Eye movements in sports research and practice: Immersive technologies as optimal environments for the study of gaze behaviour

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Abstract

Head-mounted eye tracking has been fundamental for developing an understanding of sporting expertise, as the way in which performers sample visual information from the environment is a major determinant of successful performance. There is, however, a long running tension between the desire to study realistic, in-situ gaze behaviour and the difficulties of acquiring accurate ocular measurements in dynamic and fast-moving sporting tasks. Here, we describe how immersive technologies, such as virtual reality, offer an increasingly compelling approach for conducting eye movement research in sport. The possibility of studying gaze behaviour in representative and realistic environments, but with high levels of experimental control, could enable significant strides forward for eye tracking in sport and improve understanding of how eye movements underpin sporting skills. By providing a rationale for virtual reality as an optimal environment for eye tracking research, as well as outlining practical considerations related to hardware, software and data analysis, we hope to guide researchers and practitioners in the use of this approach.

Keywords: virtual reality; augmented reality; mixed reality; expertise; eye tracking; attention;

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1. Introduction

Human thoughts, actions and behaviours are not isolated processes, and are best understood as a product of interactions with our environment. Whether drawing from an ecological or cognitive perspective, there is an increasing acceptance that internal processes exhibit reciprocal relationships with the external world (Gibson, 1950; Wilson & Golonka, 2013; Wilson, 2002). The same holds true for gaze behaviour. Studies have demonstrated how eye movements influence thinking and reasoning (Grant & Spivey, 2003; Thomas & Lleras, 2007) and conversely how expectations and beliefs drive eye movements (Becker & Fuchs, 1985; Diaz et al., 2013; Friston et al., 2012). Sporting environments provide a rich and dynamic environment in which to study the visual guidance of skilled behaviours. Yet, the complexity of sporting environments also poses a challenge for researchers and practitioners, where fast-paced, physical activities are often not conducive to tightly controlled experimentation and precise ocular measurements. Consequently, the complex reciprocal relationship between eye-movements and the environment is not always captured well.

In this chapter we aim to outline how the long-running tension between experimental control and ecological validity in sports eye tracking research might, in part, be resolved through the use of immersive technologies. Virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies (collectively XR) may enable a step-change for eye tracking research in sport. Indeed, there is already mounting interest from researchers and practitioners (Bird, 2019; Le Noury et al., 2020; Michalski et al., 2019; Neumann et al., 2018; Wood et al., 2020). In the present work we do not discuss foundational principles of eye tracking, or the typology of eye movements (e.g., fixations, saccades, smooth pursuit), but we point the reader to chapters 2-5 of this volume, as well as previous reviews of these topics by Duchowski (2017), Land and Hayhoe (2001) and Yarbus (2013). Instead, we hope to provide an introduction and guide to the emerging field of eye tracking within immersive simulations; a methodology which looks set to play a major role in both research and practice in the field of sport.

2. Eye Tracking in Sport

Eye tracking is used in sports research and practice for a number of purposes. These include: Understanding the perceptual skills which underpin expertise (Harris, Wilson, et al., 2020; Mann et al., 2007; Moore et al., 2019; Williams & Ericsson, 2005); understanding the effect of performance pressure, task constraints or training on skill execution (Dicks et al., 2010; Nieuwenhuys et al., 2008; Williams et al., 2004; Wilson et al., 2009); and as a method for accelerating skill learning (Crowe et al., 2020; Vine et al., 2014). For instance eye tracking has been used to firstly understand, and then train, optimal eye movement strategies in relatively static aiming tasks like shotgun shooting (Causer et al., 2011), golf putting (Vine et al., 2011), and basketball free throw shooting (Oudejans et al., 2002; Vickers et al., 2017). It has also been applied to understanding visual behaviours during more dynamic skills like 11-a-side soccer match play (Aksum et al., 2020). A well-established effect is that sporting experts (and experts in other domains) do not necessarily possess better 'hardware' (e.g., visual acuity or reaction time), but instead use their resources more efficiently. Experts are adept at directing their gaze to only the most informative information in the visual scene (Brams et al., 2019; Mann et al., 2007; Memmert, 2009). Instances of such perceptual expertise include long, stable fixations to the target during aiming tasks (Vickers, 1996); attending to the most informative bodily locations when anticipating opponents' movements (Savelsbergh et al., 2002); and more efficient visual search (Mann et al., 2007).

The understanding that certain gaze behaviours confer a functional advantage logically leads to interventions that teach or cue those gaze behaviours. For instance, eye tracking technology can be used to gather data on an expert's eye movements to provide a model for novices, or to record trainees' own gaze as a means of feedback. Instructing novices to adopt the gaze behaviour of experts has been shown to accelerate learning as well as help performers to maintain appropriate goal-directed attention when placed under performance pressure (Vine et al., 2014). These findings from the sporting literature demonstrate both theoretical insights as well as practical training solutions arising from eye tracking (Crowe et al., 2020; Panchuk et al., 2015). Yet, as alluded to above, sport also provides a number of challenges for the use of eye tracking.

Head-mounted eye tracking in realistic sporting tasks poses a number of practical difficulties. Eye tracking equipment can interfere with the movements of the performer, restrict their field of view and may not fit under protective head gear. The cost of eye tracking equipment means that exposing it to live sporting situations may just be too risky in some scenarios. Next, the inherent sweating and movement (running, physical contact, face touching) of athletes can alter the physical placement of the eye trackers, which disrupts the calibration with the visual scene and the quality of the resulting data. Re-calibration at regular intervals is good practice but may not be possible in continuous sporting tasks. The vagaries of natural lighting in real sport poses further issues for accurately tracking the eye.

Analysis of gaze data from real-world scenes is also challenging, as meaningful parameters must be extracted from a continuous stream of task relevant and task irrelevant ocular behaviour. The timing and location of ocular events relative to scene locations is often analysed using time-consuming manual coding, which limits the volume of data that can be feasibly used (Kredel et al., 2017). The need to operationalise a dependent variable means that a simple parameter is often chosen (e.g. the duration of the final fixation before aiming a projectile; Vickers, 2007), ignoring the more complex time course of visual sampling during a task (Button et al., 2011). All these factors further combine to drive down sample sizes as data collection and analysis incurs significant time costs (e.g. Mann et al., 2013).

A review of 40 years of eye tracking research in sport by Kredel, Vater, Klostermann and Hossner (2017, pp. 1) recently proposed that “as the fundamental trade-off between laboratory and field research cannot be solved by technological means, researchers need to carefully weigh the arguments for one or the other approach by accounting for the respective consequences”. While Kredel and colleagues argue that developments in eye tracking technology cannot solve this long-running trade-off problem, we contend that other technological developments can do just that. Recent investment and technological progressions have led to a step-change in the fidelity of AR, MR and VR technologies. These technologies have also become sufficiently affordable and portable that they are now realistic tools for researchers and practitioners. In the remainder of this chapter we outline how XR technologies may facilitate a number of benefits for eye tracking research in sports, including genuine replicability between trials and participants while avoiding the need to compromise realism for accuracy.

3. Immersive Technologies for Sports Simulation

Not only do VR environments offer possibilities for more innovative and convenient training methods (e.g., Rezzil's VR soccer trainer; Wood et al., 2020), but they can provide an environment for eye movement research that is both controlled *and* realistic (Bideau et al., 2010; Craig, 2013; Harris, Buckingham, et al., 2020a, 2020b; Le Noury et al., 2020; Zaal & Bootsma, 2011). Compared to field research, or even lab-based sporting tasks, a VR environment provides more experimental control, as the researcher is able to entirely programme the visual information presented to the participant. This opens the door to new research questions through the manipulation of sensory input in ways that would not otherwise be possible (e.g., Harris, Wilson, et al., 2020). Concurrently, a simulated environment can, if of sufficient fidelity[1], also provide perceptual information that is more representative of the real sporting arena. Crucially, rather than using pared-down lab-based tasks, VR enables researchers to study sporting skills with perception and action coupled (Brunswick, 1956; Craig, 2013; Le Noury et al., 2020).

As discussed at the outset of this chapter, there exists a reciprocal relationship between the performer and the environment, such that studying eye-movements when they are decoupled from a realistic environment is less than ideal. Brunswick's (1956) representative design framework stresses that experimental stimuli should be drawn from those in the organism's natural environment in order to produce generalisable results. Realistic environments elicit different gaze behaviours (Kurz & Munzert, 2018) and perceptual-cognitive expertise is more clearly displayed under more representative stimulus presentation conditions (Mann et al., 2007, 2010). Being able to execute realistic actions also affects visual behaviours. For instance, Dicks, Button and Davids (2010) showed that when asking a soccer goalkeeper to respond to the direction of a penalty kick presented in a video simulation, visual sampling was modified by the response modality. When the goalkeepers were required to respond with a realistic penalty saving movement the distribution of gaze across the ball and the kicker's body was different to the simplified verbal or joystick response conditions. This work (see also Farrow & Abernethy, 2003; Shim

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[1] Fidelity is the extent to which a simulation recreates the appearance of the real-world, but also the way in which it elicits affective states, cognitions and behaviours that are similar to the real-world (see Harris, Bird, et al., 2020 for a review of fidelity and immersion terminology).

et al., 2005) illustrates that a coupling of representative perceptual information with a realistic behavioural response is necessary to elicit realistic eye movements. While VR may never be able to exactly replicate the real sporting environment (its perceptual properties and movement possibilities), it may be able to provide environments more representative than many lab tasks.

Virtual environments can elicit highly realistic behaviours, provided that they are of sufficient *fidelity* and are able to induce a sense of presence in the user (Slater, 2009). Terms like 'high-fidelity' are often used to describe virtual environments and generally refer to the level of graphical detail present in the simulation. But more importantly – for both research and applied training purposes – the simulation must be 'high-fidelity' in terms of creating perceptual and cognitive responses that are similar to the real-world (Gray, 2019; Harris, Bird, et al., 2020). Consequently, assessments of workload, user experience, and gaze behaviour may be important for establishing the fidelity of XR environments (Bright et al., 2012; Harris, Wilson, et al., 2019). Related to the fidelity of the environment, is the sense of *presence* the virtual environment creates in the user. Slater (2009) defines presence as the experience of truly existing in the virtual world (even though one retains a sense that it is not real). Once a sense of presence is induced, the user will tend to behave in realistic ways. Hence, when XR technologies achieve the requisite fidelity and create a sense of presence, it may be possible to record eye movements, and other behaviours, that are representative and generalisable. An important caveat, however, is that while behaviours may appear similar in VR, uncertainty about sensory input may affect the way in which motor actions are controlled. Lack of haptic feedback in VR, paired with uncertainty about 3D depth, may induce a more conscious form of action control (see Harris, Buckingham, et al., 2019 for a discussion of this issue). Altered modes of motor control may not affect eye tracking in VR directly but do raise some questions about task representativeness.

In practical terms, XR technologies (and VR in particular) provide a more controlled way of conducting eye tracking. Many commercial VR headsets now have built-in eye tracking, mainly for the purposes of gaze reactive stimuli, gaze-based navigation or foveated rendering (i.e., only generating high-definition images around the foveated region to save processing power). This development of eye tracking technology also affords research possibilities. One of the advantages of in-VR eye tracking is that the spatial location of every element in the virtual scene can be recorded so that gaze can be automatically allocated to real-world objects using coordinate matching, rather than lengthy manual coding. Headsets are also well-fitting so that slippage (and disrupted calibration) is less likely and issues with natural light fluctuation are avoided.

For training purposes, the possibilities of gaze reactive VR are waiting to be exploited. Gaze reactive VR environments allow aspects of the visual scene to automatically change when the user's point of gaze collides with them. This functionality could be used to guide and cue gaze behaviour towards an ideal pattern. In a darts simulation, for instance, the bullseye of the dart board could change colour when a stable fixation is maintained on it. There is certainly debate about teaching 'optimal' gaze patterns in this one-size-fits-all manner (Davids & Araújo, 2016; Dicks et al., 2017), but the continued success of gaze training suggests that this approach has its place (Janelle et al., 2003; Słowiński et al., 2019; Wilson et al., 2011). For instance, a form of gaze training known as *quiet eye training* aims to teach long pre-movement fixations in target and aiming tasks. During quiet eye training, verbal instruction or gaze videos of elite performers are used to teach novices to adopt the eye movements of experts (Harle & Vickers, 2001; Vine et al., 2014). However, a virtual environment could easily be augmented to provide feedback in a more automated way when gaze is not allocated optimally. This could be achieved via visual cues (changes in target colour) or by preventing certain actions until the target has been sufficiently attended to. A 'gaze window' of greater acuity or luminance could also be used to cue the user to the most informative areas of the scene. Additionally, as VR training environments are rapidly being adopted in fields like sport, medicine and safety critical industry, in-VR eye tracking can be used to monitor and maximise learning. Overall, there are a number of practical and theoretical (i.e. representative design) benefits to adopting an XR approach for eye tracking in sport. In what follows we outline some of the background to the hardware and software needed for eye tracking in immersive environments.

3.1. Hardware

XR technologies use high resolution displays and tracking sensors to present stereoscopic images that realistically adapt to the users' viewpoint. In head-mounted VR (e.g., in Figure 1), the user is immersed in an entirely virtual world, with all vision of the real-world occluded. In contrast, AR and MR[2] employ semi-transparent displays to place virtual objects within the real-world. The capacity of XR technologies to replace natural sense perceptions with computer-generated ones allows individuals to perceive the simulated environment through natural sensorimotor contingencies (Slater & Sanchez-Vives, 2016) and exhibit realistic behaviours (Slater, 2009). In the present work we focus mainly on head-mounted VR, as the accessibility of commercial devices like the Oculus Rift/Quest and Samsung Gear VR mean they have rapidly assumed a prominent role in sports training, as well as in entertainment and psychological laboratories (Bird, 2019).

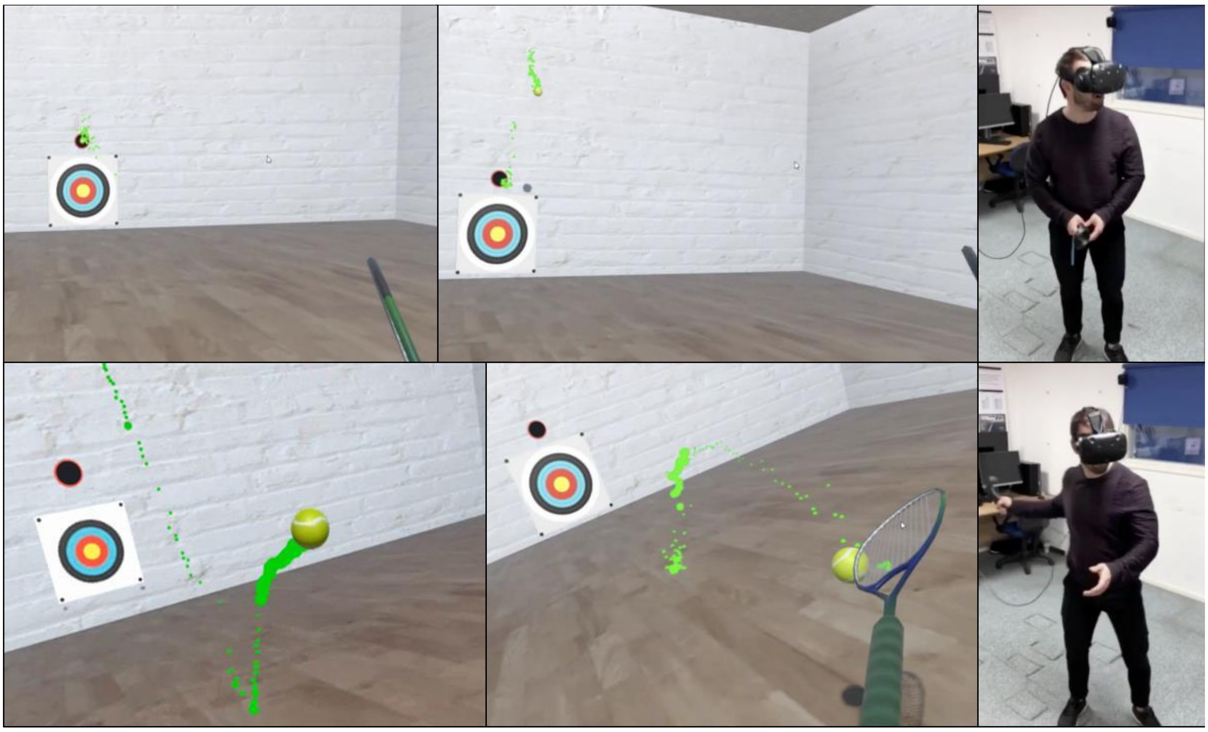

Figure 1 – Screenshots from a virtual racquetball task, in which the ball is fired from above the target and the participant tries to return the ball towards the target centre. The racquet is linked to the motion tracked controller held by the participant (right of figure). Light green dots indicate the point of gaze of the performer (captured by the built-in eye tracker) in real time and illustrate the tracking/prediction strategy used by the performer to intercept the ball.

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[2] The difference between AR and MR is the degree of interaction between real and virtual objects. In AR digital elements are just overlaid onto the real scene (e.g. using the camera of a smartphone), whereas in MR the real-world and digital assets interact (e.g. throwing a digital ball with your real hand), such as in Microsoft's HoloLens headset.

VR head-mounted displays (HMDs) contain sensors that are capable of tracking orientation of the head (i.e., pitch, yaw and roll) using accelerometers, and position in space using either internal cameras or communication with external sensors. HMDs are usually paired with hand controllers which also have orientation and positional tracking sensors, enabling participants to interact with virtual objects using their hands. Supplementary tracking sensors can also be added to animate objects (e.g., sports equipment) in the virtual world, to enable more representative behavioural responses and actions. This is an approach we have previously used to enable realistic actions in the study of golf putting, by attaching a Vive positional tracker to a real golf club (Harris, Buckingham, et al., 2020a, 2020b).

Eye tracking is not yet standard within XR headsets but can be achieved either using externally developed modular add-on eye trackers – those designed to be placed inside a VR headset or attached to AR glasses (e.g., Pupil Labs; https://pupil-labs.com/) – or with HMDs that have eye trackers built-in (e.g., HTC Vive Pro Eye with Tobii eye tracking). Mixed reality headsets like Magic Leap and Microsoft's HoloLens also offer built-in eye tracking and rely more heavily upon it as a system for interacting with virtual assets. The additional cost for either modular or in-built eye tracking is a consideration, and damage during sporting task is possible, although less likely than the damage to head-mounted eye trackers in real sporting scenarios. The commercial impetus from the gaming industry, however, means that in-built eye tracking is becoming more common, and a VR headset with eye tracking is often cheaper than a comparable standalone eye tracker. The current specification of in-VR eye tracking is very similar to standard head-mounted eye trackers but looks set to advance rapidly towards the sampling rates and precision of more accurate externally mounted eye trackers.

3.2. Software and Analysis

XR environments can be developed using gaming engines such as Unity (https://unity3d.com/), Unreal Engine (https://www.unrealengine.com/) or Vizard (http://www.worldviz.com/vizard-virtual-realitysoftware/). Frameworks for assisting in the design of psychological experiments using these engines are also now being developed (e.g. the Unity Experiment Framework; Brookes et al., 2019), making the creation of XR environments more accessible to researchers and practitioners. In addition, 360^{o} video may provide a route that is more accessible but still immersive. 360^{o} video footage of a sporting scenario can be viewed through an HMD to provide a stimulus that is realistic and immersive, although not fully interactive. 360° video is generally created using a single camera lens hence the output is monocular and lacking the depth information provided by software rendered VR, or stereoscopic 360 video (i.e. captured with two lenses to facilitate binocular vision). The way in which the eye tracking data is accessed will depend on the hardware and software being used but will most likely need to be integrated into the environment development. While different engines and hardware providers offer some bespoke software for visualising and analysing gaze data, the most versatile means of output is still a timestamped file of gaze vector coordinates.

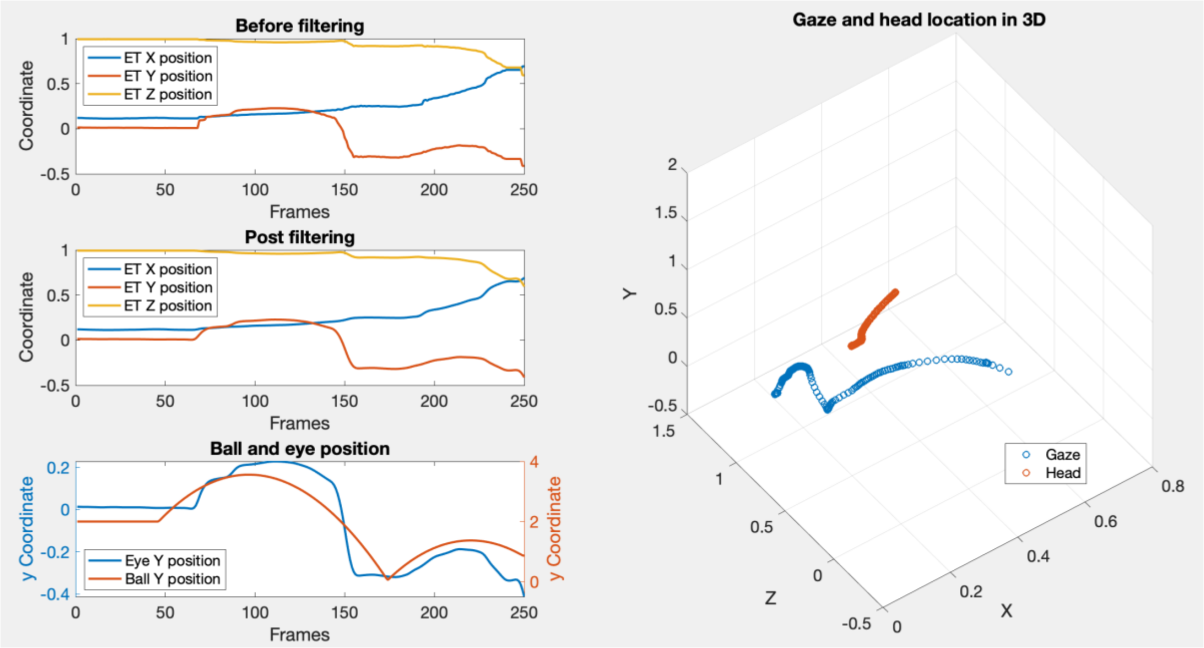

Figure 2 – Plots of eye tracking data from the racquetball task in Figure 1. The top two panels on the left had side illustrate the coordinate data before and after data filtering. The bottom left figure illustrates the relationship between the ball and eye in this task, and the right-hand figure illustrates a 3D plot of the location of the participant's head and point of gaze in the VR environment.

The analysis pipeline for the processing of this gaze data is not as well developed as for standard eye trackers, so may require some programming or data processing skills. Commercial eye tracking glasses often offer their own software for the filtering and identification of eye movements and similar software solutions are also available for VR (e.g., see screengrab from Tobii Pro VR Analytics in Figure 3). However for some purposes, and some modular VR eye trackers, users might need to develop their own analysis pipeline (e.g., see Figure 2) using other open-source software or code packages, such as EyeMMV for MATLAB (Krassanakis et al., 2014) or eyetrackingR for R (Dink & Ferguson, 2015). While this approach requires some decisions to be made by the user around filtering and the identification of ocular events (Salvucci & Goldberg, 2000), there are a number of advantages to analysing gaze data in VR. Contrary to real-world eye tracking, in VR it is straightforward to define regions of interest in 3D space and trace when they were attended to (Clay et al., 2019). One simply needs to determine the intersection between the gaze vector and bodies in the virtual world, although identifying the size of the foveal region at varying depths requires additional computations of relative distance. Gaming engines like Unity and Unreal facilitate this using a 'ray cast' system, which effectively shoots an invisible ray from an origin point in a specified direction. The ray cast detects when it collides with an object and returns information about the hit point. By shooting a ray from the subject's head position, guided by the gaze vector, it is possible to extract information about the object the user is currently viewing, and generate heatmaps of gaze locations (see Figure 4). Contrastingly, AR and MR offer an additional challenge as while gaze coordinates can be mapped to virtual assets there remains a difficulty in mapping gaze to real-world objects.

Figure 3 – 3D heatmapping with gaze vectors projected in 3D using Tobii Pro VR Analytics interface. This version shows multiple participants which were collected individually and then the data was aggregated. Image accreditation: Tobii Pro, Sweden.

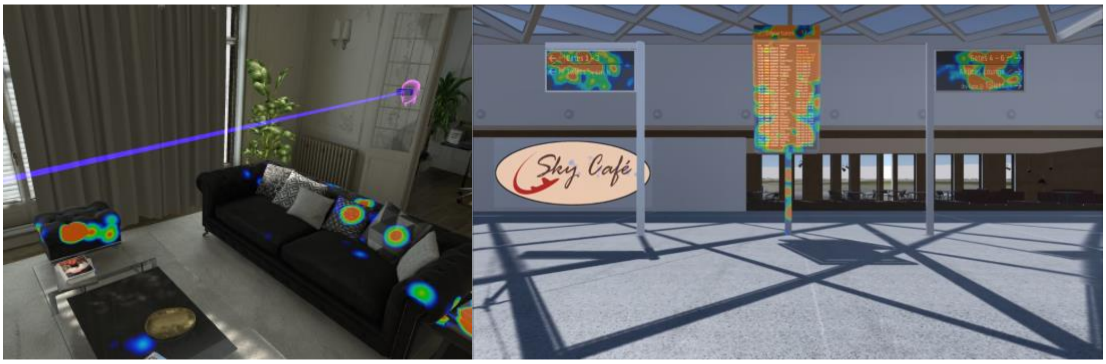

Figure 4 – Left panel: An example of 3D heatmapping with gaze vector projected in 3D. Image accreditation: Tobii Pro, Sweden. Right panel: 3D heatmapping in a study to investigate the use of signage in a virtual airport. Image accreditation: Tobii Pro, Sweden; Paravizion Ltd, UK; CCD Design & Ergonomics, UK.

A similar method can also be used to calculate the location of gaze in depth (Clay et al., 2019). Technically, the location of gaze in depth can be calculated from standard head-mounted eye trackers based on the vergence of the eyes (the synchronous horizontal in/out rotation of the eyes to maintain binocular fixation), but this calculation is imprecise for all but the most perfect of calibrations (Jansen et al., 2009). In VR, the complete knowledge of the distance between eyes and objects means that estimated depth of gaze can be corrected by calculating the intersection of the gaze vector with an object.

3.3. Challenges and Limitations

Despite a number of advantages over traditional eye tracking, there are challenges to be overcome and questions to be answered for VR eye tracking. One of the most pertinent is whether we can use established metrics for fixations and saccades, and whether established eye tracking concepts hold in VR (Clay et al., 2019; Steil et al., 2018). The study of eye movements in VR is very new (the first prominent application seems to be Duchowski et al., 2000) and the way in which VR affects the human visual system is not entirely clear (Harris, Buckingham, et al., 2019). For instance, VR is a 3D environment created on a 2D screen. Binocular disparity is used to create the illusion of three dimensions in HMDs, but this creates issues such as vergence accommodation conflict – a decoupling of the synchronous horizontal rotation of the eyes (to maintain binocular fixation) and focusing of the eye's lens (to maintain clear image over distance) that arises in VR (Bingham et al., 2001; Hoffman et al., 2008; Interrante et al., 2004; Kramida, 2016). On a fixed depth screen no accommodation is necessary, but the eyes still verge to perceived depth. Although this effect seems to be diminishing in higher fidelity systems, there remain questions about how illusory 3D may affect gaze behaviour.

Another technical problem can be differing frame rates between applications. The gaming engine, which runs the XR environment generally employs a lower frame rate than the eye tracker, so while ocular movements might be sampled at, say, 120Hz, they may only be recorded at 60-90Hz. Additionally, the frame rate of the VR application can drop when the processing load increases (generally because of large/complex objects that are difficult to render). Consequently, it is important to employ time stamping of gaze data and analysis methods that take into account variations in frame rate (i.e., resampling).

A hardware related limitation that may pose issues for sporting research is the limited field of view that is possible in many current HMDs. While not a major issue for capturing eye movement data, except on the rare occasions when the eyes display extreme rotation relative to the head, it does pose more of a challenge for ensuring the task is representative. The importance of peripheral vision is well established in dynamic sporting tasks (Klostermann et al., 2020) and a limited field of view might increase the reliance on foveal vision. However, as with accommodation-vergence conflict, field of view issues may dissipate in future technologies. Additionally, this issue can be mitigated against by considering the suitability of the sporting task and whether it relies heavily on covert attention and peripheral vision.

A limitation that is specific to the study of eye movements in sport is that high-fidelity environments that exactly recreate the sporting environment may never be fully achieved. We have argued that VR environments can be used to provide tasks that are more ecologically valid than pared-down lab tasks, and hence capable of eliciting more realistic gaze behaviour. Yet it may never be possible to exactly simulate all the sense perceptions of a sporting task; in particular haptic feedback is crucial for executing motor skills but is very challenging to recreate in VR. An aligned issue is that if the VR environment is not able to recreate the real skill sufficiently well, it may not elicit eye movements that are sufficiently realistic. If the demands of the VR task are substantively different from the real-world, gaze behaviour may be affected, which could lead to inaccurate or inappropriate data interpretation. For this reason, appropriate testing of the fidelity and representativeness of the VR environment is needed. Additionally, the nature of some tasks – contact sports, underwater sports, and those involving excessive amounts of movement – will always pose a barrier. Therefore, it is imperative that XR technologies are used selectively in order to maintain the efficacy of this approach. In summary, while there are notable opportunities, there are also a number of challenges facing the use of in-VR eye tracking. Some of these challenges will dissipate given the speed of technological innovation in this field and some will require judicious and considered implementation by researchers and practitioners.

4. Conclusions

Eye tracking in sport has been integral to our understanding of perceptual-cognitive expertise and how elite athletes efficiently extract environmental information to guide action. Yet there has been a fundamental tension between the need for realistic, representative environments and the desire for experimental control to collect accurate eye tracking data. Studying eye movements in VR may provide a solution that requires relatively little compromise. In our own work we have begun to investigate how eye movement behaviours may develop following VR training (Harris, Buckingham, et al., 2020) and how manipulation of visual information in VR can be used to examine the functional role of eye movements in motor skills (Harris, Wilson, et al., 2020). This work has highlighted the significant potential of eye tracking in VR, such as improved recording and better experimental control. Importantly for the development of research in sport, VR allows perceptual input and response modalities that are more representative of the real-world, and hence can more accurately replicate the crucial person-environment interactions that shape gaze behaviour. This approach is more realistic than lab research, and more controlled than field research. It may also afford better analysis, by enabling algorithmic approaches and accurate matching of gaze to the world, thereby supporting more convenient analysis of large amounts of gaze data. None of these things are unique to VR, but it is a platform that supports a number of benefits. Already VR is taking on a large role in sports research and practice, and in-VR eye tracking may support greater insights into the nature of sporting expertise

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