and also to complete the Karolinska Sleepiness Scale (KSS), a scale in which the participant indicated the best level of sleepiness that varies from 1 (extremely alert) to 9 (very sleepy, great effort to keep awake, and fighting sleep). Participants were also asked to complete the Pittsburgh Sleep Quality Index and the Morningness–Eveningness Questionnaire, but these were not used for the purpose of this study. Next, participants underwent the first postural control evaluation (Evaluation 1). After this first testing session, participants from both groups engaged in their regular daily activities throughout the day.

Participants in the CG were told to sleep as usual and return to the laboratory the next morning, between 8 and 10 a.m., to perform the second postural control evaluation. It was also requested that they would not drink alcoholic beverages and coffee during the night before and prior to coming to the laboratory. Participants in the SD group returned to the laboratory at the end of the day, approximately at 8 pm, and remained awake all night long. Participants were not allowed to drink alcohol and coffee and throughout the night they engaged in activities such as chatting, reading, playing cards and/or

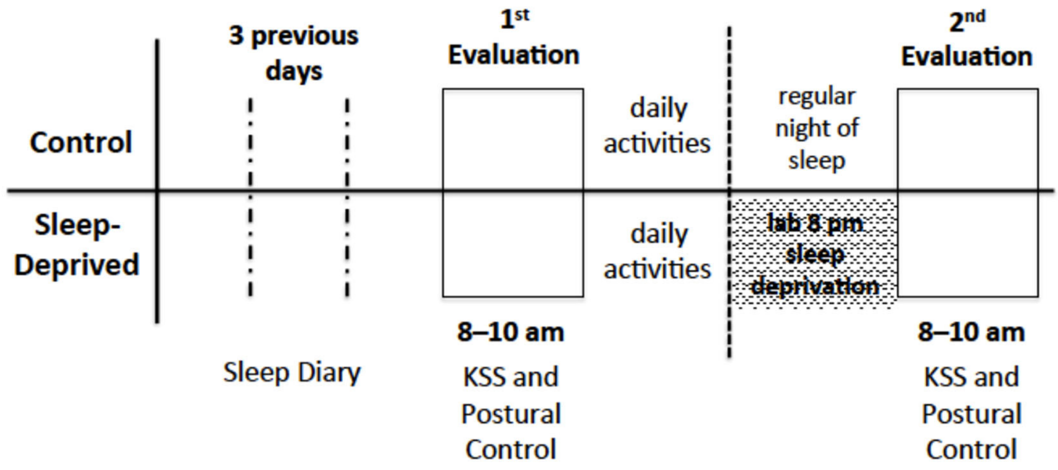

FIGURE 1 | Schematic schedule representation of sleep monitoring and evaluations of participants from both groups.

games, studying, and watching television. The next morning, between 8 and 10 a.m., participants performed the second postural control evaluation (Evaluation 2). A schematic schedule representation of sleep monitoring and evaluations is shown in **Figure 1**.

In both evaluations, participants were instructed to stand upright, with feet parallel and apart at waist width, as stable as possible, inside of a room with black curtains (1.5 m long × 1.5 m wide × 1.8 m high), in order to avoid any undesirable visual stimuli from the environment. A screen monitor (LG–Flatron L1753T8) was placed in front of the participant (1 m away) and adjusted at his or her eye level. The experimental setup is depicted in **Figure 2**. Before maintaining an upright stance, participants wore an eye monitoring system (Eye Tracking Low Cost-dev 1.0) used to automatically track the position of the dominant eye, controlled by specific acquisition software (Pupil Capture, Version 6.3), capturing and displaying online eye position at 30 Hz.

Each participant performed 3 trials, each lasting 62 s, in experimental conditions of fixation and saccades, totaling 6 trials. Participants had a resting interval between trials (about 30 s). In the fixation condition, a target of a 2 cm diameter circle filled in black on a white screen monitor background was presented in the center of the screen for the entire trial. Participants were asked to fixate on it, and the subtended visual angle of the target was ∼1.15°. In the saccade condition, the same target appeared first on the left side of the monitor, 9.75 cm away from the center, then disappeared and reappeared immediately on the opposite side (i.e., the monitor right side), also 9.75 cm away from the center. The described change in target position occurred constantly in the entire trial, with a frequency of 0.5 Hz, resulting in a total of 31 saccadic eye movements. The total distance between the right and left side targets was 19.5 cm, comprising a visual angle of 11° in the horizontal plane. Participants were asked to follow and fixate the target as quickly as possible, with eye movements and avoiding any head movement. The target appearance, in both conditions, was controlled by specific software (Flash Mx, version 6.0, Macromedia) used in previous studies (Rodrigues et al., 2013, 2015). The first condition, fixation or saccadic, was randomly defined and the following ones were alternated.

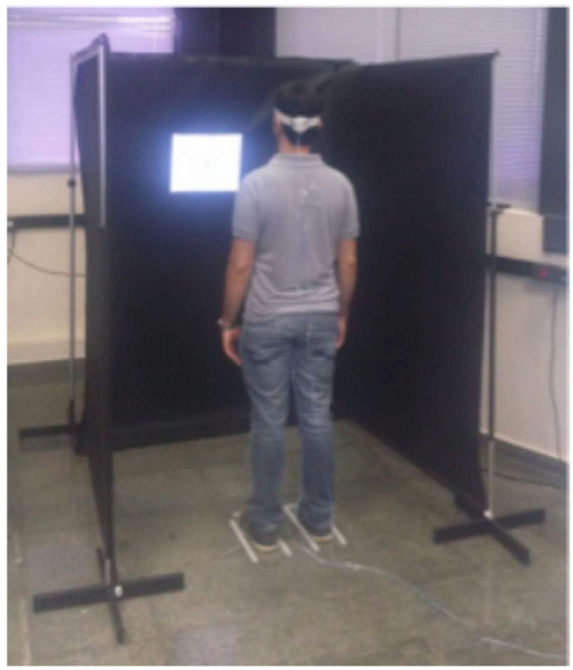

FIGURE 2 | The experimental set up with a participant standing upright, inside the room, with the monitor presented in the frontal wall.

Body sway was obtained using an infrared, light-emitting diode (IRED) marker of a motion analysis system (Optotrack Certus, NDI, Bakersfield, CA, USA) placed on each participant's back (around 8th thoracic vertebra level), providing information

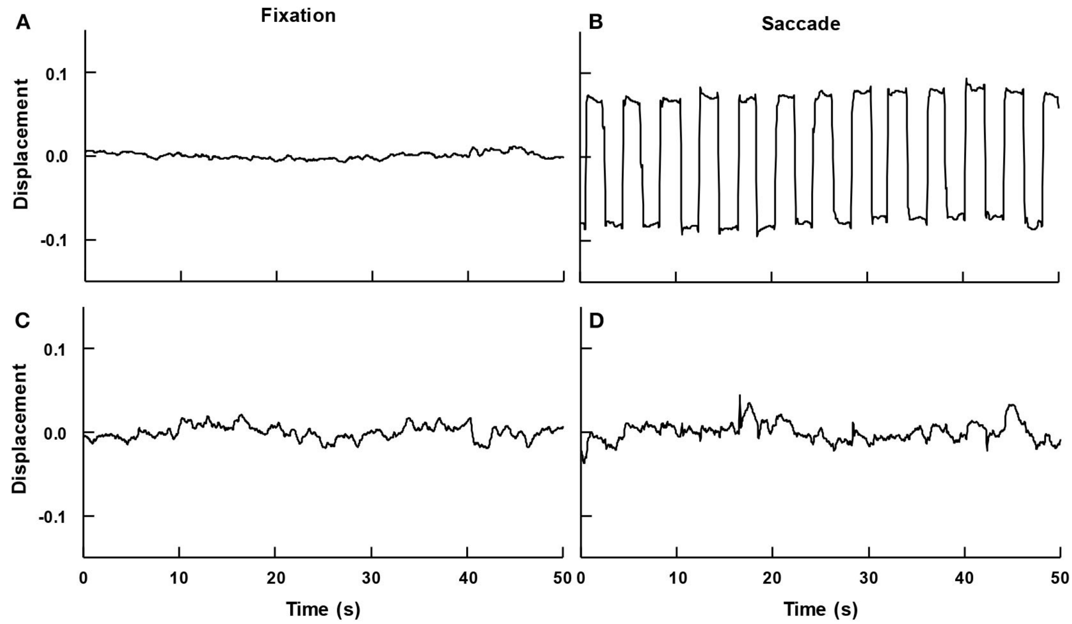

FIGURE 3 | Example time series of a participant's eye movement in the fixation **(A,C)** and in the saccadic **(B,D)** conditions, in the horizontal **(A,B)** and vertical **(C,D)** directions.

about position in both anterior–posterior (AP) and medial–lateral (ML) directions. Body sway data were sampled at 100 Hz.

Data Analysis

Although each trial lasted 62 s, only the intermediate 50 s were considered, with the first and last 6 s periods not considered for analysis. Body sway for both AP and ML directions was filtered using a second-order Butterworth filter with a cut-off frequency of 5 Hz. For each trial, mean sway amplitude and velocity were calculated for both AP and ML directions. Mean sway amplitude was computed as the standard deviation of the positional data throughout the trial, after a first-order polynomial and the mean were subtracted from each data value (detrending). Mean sway velocity was calculated by summing the absolute differences between adjacent positional data of the trial and dividing by the total time of the respective trial. Mean sway amplitude indicated the magnitude of sway variability and mean sway velocity how fast/slow the sway variability occurred.

Eye positioning, in this study, was used only as confirmatory, indicating that participants had accomplished each task requirement, fixation or eye-guided movement. All the procedures were performed using a specific routine written in MATLAB® (MathWorks, Inc., Natick, MA, USA). In addition, the average for each condition was obtained for further analysis.

Statistical Analysis

Four analyses of variance (ANOVAs), having as factors group (SD and CG), condition (fixation and saccades) and evaluation (first and second), with repeated measures on the last two factors, were conducted. First and second ANOVAs had the mean sway amplitude for the AP and ML directions as the dependent variable, respectively. Third and fourth ANOVAs had the mean sway velocity for the AP and ML directions as the dependent variable, respectively. When any interaction was statistically significant, Tukey HSD *post-hoc* tests were conducted. The significance level was set at 0.05 and all analyses were performed using SPSS software.

RESULTS

The sleep diaries showed that participants from both groups slept on average similar amounts in both the 3 previous days and in the night before the first evaluation. In contrast, prior to the second evaluation, while participants from the CG had a regular night of sleep, participants from the SD group did not sleep and remained awake. **Table 1** depicts the average sleep hours in the previous days and the night before the first evaluation and the time awake prior to the second evaluation for both groups.

Sleep deprivation induced different levels of sleepiness as shown in **Table 2**, which depicts the Karolinska Scale average values for both groups and evaluations. While the average values indicated alert and relative alert for CG participants in both evaluations, for the SD participants alert and relative alert were indicated in the first evaluation but a state of sleepiness with a great deal of effort to keep awake after sleep restriction and prior to the second evaluation.

Participants were able to maintain an upright stance and to fixate the target displayed in the center to the monitor throughout the trial or to perform saccades and fixate the target as it appeared, disappeared, and again appeared on the other side of the monitor at frequency of 0.5 Hz. **Figure 3** depicts an example eye position, vertical and horizontal directions, and time series

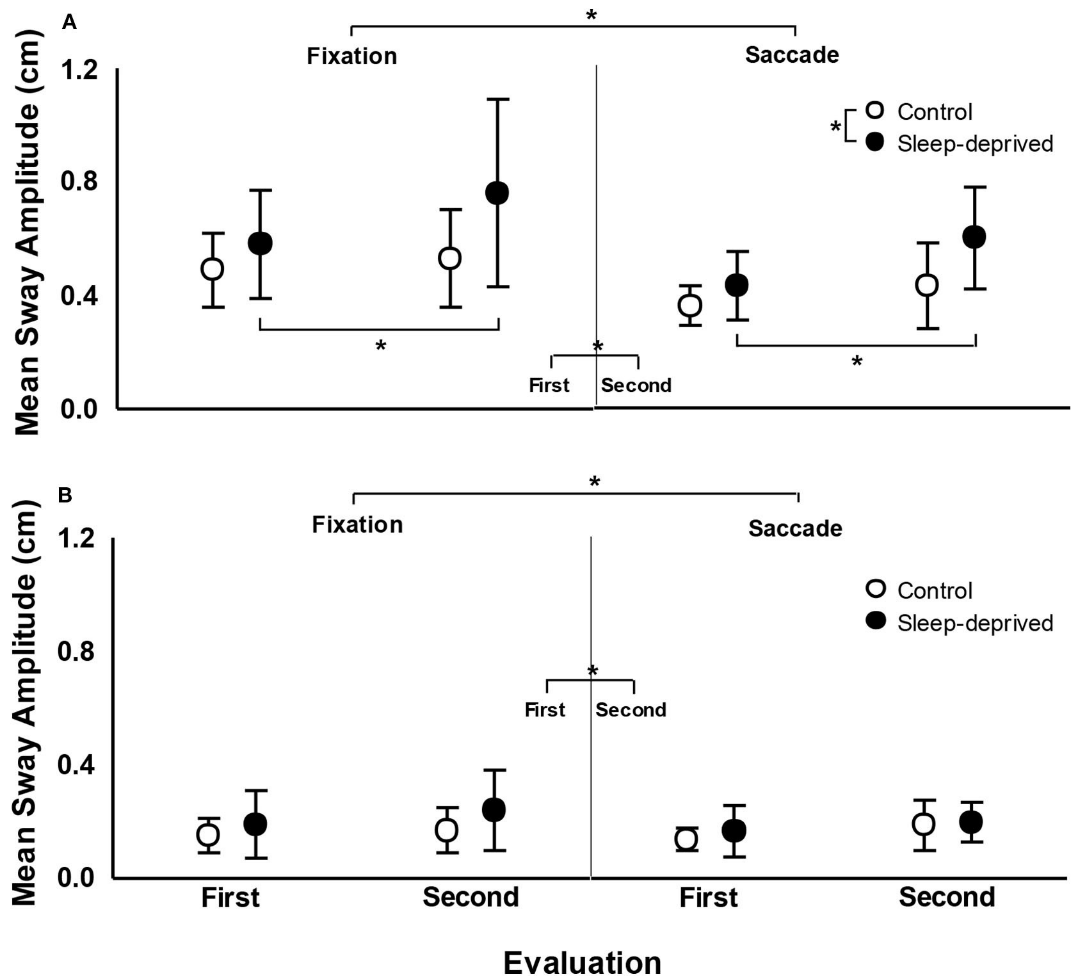

FIGURE 4 | Mean (standard deviation) of mean sway amplitude in the anterior–posterior **(A)** and medial-lateral **(B)** directions in fixation (left) and saccade (right) conditions, in the first and second evaluations, for the control and sleep-deprived groups. Note: *indicates statistical difference.

TABLE 1 | Means (standard deviations) of the sleep hours in the three days before first evaluation, night before first evaluation and hours awaked prior evaluation 2.

	Day 3 prior evaluation 1	Day 2 prior evaluation 1	Day 1 prior evaluation 1	Night prior evaluation 1	Awaked prior evaluation 2
Control	7.21 (0.82)	7.07 (1.23)	6.52 (0.41)	7.06 (1.15)	3.25 (0.73)
Sleep-deprived	7.16 (1.33)	7.09 (1.43)	7.00 (0.87)	7.17 (0.80)	25.82 (0.86)

TABLE 2 | Means (standard deviations) of the Karolinska sleepiness scale values for both control and sleep-deprived participants obtained prior to both evaluations.

	Evaluation 1	Evaluation 1
Control	3.69 (0.95)	3.77 (1.77)
Sleep-deprived	3.69 (1.55)	8.38 (0.77)

Note: Values 3 and 4 indicate alert and fairly alert, respectively, and values 8 and 9 indicate sleepy, some effort to keep alert and very sleepy, great effort to keep alert, fighting sleep, respectively.

for both conditions of a participant. As can be seen, in the fixation condition (left panels), horizontal and vertical positions indicate that the eye displayed small displacement as it fixated on the target. On the other hand, in the saccade condition (right panels), the horizontal position indicates eye movements to the left/right direction as the target was also displayed in the left/right side of the monitor. The vertical position also displays small displacement as the target position did not vary up or down.

Figure 4 depicts mean sway amplitude for both SD and CG participants, in both the first and second evaluations, in

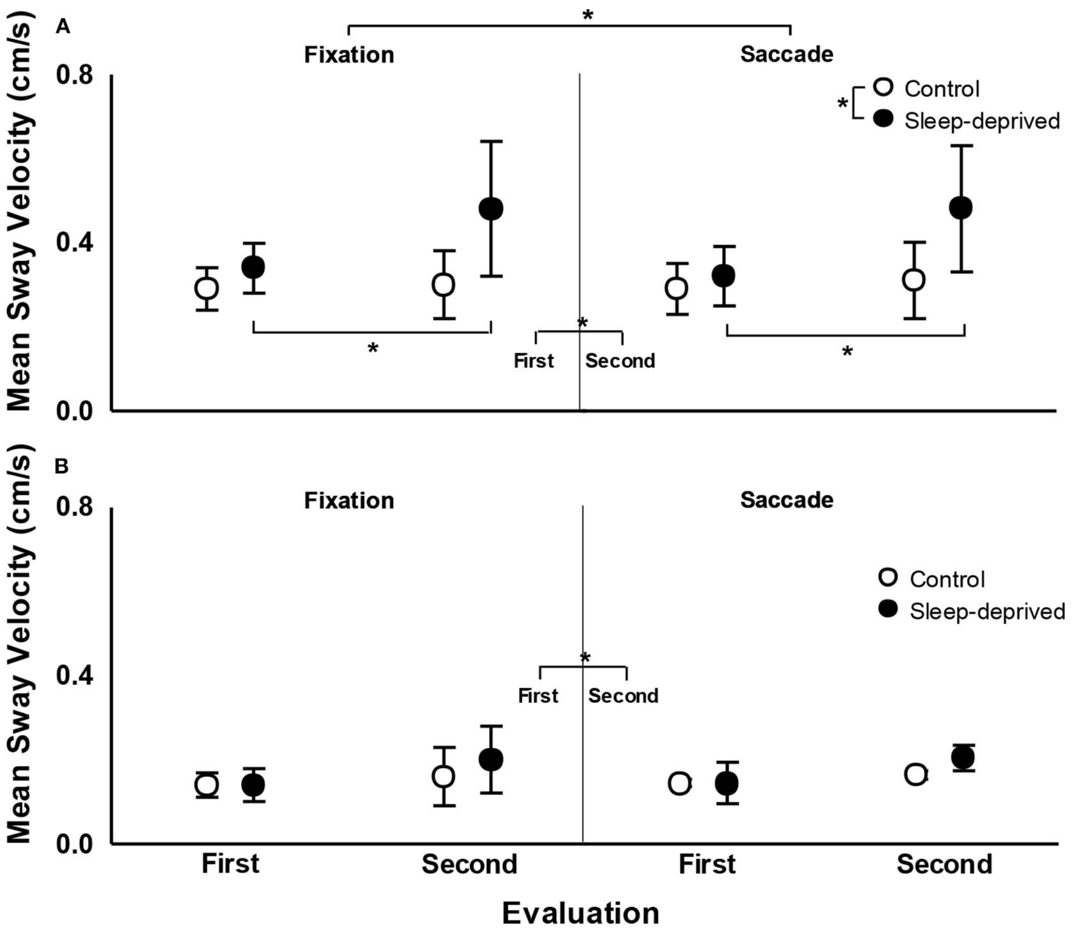

FIGURE 5 | Mean (standard deviation) of mean sway velocity in the anterior–posterior **(A)** and medial-lateral **(B)** directions in fixation (left) and saccade (right) conditions, in the first and second evaluations, for the control and sleep deprived groups. Note: *indicates statistical difference.

the fixation and saccade conditions. For the AP direction, ANOVA revealed effect of group, $F_{(1,24)} = 4.39$, $p < 0.05$, $\eta^2_p = 0.155$, condition, $F_{(1,24)} = 25.22$, $p < 0.001$, $\eta^2_p = 0.512$, evaluation, $F_{(1,24)} = 17.31$, $p < 0.001$, $\eta^2_p = 0.419$, and group and evaluation interaction, $F_{(1,24)} = 4.91$, $p < 0.05$, $\eta^2_p = 0.170$. Participants with SD swayed with larger magnitude than CG participants; sway magnitude was larger in the fixation than in the saccade condition; in the second evaluation, sway was larger in magnitude than in the first evaluation. Finally, *post-hoc* tests indicated that while CG participants did not differ between first and second evaluations, SD participants swayed with a larger magnitude in the second, after sleep deprivation, compared to the first evaluation. For the ML direction, ANOVA only revealed condition, $F_{(1,24)} = 5.59$, $p < 0.05$, $\eta^2_p = 0.189$, and evaluation, $F_{(1,24)} = 4.73$, $p < 0.05$, $\eta^2_p = 0.165$, effects. Sway magnitude was larger in fixation than in the saccade condition and was larger in the second than in the first evaluation.

Figure 5 depicts mean sway velocity for both SD and CG participants, in both the first and second evaluations, in the fixation and saccade conditions. For the AP direction, ANOVA revealed effect of group, $F_{(1,24)} = 11.90$, $p < 0.005$, $\eta^2_p = 0.332$, evaluation, $F_{(1,24)} = 13.76$, $p < 0.005$, $\eta^2_p = 0.364$, and group and evaluation interaction, $F_{(1,24)} = 9.46$, $p < 0.01$, $\eta^2_p = 0.283$. Participants with SD swayed with higher velocity than CG participants and in the second evaluation sway velocity was higher than in the first evaluation. Finally, *post-hoc* tests indicated that while CG participants did not differ between first and second evaluation, SD participants swayed with higher velocity in the second evaluation, after being sleep deprived, compared to the first evaluation. For the ML direction, ANOVA only revealed effect of evaluation, $F_{(1,24)} = 6.24$, $p < 0.05$, $\eta^2_p = 0.206$, and evaluation and condition interaction, $F_{(1,24)} = 5.14$, $p < 0.05$, $\eta^2_p = 0.176$. Sway velocity was higher in the second compared to the first evaluation. *Post-hoc* tests did not indicate any pairwise difference for the evaluation and condition interaction.

DISCUSSION

The goal of this study was to examine upright stance postural control performance of young sleep-deprived adults during continuous fixation and horizontal saccades. Our hypothesis was that sleep deprivation would deteriorate postural control performance and also would impair the usage of additional cues from eye-guided movements to improve postural control performance. Our results corroborate the first part of our hypothesis but refuted the second part, as sleep-deprived participants reduced sway magnitude when using horizontal saccades compared to when only fixating a stationary target. Moreover, sleep deprivation deteriorates postural control performance on a regular basis and despite improving postural control performance, horizontal saccades are not sufficient to overcome the deleterious effects of sleep deprivation, as young sleep-deprived adults still sway with larger magnitude than non-sleep-deprived adults in the AP direction.

Contrary to our hypothesis, results showed that sleep-deprived adults are capable of using saccadic eye movements in order to improve postural control, reducing sway magnitude. Such reduction has been observed for adults not sleep deprived (Stoffregen et al., 2007; Legrand et al., 2013; Rodrigues et al., 2013) and attributed to an attempt to spatially perform the saccades more accurately to the target (Stoffregen et al., 2007) and due to efferent information available to the postural control mechanisms (Guerraz and Bronstein, 2008). Thus, sleep deprivation does not prevent the use of any of the possible mechanisms related to any of these explanations. The improvement in postural control due to eye movement in sleep-deprived adults is relevant considering that it would involve a synergistic relation between the postural and visual systems (Bonnet and Baudry, 2016a), with the central nervous system cognitively involved with both the control of both eye movements and postural sway. In this case, even 24 h of sleep deprivation would not prevent the use of such interaction. The suggestion that sleep deprivation would impact attentional resources (Lim and Dinges, 2008; Martella et al., 2011; Roca et al., 2012; Vargas et al., 2017) requires further understanding because certainly a more complex task such as maintaining an upright stance and producing specific eye movements requires more attention but still provides improvement in postural performance. It might be that postural control and eye movements are not competitive but, conversely, they are congruent (Bonnet and Baudry, 2016a) and the central nervous system still has attentional resources to cognitively couple them.

The impact of sleep deprivation in postural control performance deterioration has been observed in several previous studies (Liu et al., 2001; Nakano et al., 2001; Fabbri et al., 2006) and it was shown in this study as well. Our results clearly showed increased sway magnitude and velocity, in the AP direction, after sleep deprivation when compared to both prior sleep deprivation (within participants) and to not-sleep-deprived participants. Moreover, our results showed that such postural control performance deterioration was observed for both fixation and saccade conditions. Therefore, sleep deprivation deteriorates postural control performance and even the improvement due to eye movement was not sufficient to overcome such a decrease in performance.

Previous studies have generally shown a reduction of approximately one third of body sway magnitude due to saccades as compared to the fixation condition. Mean trunk sway amplitude was reduced in the AP direction between 25 and 30% (Rodrigues et al., 2013) in adults. Additionally, saccadic eye movements consistently reduced postural sway in about the same percentage of young adults in fatigued and unfatigued conditions (Barbieri et al., 2019), in mildly affected people with multiple sclerosis (Santinelli et al., 2019), and even in children with dyslexia (Barela et al., 2020). Interestingly, our results show a similar amount of sway reduction comparing the respective visual conditions, fixation and saccade, to the sleep and sleep-deprived evaluations. In contrast, the sway magnitude observed after sleep deprivation was about the same as that observed in the fixation condition prior to the sleep deprivation. These results indicate that the overall underlying mechanisms related to postural control functioning are in place and working, but after sleep deprivation the magnitude of body sway is already larger and any reduction due to eye-guided movement is not sufficient to overcome the deterioration produced by the absence of sleep.

Recently, it was observed that visual manipulation, inducing postural sway, was maintained after sleep deprivation in young adults but the accuracy with which body sway was produced related to the visual cues and the stability between the visual cues and body sway was clearly affected by the lack of sleep in young adults (Aguiar and Barela, 2014, 2015). The lack of accuracy and stability indicated that individuals with sleep deprivation could couple to the manipulated visual cues but could not uncouple to other sensory cues and, in doing so, their postural control performance was worsened. Results from the present study resemble those in previous ones (Aguiar and Barela, 2014) such that saccadic eye movements were used to improve postural control performance but not to overcome all the deleterious effects of sleep deprivation. Considering that both explanations for using saccadic movements to improve postural control performance are based on the use of additional cues, such enhancement of available sensory cues is not enough to improve performance to the one observed for normal conditions of sleeping. If this is the case, any change and/or impairment in sleep-deprived adults' sensorimotor coupling is still affecting cues coming from the saccadic eye movements. Future studies should aim to carefully examine eye movement characteristics such as velocity, accuracy, and variability of sleep-deprived and control participants. If eye movement characteristics were to be preserved, sleep deprivation would not affect the sensory cues acquisition but instead their usage by the postural control system. Conversely, if eye movement characteristics were to be affected, sleep deprivation would also affect sensory cue acquisition.

In sum, postural control performance of young adults is affected by sleep deprivation. Saccadic eye movements improve postural control stability even after sleep deprivation, but still not to the level observed when there is no sleep deprivation. Therefore, sleep deprivation seems to deteriorate postural control functioning, altering underlying mechanisms that might be overcome by enhanced information furnished by eye movements.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

All procedures of this study were reviewed and approved by the Cruzeiro do Sul Ethical Committee (CEP-Cruzeiro do Sul #156_2015) and prior to participation, all human volunteers signed a written consent form.

AUTHOR CONTRIBUTIONS

IV and LB were responsible to designed the study, obtained and analyzed the data and to organized and wrote the manuscript. SR involved in the discussion and interpretation and revision of the manuscript. JB advised the study development, data analysis and interpretation, and revision of the manuscript. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2020.00097/full#supplementary-material

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