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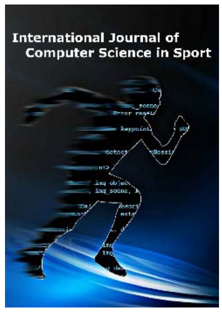

Eye tracking in high-performance sports: Evaluation of its application in expert athletes

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Abstract

In the last thirty years, an increasing interest in sport sciences regarding the analysis of expert athletes' gaze behavior has become apparent. This narrative review provides an overview of the use of eye tracking systems in high-performance sports from 1987 to 2016. A systematic search of the PubMed, Scopus, SPORTDiscus, and WebofScience databases was conducted. The search was performed using the keywords *eye tracking*, *eye movement*, *gaze behavior/patterns*, and *visual search strategies* in combination with *high-performance sports*, *elite athletes*, *high-class athletes*, *sport experts*, and *top-athletes*. It yielded a total of 86 studies of which almost half were conducted computer-based or in front of a screen. Most studies dealt with the analysis of gaze behavior during dead ball situations while also focusing on differences between expert athletes and novices. More high-quality intervention studies are essential to determine if there are ideal gaze strategies and, if yes, how it is possible to learn/implement these.

KEYWORDS: EYE MOVEMENTS; GAZE BEHAVIOR; SPORT EXPERTISE; QUIET EYE

Introduction

Especially in high-performance sports there are not only superior motor skills that can be observed in expert athletes, but often also better cognitive capabilities than in less-skilled athletes (Mann, Williams, Ward, & Janelle, 2007). To successfully initiate motor reactions to prior movements or decisions on time, it is necessary to visually perceive relevant information as quickly as possible. It seems as if the point in time of information absorption and the information localization (information-rich areas, Magill, 1998) are relevant (Abernethy, 2001). As 95% of the environmental stimuli are registered by the human visual system, it is undisputed that efficient gaze behavior in combination with motor skills is considered of utmost importance for achieving top performance in sports (Williams, Davids, & Williams, 1999).

The number of studies analyzing athletes' gaze behavior has seen an increase in recent years. The timely and successful initiation of motoric reactions depends on capturing information carrier in time with the eyes, when executing movements or making decisions in sports. The point in time when (moment of an information) an athlete looks somewhere (location of an information) seems to be crucial. Duration and location of a fixation enable suggestions on perceptual strategies that are used to extract relevant information. Therefore, gaze behavior is an expression of a searching strategy which enables the processing of information from different areas (Abernethy, 1987; Goulet, Bard, & Fleury, 1989). Examining specific gaze patterns can lead to improved performance by allowing for better information processing and is highly important for athletes, coaches, and also scientists.

However, a series of difficulties and problems which arise from the use of eye tracking systems (e.g., limitations of measurement methods in types of sports with high action speed) has been preventing the broad application in sports (Panchuk, Vine, & Vickers, 2015), especially in high-performance sports, until now. A recently published review article of Kredel, Vater, Klostermann, and Hossner (2017) provides a comprehensive overview of the large variance of methods applied, analyses performed, and measures derived within the eye tracking studies being published over the last 40 years in sports-related research. The authors extensively documented details about the researched tasks, the applied eye tracking systems and analysis methods as well as about the derived gaze measures in eye tracking studies relating to sport. However, while Kredel and colleagues focused on the dynamics of natural gaze behavior in sports in general, it remains unclear whether their conclusions apply for single groups of various expertise levels as well. The meta-analyses by Mann et al. (2007) as well as by Gegenfurtner, Lehtinen, and Säljö (2011) revealed, among others, expertise effects in gaze behavior and decision making, in particular for those studies performed in situ. Moreover, considering the group of expert athletes in more detail seems also reasonable because, as the saying goes "learn from the best" it is often helpful, among others for lower-level athletes, to obtain an understanding of expert athletes' visual strategies and their application. Even if it is not always possible to effectively apply, the awareness about the behavior of the best often already helps to improve the own performance (Baker, Côté, & Abernethy, 2003). Furthermore, knowledge on some less functional patterns in gaze behavior may also help expert athletes to improve their performance. Therefore, the current review provides a detailed assessment of eye tracking's applicability and underlines the relevance of the analysis of eye movements in high-performance sports.

While this review article is supposed to show to what extent current research can actually make a relevant statement for high-performance sports, it focusses on three main questions: a) Is the level of expertise in previous eye-tracking studies representative for real/true expert athletes? b) Do the chosen study design and used technology (on a continuum from computer-based to representative design) allow conclusions on behavior in real competitions/sport actions? c) Which sports, respectively aspects of sports, were predominantly analyzed? That is asking if gaze behavior in specific sport situations provides sufficient information to draw conclusions on elite behavior. Hence, the literature at hand will be evaluated regarding different aspects and study characteristics: how much research exist examining the gaze behavior of expert or near expert athletes, and is there sufficient evidence to describe what constitutes expert athletes' gaze behavior during sport actions. In this regard, it will first be examined which study designs have been predominately used (lab, field), which eye tracking systems (computer-mounted, head-mounted) were utilized and if these constrained participants' way of responding (computer-mounted, head-mounted). This analysis is vital, as problems with the external validity of results might be associated with certain utilized methods and designs. Furthermore, it is taken into consideration which sports were mainly considered and what kind of tasks and situations were targeted in previous research. The purpose is to identify whether statements can be made solely for specific high-performance sport types and tasks, or whether studies cover a broad field. While differences in perception and visual attention between expert athletes, less-skilled athletes, and novices are frequently discussed in sport science (for reviews, see Hüttermann & Memmert, 2017, as well as Voss, Kramer, Prakash, Roberts, & Basak, 2010), this review deals with features, advantages, and disadvantages of all publications over the last thirty years that have focused on the gaze behavior of expert athletes (including differences to other performance groups/novices) by using eye tracking systems. A central issue is the consideration up to which extent it is intended/possible to transfer findings on the expert athletes' gaze behavior in experimentally controlled situations to their gaze behavior in real sport situations/competitions. That is also asking, in what way the current state of research can make any statements on gaze behavior of expert athletes or near expert athletes (because this would be essential for comparing gaze behavior at different levels of expertise) and if the current state of knowledge allows for training interventions that aim to improve performance by changing athletes' gaze behavior. Finally, limitations and restrictions, which are associated with eye tracking research and which might also prevent an examination of expert athletes' gaze patterns are presented. The overall goal of this review is thus to get a complete overview of the applied methods/designs as well as research priorities identified in high-performance eye tracking publications over the past thirty years to allow conclusions on how much eye tracking technologies have improved our knowledge of expert athletes.

Method

Design

Considering that the eye tracking literature is very heterogeneous, neither a systematic review (see recommendation of Dixon-Woods, Fitzpatrick, & Roberts, 2001) nor a theoretical qualitative meta-synthesis was implemented (cf. recommendation of Sandelowski, Docherty, & Emden, 1997). Although the current review was planned and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (e.g., literature was selected through a four-step screening process; Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009) it rather resembles a narrative approach without any acknowledged guidelines (Collins & Fauser, 2005). As usual for narrative reviews neither a use of explicit standards to evaluate the quality of the studies is involved nor an attempt to quantitatively synthesize the data. The current review rather delivers an overview of all studies in the area of competitive sports using eye tracking systems to get an overview of more or less examined areas of the research field. We pay particular attention to the level of expertise, to the design and used technologies as well as to the different types of sports and sport situations that have primarily been analyzed in previous publications.

Literature search

The current narrative review includes studies that were published in the period of 1987-2016. As the primary focus of the review is on expert athletes’ gaze behavior, studies that exclusively dealt with the gaze behavior of obviously less-skilled athletes or novices were not included. All studies with participants that were described as “elite”, “expert”, “high-class”, or “professional” athletes were involved. Furthermore, only publications that used eye tracking systems were integrated; studies in this field of research that used other analytical methods, for example an electro-oculogram amplifier, were excluded, amongst others, because statements based on such paradigms are difficult to be transferred to actual game situations or natural movements in sport.

A systematic search of the PubMed, Scopus, SPORTDiscus, and Web of Science databases, from December 1987 up to October 2016, was conducted. The search was performed using the keywords: “eye tracking”, “eye movement”, “gaze behavior/patterns”, and “visual search strategies” in combination with “high-performance sports”, “elite athletes”, high-class athletes, “sport experts”, and “top athletes”. Manual searches of other literature sources such as books were conducted as well. Considering that the definition of “experts”, “elite athletes”, “high-class athletes”, or rather “top athletes” can be quite divergent, it was checked how expertise was actually defined and which performance class/league participants were assigned to in published research. In the current review the term “expert athletes” is used consistently for the description of the participants who took part in the selected eye tracking studies. However, sport scientists often characterize athletes’ expertise differently so that not all of the athletes necessarily have the same expertise level. For readers it is often very difficult or almost impossible to evaluate the actual expertise level of these athletes, in particular if necessary information is missing in publications. Following the review of Swann, Moran, and Piggott (2015), a classification between different groups of expert athletes was carried out by the specific information given in the studies (when available).

Results and discussion

Literature for the review was selected through a four-step screening process (Figure 1). The search yielded a total of 4.045 records. After removing duplications, excluding irrelevant studies (e.g., publications that used other methods of eye movement analyses instead of eye tracking or studies without expert athletes) as well as conducting a final manual search of the literature (i.e., screening of references), a total of 86 studies were included in this review. They are listed and their characteristics are summarized in the supplemental material in Table 1.

Level of expertise

On average, expertise research applying eye tracking methodology included 13 subjects (*SD* = 8; minimum = 1, maximum = 64) with a mean age of 25 years (*SD* = 6 years, minimum = 12, maximum = 49). For all studies integrated in this review we first assessed the definition of the expertise of participants/the expert group (in their comparison of expert and novices). According to Swann et al. (2015) experts can be defined based on their performance/participation in national and international competition, on their experience at a certain level of competition, regarding their professionalism, on the amount/frequency of training, on their involvement in talent development programs, on their expertise in comparison to other regional athletes or other athletes at university level, and on specific measures, as for example a black belt in judo. Of the total of 86 publications in the current review, 31 involved athletes that previously participated in/won national or international competitions (e.g., national leagues). Thirty-one more expert groups were described based on their training program, experience, participation in talent development programs, and professionalism, 16 were regarded as experts because of a comparison with regional competitions or at university level, and 7 because of sport specific measures. One publication lacked sufficient information on the expert group’s composition.

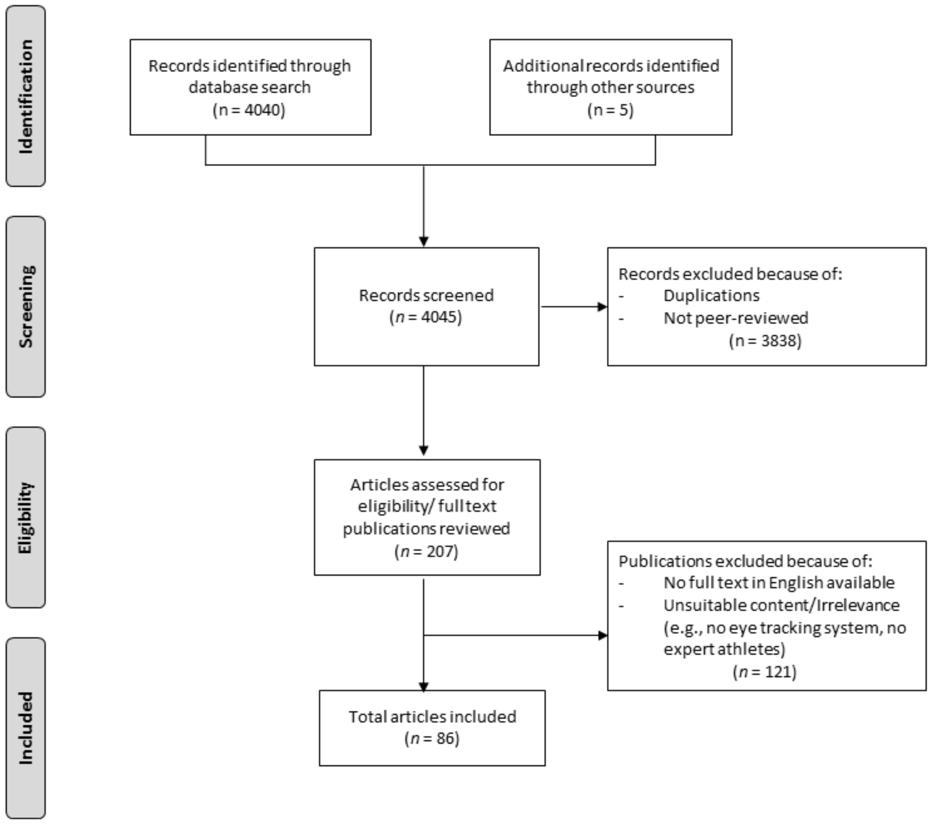

Figure 1. Flow diagram of the literature selection process for the current review article (according to Moher et al., 2009). English language publications between December 1987 and October 2016 were included in the current review.

While almost all studies involved experts that can be regarded as *true* expert performers, it also stands out that many studies use different definitions of expert athletes. Furthermore, it remains questionable if good regional or student athletes can always be considered as *true* expert performers. In total, it should be emphasized that due to the partly imprecise and unclear information about the participants’ expertise level it is not always easy to formulate generalizing statements based on the study results, especially if considering that definitions of expertise differ greatly between the reviewed studies. When trying to draw conclusions based on several publications particular attention must therefore be paid to the reported information about the level of expertise in the respective studies in order to classify the results accordingly and to give athletes and coaches appropriate recommendations.

In total, nearly two third of all included eye tracking studies (*n*=50) focused on differences between gaze behavior of less-skilled and expert athletes. One advantage of such studies is surely that the differentiation between experts and non-experts reveals how much less experienced and younger athletes can theoretically improve when modifying their gaze behavior or at least how much both groups differ in the way they direct their gaze. However, one disadvantage of such studies is that expert athletes benefit less from these designs than less skilled athletes. That is, information about the novices' gaze behavior does not help expert athletes as much as information about experts' gaze behavior can help novices. In order to improve their own gaze behavior (or analyzing if there is something to improve) it seems to be more helpful to compare it with eye movements of other expert athletes.

Research carried out over the past few years has revealed that expert athletes differ from novices regarding their (anticipatory) gaze behavior in various sport situations (e.g., Abernethy, 1990; Savelsbergh, Williams, van der Kamp, & Ward, 2002). A more efficient seeking and optimized gaze strategy support their better anticipation capacity (Hodges, Starkes, & MacMahon, 2006; Mann et al., 2007; Williams & Abernethy, 2012). Comparing the gaze behavior of expert athletes and novices is in so far meaningful, as it seems to be the most straight forward way to identify differences between experts' and non-experts' behavior, especially if definitions of expertise (and also groups that are missing expertise) differ across studies. That is, when different publications use various definitions of experts and non-experts it is hard to contrast findings appropriately. This is certainly not a problem when a single study contrasts two groups.

To sum up, the level of expertise in the reviewed studies does not seem to be a problem for identifying expert athletes' gaze behavior. The level of expertise seems reasonably high (but also considering that this was a selection criterion and that a number of studies was not included in the review because expert performers were less skilled than anticipated) and the majority of all studies compared expert athletes' and non-experts' gaze behavior directly to allow conclusions on differences between these two groups. The biggest concern with the level of expertise at this point is that different definitions of expert groups make comparisons between studies sometimes difficult. In order to provide accurate information and to make recommendations for expert athletes and their coaches, two important actions are required: First, it is necessary to thoroughly check the reported characteristics of expert athletes who took part in research studies and second to consider in how far findings can be of importance to someone's own behavior and performance improvement.

Designs of research studies

For a long time, only static environments, i.e. standardized and controlled study designs in the lab (most often in front of a computer screen), were appropriate for visual perception analyses due to different applied problems with some conventional eye tracking systems (e.g., a low robustness for dynamic movements). This means that in the past there were good reasons for planning gaze movement studies in the laboratory in front of a (computer) screen (there are still good reasons but we try to focus on studies that want to draw conclusions on expert athletes' behavior in their natural environment and therefore should care about external validity). Due to technical restrictions, it was to some extent difficult to conduct *more representative* studies in case researchers' main concern was to provide applicable knowledge. However, through developments of modern eye tracking systems in recent years the application of mobile eye tracking systems is possible in quite naturalistic environments (e.g., on the playing field) nowadays. This makes it much easier to set up studies in a way that allows drawing conclusions for actual behavior of (expert) athletes in their natural performance environment. Obviously, there are also a few problems with this study design, for example that measurements often cannot be controlled sufficiently and carried out in a standardized manner (i.e., there is less experimental control). That is probably why researchers also make use of the possibility to analyze gaze behavior of expert athletes in a simplified, standardized, yet relatively representative environment in the lab to transfer the results to the field.

Eye tracking studies can be considered on a continuum from computer-based designs that do not allow any body or head movements up to recordings of gaze behavior in the natural environment of performers. As a whole, over half of all eye tracking studies (69%) being published over the past 30 years were carried out in the lab, whereby a distinction must be made between different settings/study designs. Figure 2 gives an overview of the designs that have been implemented in the 86 publications. Lab studies in which participants are sitting in front of a screen (31%) can be subdivided depending on whether body and head movements are allowed (5%) or not (26%). In these studies, participants usually have to respond to visual information by pressing buttons on a keyboard.

Furthermore, studies are distinguished that are conducted in a laboratory, but at the same time demand a movement of the participants as a reaction to the presented stimulus which is presented on a monitor or a screen (15%). In these studies, gaze behavior is often analyzed in situations in which an athlete has to react to the behavior of opponents shown in a video. However, regarding these publications it is rather questionable up to which extent results are representative for the actual behavior of athletes during competitive situations (see Brunswik, 1955; Dicks, 2010). Of the remaining lab studies integrated in this review, 23% were carried out in a simplified and standardized but representative environment in the lab. Here, participants also were tested in laboratories but carried out natural movements/had to respond as they would have done in natural performance environments (e.g., kicking a ball).

As also shown in Figure 2, it can be distinguished between lab studies without an exact realistic setting (1%) and studies with a realistic setting (22%; e.g., cricket players hit a ball over an indoor practice net on a synthetic carpet surface; cf. Croft, Button, & Dicks, 2010). In these settings, conditions resemble the real environment, but they are still standardized because of the implementation in a laboratory. Contrary to this, the implementation of a field study takes place outside the lab under (almost) natural conditions of the environment. Here, gaze behavior is not examined isolated from the motoric reaction but while athletes are moving in their natural environment. This helps to gain knowledge about the coupling of perception and action (Gibson, 1979). But despite the high value of gaze behavior analyses outside the lab for different applied areas, for example high-performance sports (e.g., Dicks, Button, & Davids, 2010; see also vision-in action-approach, Gibson, 1979), only one third of all eye tracking studies in high-performance sport (31%) were conducted in a (more) natural environment in the field, as for example on a soccer or volleyball field. Moreover, as presented in Figure 2, these studies can be distinguished insofar as they are conducted outside of the lab with restrictions (18%), i.e. with specific guidelines/restrictions of the examiner or because of technically limited capabilities (e.g., judo fighters were tested while performing a first grip either in two predetermined attacks or in two defense conditions; cf. Piras, Pierantozzi, & Squatrito, 2014), or indeed during realistic competition or training situations (13%; e.g., tennis players were requested to hit the most effective return possible to a serve on a tennis court; cf. Singer et al., 1998). The lack of publications in this area, especially of field studies without any restrictions, may be due to the fact that the majority of researchers prioritize experimental control and internal validity over external validity and the usefulness of findings for expert athletes and coaches. However, the fact that analyzing mobile eye tracking data in a dynamic and ever changing environment takes quite a lot of time might play a role as well.

Internal and external validity

Internal validity refers to the state in which the effects observed in a study are due to the manipulation of the independent variable and not to other factors. This means, it refers to the degree up to which the cause and effect relationship is warranted in the experiment. This is simultaneously ascertained by the extent to which the experiment avoids systematic errors. The less confusion in an experiment, the higher is its internal validity.

Data quality including the aspects of tracking loss or sensitivity to an athlete's movements (e.g., Niehorster, Cornelissen, Holmqvist, Hooge, & Hessels, 2018) and the end-to-end latency (e.g., Reingold, 2014) largely depends on the chosen eye tracking system. While the average accuracy (validity) normally ranges from around 0.4° to around 2° (Holmqvist et al., 2015), the precision (reliability) varies between 0.005° root-mean squared (RMS) and 0.5° RMW. If objects are positioned close to each other, fixations can be assigned to wrong areas of interests, and possibly causing false positive for a neighboring object. By changing the size of areas of interest or the distance between these areas it is possible to improve the fit of a model (Orquin, Ashby, & Clarke, 2016). Depending on the type of sport, not only the sizes and the distances vary between the relevant gaze targets, but the precision of the gaze tracking also depends on the objects' movement (static areas of interest e.g. in darts vs. dynamic areas of interest e.g. in open game situations in badminton).

External validity identifies the correctness of the research findings by examining its applicability from one setting to another. In their review article, Schulte-Mecklenbeck, Fiedler, Renkewitz, and Orquin (2017) described that it is common to find eye tracking studies with only one or two critical trials (referred to laboratory settings) although a limited number of trials leads to lower statistical power. In their review article, Orquin and Mueller Loose (2013) warn against the fact that whenever studies rely on natural stimuli—such as in real sport situations—images may be (slightly) different (e.g., brightness differences) and could affect the athletes' eye movements. In general, the inclusion of more heterogeneous stimuli increases the robustness of the conclusions (e.g., Cooper, Hedges, & Valentine, 2009), however, this necessity is not easy to realize, especially in playing situations in team sports with changing requirements and challenges, except in standard situations. Eye movements are highly susceptible to slight changes in the environment and it is often difficult to generalize eye movements beyond the laboratory environment (Orquin & Holmqvist, 2018).

One specific type of external validity that is of importance in eye tracking research is the ecological validity, meaning the extent up to which the conclusions of a research study can be generalized to the settings and situations in which the examined phenomenon/process would naturally occur. If a study has high ecological validity, the findings can be generalized to real-life settings. In general, external validity can be improved by setting experiments in a more natural setting (by avoiding artificiality). Eye tracking studies may provide a powerful balance between ecological validity and experimental control. These studies being conducted away from the laboratory offer greater ecological validity through context specific field based research and dynamic movements in sport. Although eye tracking studies in the lab normally provide extremely accurate and reliable data (especially when using desk-mounted systems), the findings are mostly limited and restricted to laboratory settings. Head-mounted systems allow participants to move so that data can be collected in more ecologically valid environments. However, only a few studies have made use of head-mounted systems in live sports (e.g., Croft et al., 2010; Land & McLeod, 2000: cricket; Rodrigues, Vickers, & Williams, 2002: table tennis; Singer et al., 1998: tennis). The low number of studies is certainly due to the fact that one of the greatest challenges for eye tracking research in high-performance sport is the maintenance of ecological validity.

Taken together and prioritizing external over internal validity, study design seems to be a bigger problem for identifying expert athletes' gaze behavior (and how it differs from non-experts' gaze behavior). Only 53% of all studies (field studies and studies inside a lab with a simplified/standardized but still representative performance environment taken together) seem to allow drawing conclusions on how expert athletes behave in their natural environment and how their behavior differs from non-experts. For studies comparing expert athletes' and novices' gaze behavior directly two thirds (68%) of the implemented eye tracking studies were carried out computer-based in the lab (in front of screen) or in the framework of non-realistic settings during the last 30 years. This is critical because expertise effects appear more clearly under natural experimental conditions compared to video-simulated laboratory settings (Dicks et al., 2010; Mann et al., 2007). Furthermore, the meta-analyses by Mann et al. (2007) and Gegenfurtner et al. (2011) revealed that an increase in the external validity of the experimental conditions results in more pronounced expertise effects in both gaze behavior and decision making. However, comparing our results of all sport-related eye tracking studies including expert athletes with the findings of Kredel and colleagues, the relative frequency of field studies is unexpectedly lower in high-performance studies (31%) compared to eye tracking studies dealing with sport in general (49%; cf. Kredel et al., 2017). Furthermore, the relative frequency of laboratory studies with artificial responses—i.e. designs in which either a motor response (e.g., a button press or a joystick movement) or a verbal response was required—was also higher in eye tracking studies dealing with sport in general (39%, cf. Kredel et al., 2017) than in our review focusing on a special investigation group in particular (31%). In the remaining publications (Kredel et al., 2017: 61%, current review: 69%) participants were asked to respond naturally to the presented situations either in a laboratory setting (e.g., mimicking a whole-body dynamic response) or in a field research setting (e.g., performing a defensive movement in response to an opponent's attack)[1].

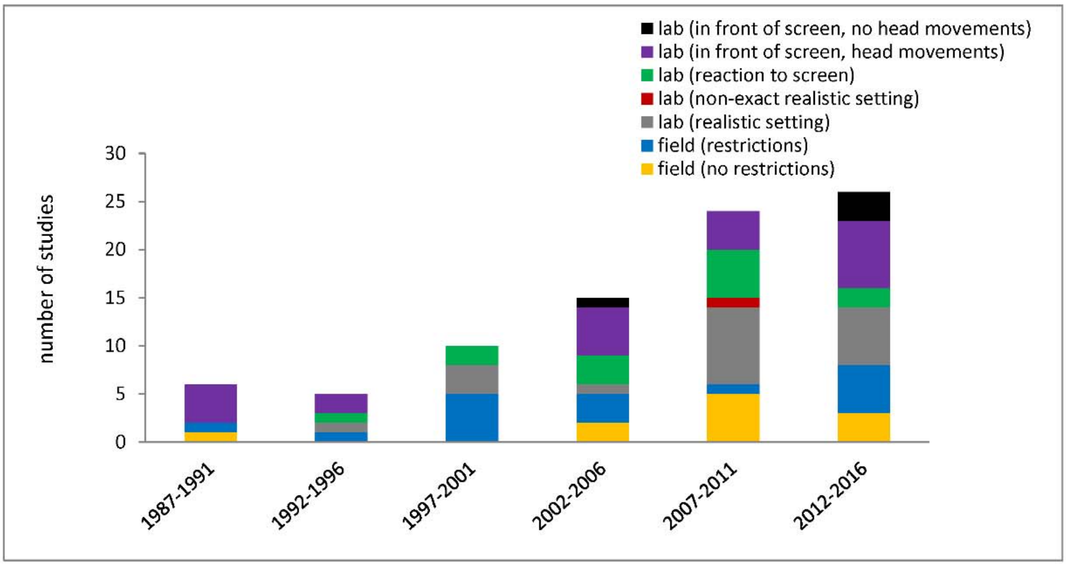

Figure 2. Number of eye tracking studies including expert athletes subdivided into publication year (from 1987 to 2016) as a function of study design. Studies are categorized as either lab or field studies.

Use of different eye tracking systems

Although there are technical differences, and thus also disparities in the application of both possible eye tracking systems—static and mobile ones—there is not an advantage of one

[1] However, please note that while Kredel et al. (2017) focused on eye tracking studies in sport being published over the last 40 years, this review provides an overview of the use of eye tracking systems in high-performance sports over the last 30 years. This means that figures are not entirely comparable due to the different time periods.

system per se. In their recently published review article, Kredel and colleagues (2017) precisely described differences between various eye tracking systems and technologies by taking up, among others, essential device properties and measurement requirements (e.g., sample rate). Therefore, a separate and detailed description of the technical demands of eye tracking studies in dependence of different research designs did not appear necessary in this review. While computer-based lab studies in which participants' head movements are mostly eliminated could certainly benefit from the use of static eye tracking systems, in the field, mobile eye tracking technologies are indispensable. However, a mobile eye tracker must not necessarily be used in the field, but can also be applied in the lab if head or body movements are allowed/requested. Anyway, the external validity of eye tracking studies (involving expert athletes) depends, among others, on the set-up, respectively environment, of the study. That is, next to analyzing the application of mobile and static eye tracking systems, it is decisive for the generalization of the results on expert athletes' gaze behavior to test how many studies have been carried out in the lab and how many have been conducted outside the lab (with or without any restrictions) so far. In total, 97% of all publications integrated in this review made use of head-mounted eye tracking devices. (Please note that some of the systems which are referred to as head-mounted here, especially in early eye tracking studies, were head-mounted systems that only allow for a small range of movements and would not allow recordings of gaze behavior in field studies). In comparison, Kredel et al. (2017) reported that in 85% of all eye tracking studies in sport (not only these including expert athletes) a mobile eye tracker was used and in 15% a stationary device.

The fact that not only field studies but also most lab studies make use of mobile eye tracking systems indicates that the use of a static or mobile system depends not necessarily on the study environment (lab vs. field), but rather on the research question and the study design, for instance, whether head or body movements are requested or not. Consequently, a meaningful analysis regarding the use of different eye tracking systems requires more than only the distinction between static and mobile tools. Figure 3 provides an overview of more subtle subdivisions that have been used in the 86 publications integrated in this review article. Probably due to the research design, all studies outside of the lab made use of mobile, head-mounted, eye tracking systems. However, the analysis of the use of eye tracking systems depending on the study design reveals that also in computer-based studies (in which participants are sitting directly in front of a monitor) head-mounted systems were primarily used rather than computer-mounted systems. In those lab studies in which a movement of the participant as a reaction to the stimulus presented on the monitor or screen embedded in an (almost) realistic setting or another sport-specific movement was demanded, a head-mounted eye tracking system was always used (see Figure 4).

To summarize, it can be noted that, regardless of the study design (lab vs. field), the application of a head-mounted eye tracking system predominates in high-performance sport research. By using a mobile system movements of the head are fully doable (since measurements take place directly at the eye) and participants are less restricted in any of their movements. Moreover, the use of (newer) mobile systems enables testing athletes in a quite natural (performance) environment when their responses are not restricted to pressing buttons on a keyboard or other substitute responses. This means that participants can respond to their natural environment or other forms of presenting visual information (e.g., projections of pictures on a big screen) as they would in their natural environment. Clearly, that makes drawing conclusions for athletes' performance and behavior within a realistic lab setting or especially outside the lab more valid (Mann et al., 2007). Considering this and probably also due to the permanent technical development and the simplified operation of eye tracking devices during the past 30 years, Figure 2 presents an increase of these research designs in high-performance sports, in particular over the last ten years as compared to previous years. This implies that the number of studies with a more representative environment, i.e. lab studies with a realistic setting, has increased over the past years not least because new technologies made it possible. While the validity of findings in the area of gaze movement analysis in sports based on laboratory experiments is continuously criticized as it remains vague in how far results can be applied to practice and have a meaning for expert athletes (cf. Araújo, Davids, & Passos, 2007), lab studies with a simplified and standardized but representative environment seem to represent a compromise between computer-based lab studies and field studies in a natural environment. In this type of study, significantly more control is given than in field studies and the relevance for athletes compared to the possible significance of pure computer-based tasks is clearly higher. To sum up, though researchers often make use of head-mounted eye tracking devices they less often make use of these systems in natural environments outside a lab. This is probably due to the fact that research carried out in a lab allows for higher experimental control while data analysis is less time intensive.

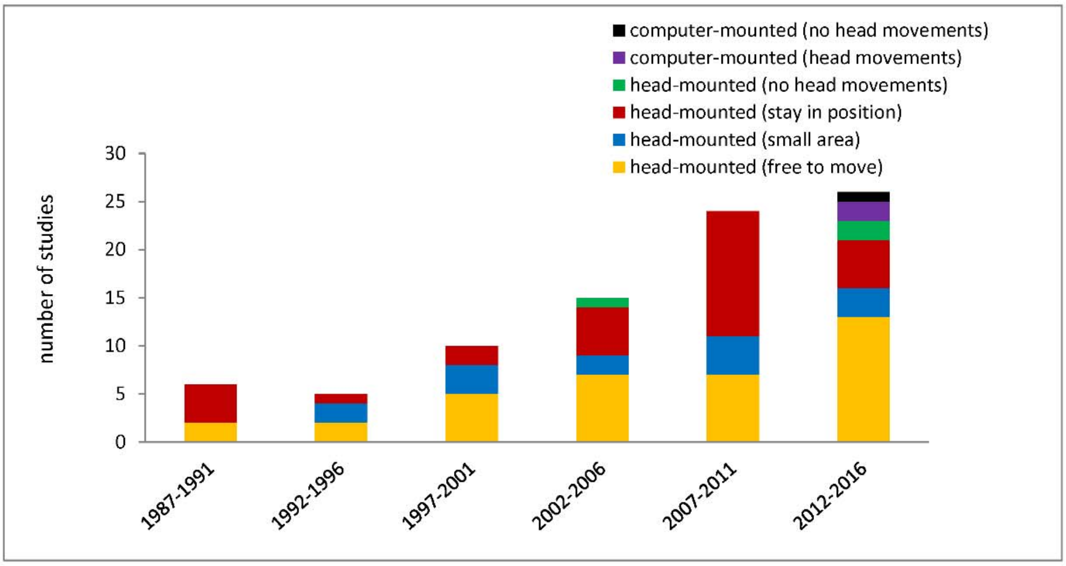

Figure 3. Number of eye tracking studies including expert athletes subdivided into publication year (from 1987 to 2016) as a function of eye tracking system. Eye tracking systems are categorized as either computer-mounted or head-mounted tools.

Different types of sports and sport situations

Besides the set-up of experiments, different requirements and tasks in the selected types of sports can affect the informative value of these scientific approaches as well. Altogether, the 86 publications integrated in this review refer to 25 different sports. Figure 5 gives an overview on the frequency of the eye tracking studies with expert athletes of selected sports. While sports can generally be divided into different categories according to specific aspects (e.g., number of participants, organization form, location), it seems to make sense to divide types of sport into those with rather static (please note that settings we refer to as static often also have dynamic elements, e.g. moving targets) versus those with rather dynamic or complex settings. Requirements of rather static conditions (experimentally well controllable) can roughly be integrated to the category of closed/stable systems (e.g., dart throw, golf putt), whereas dynamic settings (experimentally not well controllable) have far more variable requirements to the athlete and his/her information processing and thus are assigned to the category of open systems (e.g., handball, soccer). Taking up on this approach, we differentiate between ball games (sport games) and non-ball games (non-sport games). Especially the dynamic setting in team sports, such as soccer, handball, or (ice) hockey, and especially the speed of the game ball in these types of sport make investigations of gaze behavior more complex (Farrell, 1975; Gentile, Higgins, Miller, & Rosen, 1975; Poulton, 1957). Despite the impeded test conditions and confounding factors, the majority of the included eye tracking publications in high-performance sports dealt with ball games (81%, non-ball games: 19%), primarily in soccer (19%), basketball (11%), tennis (8%), and golf (8%). Thirty-three percent of these studies were carried out computer-based in the lab, 36% with a reaction to the screen or other sport specific movements in the lab, 23% outside the lab with some behavior restrictions of the participants, and 8% in a natural environment in the field. The low number of studies on gaze behavior of expert athletes in non-ball games makes clear that we are currently not able to tell much about experts' gaze strategies in many sports. Especially in light of the so-called replication crisis and the usually low number of participants involved in relevant studies (cf. Schweizer & Furley, 2016), it seems necessary to wait for much more research on gaze behavior in non-team sports until drawing conclusions on how athletes should direct their gaze in order to improve performance.

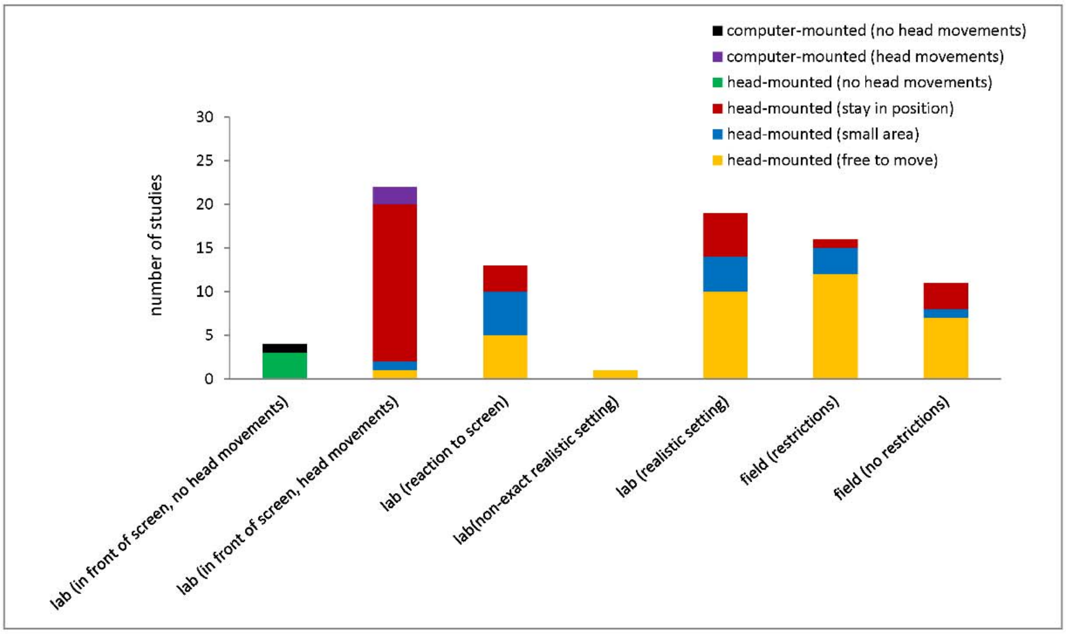

Figure 4. Number of eye tracking studies including expert athletes subdivided into different study designs (lab vs. field) as a function of eye tracking system (computer-mounted vs. head-mounted).

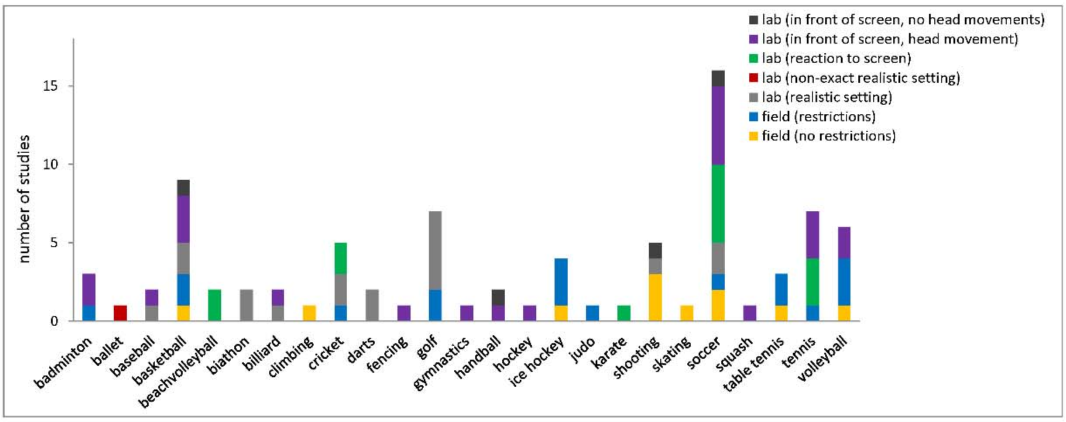

Figure 5. Number of eye tracking studies including expert athletes subdivided into 25 different sports as a function of study design (lab vs. field).

Differentiation between game and dead ball situations

Since gaze movement analyses in dynamic settings, such as in team sports, are more complex and more difficult to carry out in comparison to the non-ball games, the superior number of eye tracking studies in team sports is at first surprising. However, a detailed analysis of the tasks which were performed within these studies showed that the gaze behavior of athletes was restricted to dead ball situations (i.e., when the ball is not in motion; closed situations), as for example penalty shoot-outs in soccer, free throws in basketball, or penalty shooting in ice hockey. The analysis of gaze behavior during open situations on the field has mostly been disregarded in eye tracking research in high-performance sports so far (potentially because body contact between different performers is associated with higher risks of damaging eye tracking devices and because data of dead ball situations is easier to analyze and compare across different trials/conditions/experiments). Only in two of the publications integrated in this review, eye movements were actually measured out of dead ball situations. Martell and Vickers (2004) as well as Vickers et al. (2017) analyzed gaze behavior of ice hockey players during game situations outside the lab. However, it is clear that an analysis of athletes' gaze behavior solely in dead ball situations does not suffice if the goal is to improve sport performance by optimizing visual systems. Especially racket sports, such as tennis, or team sports, such as soccer or handball, have high demands on the athletes' visual system because of their dynamics and complexity. Athletes are partially dealing with object speed (e.g., of a ball) which is too high to follow with the eyes. However, different studies have shown that expert athletes' gaze does not follow the movement of the ball all the time, as one might expect, but rather eye movements anticipate the ball's trajectory (for a meta-analysis, see Mann, et al., 2007). This implies that very fast anticipating gaze jumps are one reason for outstanding reactions and actions of expert athletes. Learning how to correctly apply the temporal and local use of gaze fixation, thus seems to be highly relevant in dynamic sports to reach top performance, as anticipation is a substantial part of an expert athlete's abilities, and reactions to occurrences and movements alone do not suffice. As gaze behavior in high-performance sports has so far only been analyzed in standardized situations, many aspects of expert athletes' gaze behavior in actual open game situations are still unknown. A core question that should be taken up in future research is in how far physical strain changes the expert athletes' gaze behavior. Previous research has already shown that different levels of physical activity cause changes in perceptual and cognitive skills (Chmura, Nazar, & Kaciuba-Uscilko, 1994). However, this issue has not yet been explored in eye tracking studies with expert athletes. It could be assumed that gaze behavior changes as a function of load intensity and fitness level.

Application of eye tracking systems as sport-specific training method in expert athletes

Previous eye tracking studies have dealt with various research questions. One important question, especially for athletes and their coaches, is whether and how eye tracking systems are suitable as sport-specific training methods. In general, eye tracking technologies are applied for diagnostic purposes in professional sport fields, for example, to analyze visual search strategies, trajectory estimations, or hand-eye coordination (Grushko, Leonov, & Veraksa, 2015). However, due to methodological efforts and restricted movements in part, the application of eye tracking tools in regular training programs is somewhat rare, especially in the natural performance environment of athletes. This is the more a pity because changes of gaze behavior over time associated with performance improvements would allow closer examination of the relationship between gaze behavior and performance than investigations of expert athletes' gaze behavior alone. Merely a few studies like the one of Wood and Wilson (2011; quiet eye training for football penalty kicks) or of Adolphe, Vickers, and Laplante

(1997; expert volleyball athletes participated in a six week visual training program that involved video feedback of gaze behavior and on-court training to improve ball detection, tracking, and forearm passing skills) exemplarily reveal a possible type of training. In most research, eye movements are usually only measured once; after this, training recommendations are often already derived from these data. How exactly gaze behavior can be changed through various training exercises and how it changes naturally in the long run remains unconsidered at least in complex team and racket sports. This is especially due to the fact that also the latest eye tracking systems at least to a lesser extent restrict athletes in their movement and thus influence their regular training.

However, despite a lack of studies, respectively a lack of knowledge about ideal gaze patterns (without considering that there might be no ideal gaze patterns at all) in expert athletes, various instructions regarding which gaze behavior is the most promising and how this specific gaze behavior can be applied in competitive situations can be found in different (mostly individual) sports. In modern concepts, optimal visuo-motor strategy is getting more and more a part of advanced training programs (e.g., Piras et al., 2014). Furthermore, there are rare study approaches which show that gaze behavior and thus respective anticipation efforts can be improved by having athletes learn another gaze behavior (e.g., Savelsbergh, van Gastel, & van Kampen, 2010). The extensively studied quiet eye phenomenon (cf. Vickers, 2007), which counts as an expertise and performance criterion in sports and has already led to promising sport-practical implications, constitutes one potential training approach. Although studies concentrating on quiet eye usually assess only one fixation location, we included these quiet eye studies focusing on high-performance sports (in contrast to the review article of Kredel et al., 2017 that focused on studies examining natural, dynamic visual behavior, meaning that gaze was assigned to at least two different areas of interest). In general, expert athletes exhibit longer quiet eye periods as compared with their less skilled counterparts. Amongst others, Harle and Vickers (2001) revealed that performance in basketball free throwing can be improved within a season when applying quiet eye training. The quiet eye during goal tasks (i.e., fixating the relevant goal prior to initializing the goal oriented movement) seems crucial for success (Vickers, 2007; Vickers, Rodrigues, & Edworthy, 2000; Vickers & Williams, 2007). The question how such a categorization can be integrated to more complex tasks or open systems remains unanswered though. This means, for example, the presence of opponent players can have a direct influence on players’ eye movement patterns because gaze behavior serves the acquisition of information, but can also be read easily by an outside observer (e.g., in order to predict intended actions). For the analysis of gaze behavior in sports without any direct face-off with opponents, such as in darts or bobsledding, there is no need to consider that athletes try to hide their intended action. However, in many sports it seems simply not sufficient to tell athletes to focus in the direction of a target extensively. Furthermore, problems arise in many situations (e.g., penalty kick) when having to define a point in time in which the quiet eye would be useful. During dynamic movement patterns it is often not possible to determine when one movement (e.g., run-up) ends and when a new goal-oriented movement (e.g., kick) begins. This is also the case for anticipation attempts during the regular game course.

Summing up, only few studies in the field have explicitly investigated the trainability of gaze behavior in expert athletes so far. While publications have predominantly focused on dead ball situations including targeting tasks with constant environmental conditions and little tactical requirements, deductions of direct training implications for complex sport situations are almost impossible.

Recommendations for scientists, athletes, and coaches/trainers

The choice of a suitable eye tracking system and the "optimal study/training design" depends on the data an athlete or coach aims to collect and on the technical requirements for eye tracking systems in different sports. If a researcher or a coach is interested in collecting data while participants/athletes are required to identify stimuli on a computer screen, a static (desk-mounted) eye tracking system seems to be the most suitable. By applying static eye tracking systems in lab settings, it is possible to always deploy the same stimulus material leading to a simplified and less error-prone data evaluation. The controlling of influencing factors makes it easier to allow precise statements about any changes in single gaze parameters. However, as athletes and coaches are normally more interested in optimizing their behavior on the playing field in real competitive situations, a more ecologically valid and representative design is to be recommended requiring the use of a mobile (head-mounted) eye tracking system. Although these mobile eye tracking systems normally have a slower sample frequency than static ones, in general, their sampling frequency is mostly sufficient to analyze the athletes' or coaches' concerns in the specific sport situation. Depending on the selected sports (distinction between sports involving direct contact or no contact with the opponent), however, it is meaningful to apply mobile eye tracking systems being more or less robust and insensitive.

Moreover, the choice of the suitable eye tracking systems also depends on the size of the objects/areas of interest that should be studied with eye tracking. In some cases, the obvious question is whether an athlete does observe an opponent's pathway while moving across the playing field, the demands on the eye tracking system's accuracy and precision are less important as in cases in which the objective is to observe different body parts of an opponent player. In the latter case, it should also be recognized that if objects/to be observed details are close to each other, it may lead to focusing on wrong areas of interest. As different sports require different precisions when recognizing gaze parameters (e.g., fixation spot), requirements for the needed eye tracking system change. This does not only depend on the size of target objects and the distance between the areas of interest, but it should also be differentiated between static and dynamic targets. In fast sports (e.g., badminton, table tennis) a higher sample frequency of the eye tracking system is helpful for analyzing the single gaze parameters, in contrast, systems with slower frequencies can be used, for example, in shooting tasks.

A further particular challenge for the use of eye tracking systems is the awareness about the handling and meaningful data evaluation. The highly data-driven approach has become popular in eye tracking research, because nowadays data processing tools enable a broad scan of numerous comparisons (e.g., Orquin & Holmqvist, 2018). It thus appears useful, especially for a prompt improvement of expert athletes' gaze behavior in particular situations, to avoid analyzing multiple metrics and to predetermine which aspects are of interest and which information can help to optimize the gaze behavior in future.

Despite the number of requirements and aspects that should be carefully considered in the course of the exploration of expert athletes' gaze behavior in training situations and competitions, scientists, trainers, and athletes get the chance to thoroughly understand the perceptual-cognitive processing involved in athletic performance.

Concerns, limitations, and supporting measures for eye tracking research in high-performance sports

Although the technique has improved increasingly and thus the possible applications of eye tracking systems are becoming more and more divers, gaze behavior analyses underlie various limitations nevertheless. Some issues with eye tracking studies involving expert athletes have already been mentioned (e.g., superior number in computer-based lab studies; no transmission of findings with less-skilled athletes to high-performance sports). Due to different limitations associated with eye tracking systems (for further details, see Kredel et al., 2017)—independent of the way an eye tracking experiment is set-up—the informative value of results and their applicability for expert athletes should be considered with caution in part. Eye tracking systems, for example, can only record foveal vision but information gathered from the periphery cannot be recorded. More precisely, this means that the measured gaze direction does not always have to be in-line with a person's focus of attention (Laurent, Ward, Williams, & Ripoll, 2006). However, while various studies have shown that expert athletes in sports receive most of their information through peripheral vision (e.g., Ryu, Kim, Abernethy, & Mann, 2013), it is important to note that gaze direction and spatial allocation of attention are highly correlated (Nakashima & Kumada, 2017). This does not automatically imply that location of gaze is the same as orientation of attention, but that both concepts are closely related. While it is possible to change attention and not to change gaze behavior, it is impossible to change gaze behavior without changing attention (Shepherd, Findlay, & Hockey, 1986). This emphasizes that a change in gaze behavior precedes a change in attention and underlines the relevance to analyze gaze behavior in (high-performance) sports.

Furthermore, expert athletes apparently seem to be very good at quickly creating an overall picture of all sensory influences and making decisions based on that. In order to optimally use eye tracking regarding perceptual-cognitive-strategies, a combination with the so-called *reports of thinking* might be conceivable, where participants express their thoughts loudly during accomplishing a task (or immediately after; e.g., Afonso, Garganta, McRobert, Williams, & Mesquita, 2012). Getting an insight in their thought processes would be easier by using this method (a possibility which is probably less applicable in real sport situations). In general, gaze behavior depends on cognitive processes. As fixations are used to calculate time spent looking at a particular location, they provide information about the engagement of attention and the time needed to process the stimulus/object at that location. With this information studies have gained insights into what people remember (e.g., Hannula et al., 2010), how they solve problems (e.g., Grant & Spivey, 2003), and how they perform mental computations (e.g., Green, Lemaire, & Dufau, 2007). Eye movements (saccades) being used to shift between fixations can be distinguished into controlled or automatic (stimulus-driven) shifts in attention (e.g., Luna, Velanova, & Geier, 2008). Both the accuracy and the latency of saccades can offer information about an athletes' cognitive control capacity (e.g., Munoz & Everling, 2004).

During the observation of different sport situations it has to be taken into account that the structure of the given task has a high influence on the visual behavior because not only the *when* and *where* but also the *what* and *how* (chronological order) are crucial as well. Therefore, generalized conclusions based on examinations should be handled with care because small deviations within the task could already require different gaze strategies. An athlete, for example, decides on a specific strategic procedure (explicit or implicit) prior to an action. A study on gaze behavior of penalty shooters revealed that players in the preparation phase decide on a specific strategic procedure, which then forms their gaze pattern in turn (Noël & van der Kamp, 2012). That is, the spatial and temporal gaze behavior of every athlete is decisive for the success of his/her task (Land, 2009; Mann et al., 2007; Vickers, 2007). However, researchers analyzing this behavior need to be aware that every athlete can deal with the situation/task differently. Especially in high-performance sports, it is to be expected that expert athletes pursue their own gaze strategies as there are no general recommendations or any templates available.

Another important aspect, which needs to be considered in research on visual gaze strategies, especially in (high-class) team sports, is team communication. Different team members possibly apply different gaze strategies and swap ideas on the perceived information verbally (Araújo & Davids, 2016; Fasold, Noël, Wolf, & Hüttermann, 2018). For example, the setter in beach volleyball shouts information on the positioning of the opponent players to his partner, while she/he fixes the ball trajectory before her/his attacking stroke (Künzell, Schweikart, Köhn, & Schläppi-Lienhard, 2014). This implies that in analyzing the players‘ gaze behavior, especially in team sports, it has to be considered that different useful information cannot only be perceived visually by the athlete herself/himself, but for example also by communicating with team members. That is, to make statements for the gaze behavior of expert athletes in game situations in team sports, it would be useful to equip several players of a team with eye trackers to accurately examine their gaze behavior and decisions.

Summary and conclusion

Most recently, Kredel et al. (2017) gave an overview about eye-tracking technology and the dynamics of natural gaze behavior in sports in general. The current review focused on expert athletes in particular. While some findings of Kredel and colleagues (2017) could be replicated in high-performance sports, there are some new insights providing important information for expert athletes and their coaches/trainers. In total, the analysis of eye tracking research being published over the last 30 years in competitive sports has shown that the majority of studies is still carried out in the lab (69%)—and this mostly computer-based (in 31% of these studies, expert athletes were sitting directly in front of a screen, in 15% they were reacting to a stimulus on a screen, and 23% of these studies used a (non-exact) realistic setting). Considering that the transfer of these results to more natural (performance) environments has been criticized by researchers (e.g., Araújo et al., 2007; Dicks, 2010; Dicks et al., 2010), the current state of research does not allow for genuine and valid statements regarding the gaze behavior of expert athletes in many sports, respectively sport situations. While the majority of eye tracking studies on high-performance sports has been carried out in the area of ball games, it is important to consider that solely the gaze behavior in dead ball situations, i.e. when the ball is not in motion, has been analyzed. This means that possible recommendations for the training of expert athletes can, if at all possible, only be transferred to these situations. Furthermore, results revealed that the majority of published eye tracking research in the context of high-performance sports has compared gaze behavior between expert athletes and novices. However, different findings have demonstrated that these two groups differ in their gaze behavior (e.g., Williams et al., 1999) and that results from inexperienced sportswomen/sportsmen can hardly be used to inform on high-performance sports. Differences in gaze behavior between expert athletes and novices were thoroughly discussed in the meta-analytic review by Mann et al. (2007). The findings suggest that expert athletes are better in picking up perceptual cues, as revealed by measures of response accuracy and response time, compared with novices. This means that expert athletes usually predict the direction and force of an opponent’s stroke based on kinematic information that maintain subtle clues better than novices (e.g., offensive attack patterns in volleyball; cf. Wright, Pleasants, & Gomez-Meza, 1990). In addition, expert athletes use flight cues earlier compared to novices to predict the ball’s end location. Furthermore, Mann and colleagues (2007) revealed systematic differences in visual search behaviors with expert athletes using fewer fixations of longer duration including prolonged quiet eye periods than novices. These findings lead to the conclusion that expert athletes are able to extract more task-relevant information from each fixation than novices usually do and that one should try to optimize gaze behavior by involving fewer fixations of longer duration (Williams, Davids, Burwitz, & Williams, 1993).

Despite the various listed points of criticism, concerns, and limitations referred to the previous utilization of eye tracking systems in high-performance sports, eye tracking seems to be a promising method to examine expert athletes' gaze behavior, given that it is employed meaningfully and correctly. In particular, working with mobile eye tracking systems (head-mounted systems) is a promising way of analyzing cognitive aspects of expertise in sports and its impact on performance in competitive environments. However, when conducting studies regarding gaze behavior in high-performance sports, three fundamental aspects, as initially demonstrated, need to be considered: (a) Gaze behavior of expert athletes should be analyzed. (b) Gaze behavior should be examined in the natural environment or at least in a standardized but representative environment. (c) In order to make statements in a sport, especially in ball sports, expert athletes' gaze behavior should be analyzed in diverse situations and not only in dead ball situations. In general, the limitations of eye tracking as a research method have to be always kept in mind. Taking these points into consideration potentially allows development of specific training methods and improvement of expert athletes' performance in competition.

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