Journal of Sport and Exercise Psychology, (Ahead of Print)
https://doi.org/10.1123/jsep.2023-0267

First Published Online: May 29, 2024

Human Kinetics
ORIGINAL RESEARCH

Visual Performance and Sports: A Scoping Review

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Vision is central to success in nearly all sports, and there is an emerging body of research investigating the links between visual abilities and athletic performance. This preregistered scoping review seeks to clarify the topics of study, methodologies used, populations under investigation, researchers, and disciplines driving this field. Systematic searches of English-language articles were conducted in PubMed and Web of Science, with additional literature identified through bibliographic searches. Six hundred sixty-seven articles published between 1976 and 2023 were identified with 547 empirical studies, 58 review articles, 20 commentaries, and 4 meta-analyses, among others. Among the empirical papers, 411 reported on visual assessments and 98 on vision training interventions. The most represented sports included baseball, soccer, basketball, and cricket, with over 150 articles reporting on professional, elite, or Olympic athletes. This scoping review describes the breadth of this emerging field, identifies its strengths and weaknesses, and provides recommendations for future improvement.

Keywords: vision, expertise, athletes, assessments, training

Sports performance places considerable demands on the visual system. Nearly all sports require athletes to see and react with great precision and accuracy, and the past decades have seen a growing interest in understanding how visual function contributes to athletic performance. The field of "Sports Vision" has been fueled by scientific and technological developments that have improved the ability to measure and understand the relationship between visual function and sports performance (Appelbaum & Erickson, 2018; Erickson, 2007). These developments, coupled with an explosion in data capture, and sports analytics (Morgulev et al., 2018) have created a rich platform for data-driven integration of visual assessments with sports statistics (Passfield & Hopker, 2017). As more studies within the domain of sports vision have identified the aspects of vision that underlie sports performance, athletes and teams have begun looking for ways to gain a competitive edge by using this information for scouting and player development. As such, organizations now regularly emphasize assessments of their players' visual health and associated functional vision (Apstein, 2015).

Just as all sports entail different movements, different visual skills are also essential to success. For example, it has been shown that athletes who play interceptive sports have better visual sensitivity, while athletes who play strategic sports have better visual spatial memory (Burris et al., 2020). Similarly, athletes who play sports that require a greater focus on the vertical plane of the field (e.g., volleyball) demonstrate a greater vertical breadth of attention than athletes whose sports require more horizontal attention (e.g., ice hockey and soccer), and vice versa (Hüttermann et al., 2014). It has been shown that visual abilities differ among Olympic athletes according to the sport they play (Laby et al., 2011), and that when matched for other factors, professional baseball hitters have better visual acuity and depth perception than pitchers (Klemish et al., 2018). Together these findings point to specialization of visual skills that go along with the sporting experiences of athletes.

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A central tenet in sports vision is that better visual abilities underlie better athletic performance. Past research has shown higher level athletes make more efficient eye movements, are better at detecting visual cues, and have better attentional abilities compared with nonathletes or less accomplished athletes (meta-analytic results described in Mann et al., 2007; Voss et al., 2010). In recent years, there have also been a growing number of studies demonstrating that baseline assessments, collected before the season, correlate with game performance statistics from competitive matches. These studies have shown that better oculomotor (Liu, Edmunds, et al., 2020), perceptual (Laby et al., 2019; Reichow et al., 2011), and visual-motor (Burris et al., 2018; Laby et al., 2018) skills correlate with better performance statistics, providing evidence that better vision underlies better athletic performance and pointing to specific measures that can be used to scout players for desired sports skills.

Collectively, studies showing associations between better visual abilities and better sport performance provide support for the idea that improving visual skills through targeted visual training or nutritional supplements may improve neuro-ocular processing speeds (Bovier et al., 2014; Stringham et al., 2010) and lead to better athletic performance. While there is considerable heterogeneity in training programs, they have generally aimed to improve athletic performance through three main approaches: improved detection of sensory input, better integration of sensory information with higher order processing, and enhanced visually guided motor performance (Erickson, 2021). This taxonomy of available approaches has continued to expand with increased adoption of digital, naturalistic, and mobile technologies (Appelbaum & Erickson, 2018). With dozens of published articles describing vision-based training programs to improve sports performance, there is growing evidence that this practice may hold benefits (reviewed in Laby & Appelbaum, 2021). While these studies are generally based upon small samples and often do not include matched-control training groups, some studies have begun to include greater rigor with preregistered hypotheses, placebo control, and randomization into training groups, while showing significant gains for active training over placebo training (Liu, Ferris, et al., 2020). Such rigor is rare in this field, and therefore, careful

evaluation of the strengths and weaknesses of past research studies can inform the best paths to advance this discipline.

Given the breadth of research that now addresses the role of vision in sports performance, a scoping review will provide value to clarify the topics of research, describe the methods used, reveal the sports and athletes under investigation, and identify the researchers, journals, and disciplines that are driving this new field. By doing so, this review will also highlight gaps in knowledge that can be filled in future studies and make recommendations for the most profitable future avenues of research. This scoping review therefore attempts to consolidate the existing peer-reviewed literature that relates visual abilities to sports performance, vision training to improve athlete performance, and the classification of visual impairment in sports, to fill these gaps.

Methods

This scoping review was conducted following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) Scoping Reviews guidelines and was preregistered on Open Science (https://osf.io/z2a47). The search strategy employed was intended to be broad in order to capture the research literature addressing the intersection of vision and sports performance. Peer-reviewed articles that report on vision, attention, ophthalmic, optometric, neural, and psychological research and theory, applied to vision in athletes, or relating to sports performance, were considered for inclusion. Identification of included articles consisted of both systematic search of the PubMed and Web of Science databases, as well as backward and forward bibliometric searches.

The PubMed and Web of Science databases were searched between July 26 and August 9, 2022. Subsequent bibliometric and Google Scholar searches were conducted between September 2022 and September 2023. PubMed was searched using the terms, "("athlet*"[MeSH Terms] OR "sport*"[MeSH Terms]) AND "vision"[Text Word]" as well as "("sport*"[MeSH Terms] OR "athlet*"[MeSH Terms]) AND "concussion"[Text Word] AND "vision"[Text Word]." The Web of Science database was searched using the search terms "ALL = ("sport*" AND "vision" OR "Athlet*" AND "vision") and English (Languages) and Article (Document Types) and Ophthalmology or Neurosciences or Sport Sciences (Web of Science Categories) and Ophthalmology or Neurosciences or Psychology or Sport Sciences (Web of Science Categories)" as well as "ALL = ("sport*" AND "vision" AND "concussion" OR "Athlet*" AND "vision" AND "concussion")" with the same languages, document types, and categories.

As illustrated in Figure 1, the search identified 4,388 articles, with 1,964 found on PubMed, 2,232 on Web of Science, and 192 identified through bibliometric search. Duplicates and non-English works were removed, resulting in 3,709 articles that were further screened for inclusion. Articles were rated independently by authors L. Lochhead and J. Feng on a 3-point scale; likely inclusion, possible inclusion, and unlikely inclusion, with 91% agreement by both raters across categories. Articles rated as likely by both raters were included for further evaluation, while those rated unlikely by both were excluded. Articles rated as possible inclusions were arbitrated, and any discrepancies between raters were discussed among all authors.

Books, book chapters, and academic theses were not included in the corpus to focus on primary-source, peer-reviewed literature. While there are not strict boundary conditions on what entails a sport, this scoping review tended to exclude activities that are generally not performed in competitive contexts. For example, in most cases, articles addressing mountaineering, dance, and scuba diving were excluded. eSports were not included. Studies addressing military or law enforcement performance were not included

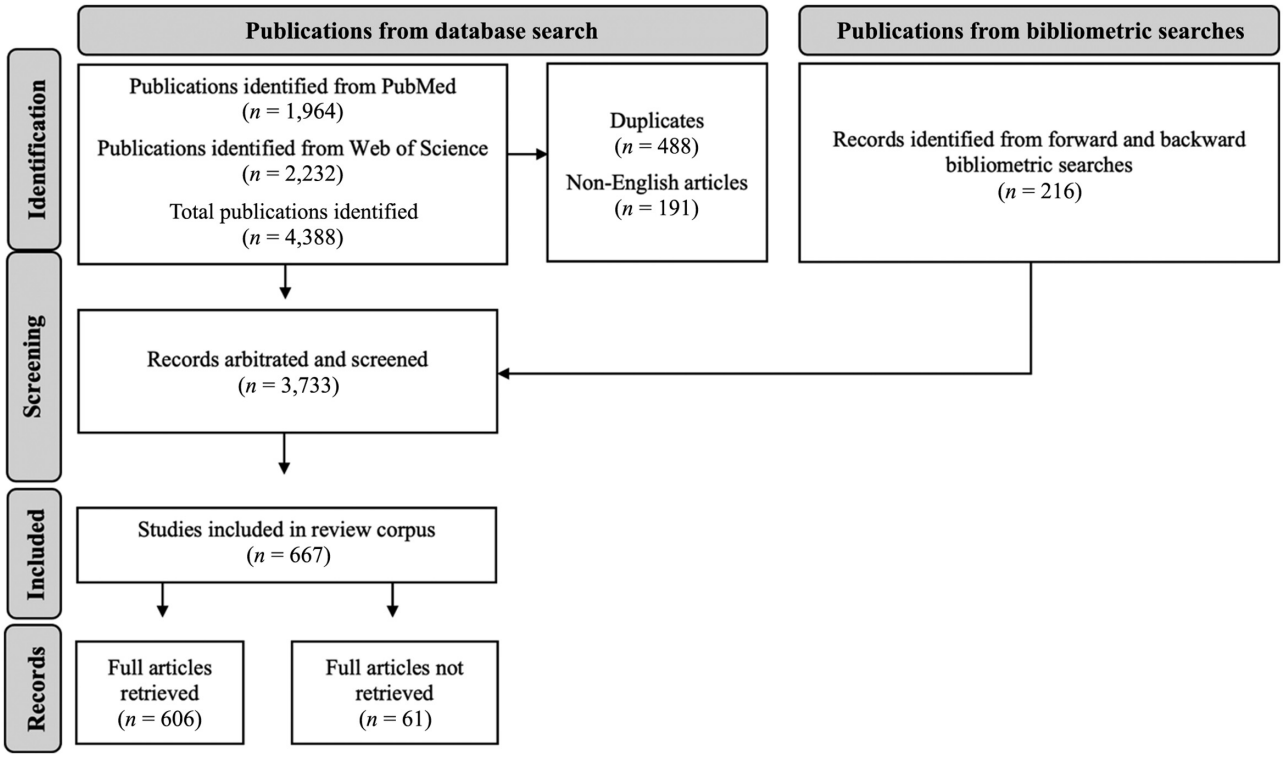


Figure 1 — PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow chart.

unless they also had a specific sport cohort. In addition, during the process of review, it was decided that studies related to concussion, eye injury, or other areas of clinical focus would not be included to concentrate this scoping review on studies addressing sports performance and not epidemiology or pathology. In cases where the full article could not be accessed through digital means (<10%), articles were included if sufficient information about the study could be obtained through the available title, abstract, and bibliometric information. Other inaccessible articles were not included.

All articles included in the final corpus were coded for their title, abstract, author, journal, publication year, type of study, and whether the article was empirical or descriptive in nature. Works were also coded for the sport under consideration, the level of experience of the athletes tested, whether the participants were para-athletes, and whether the participants were visually impaired.

Results

The Full Corpus

Six hundred sixty-seven total works, published between 1976 and 2023, were identified for inclusion (see Supplementary Materials [available online] for full corpus). As illustrated in Figure 2A, this literature grew from <10 articles per year till the 1990s, to over 20 articles per year for most years since the mid-2000s. In particular, 2011 and 2021 stand out as years with relatively more publications, due in part to special issues that focused on sports vision in the journals *Eye and Contact Lens* and *Optometry and Vision Science* in those years, respectively.

Articles in the corpus came from 200 different journals. These journals spanned fields including sports science, optometry, psychology, sports medicine, exercise science, and motor control, among others. Table 1 lists the top 14 journals that were each represented 10 or more times in the corpus along with the 2022 Scopus journal and field metrics. As of 2022, all journals were actively publishing, except for *Optometry: The Journal of the American Optometric Association*, which was discontinued in 2012. CiteScores, calculated by dividing the number of citations received between 2019 and 2022 by the number of articles published during that time, range from 2.7 to 9.8 indicating that this is a relatively impactful literature. Furthermore, 10 of the 13 journals ranked in the top third of their field of study (cite scores about 67%) according to the CiteScore Percentile with several different specialities of medicine represented.

Among the 667 articles included in the corpus, there was a wide range of topics studied. As would be expected, topics addressing vision, perception, attention, and related psychological and physiological constructs were covered regularly, as were those pertaining to athletics and athletes. Highly covered topics also included learning and expertise, and the scientific methods of discovery used in this research. Figure 2B shows a word cloud of the top 130 occurring words in the titles of all articles, with the size of the word reflecting its frequency of occurrence.

Within the corpus, roughly 800 unique authors were represented. Table 2 shows the most frequently appearing authors in the corpus, the count of their authored works, and the primary countries from which they were published. As illustrated in this table, there is broad representation of different countries, underscoring the international scope of researchers who publish on topics related to sports vision.

As indicated in Table 3, the corpus included 547 empirical studies and 120 descriptive articles. The empirical studies were comprised of 411 articles that conducted assessments in which measurements of visual, visual-cognitive, or visual-motor abilities were the central aims of the study. Typically, these studies focused on comparing assessments with sports performance statistics, analyzing cross-sectional differences between groups, or evaluating the test/retest reliability of these measurements. Ninety-eight articles reported on training studies in which a vision-based intervention was implemented longitudinally to evaluate changes in visual abilities and/or changes in sports performance. Additional empirical studies included 14 survey studies, 11 retrospective analyses of athlete data (frequently chart reviews), seven modeling papers, four meta-analyses, and two bibliometric analyses. Among the descriptive articles, there were 58 review papers, 20 commentaries, 18 editorials, and an assortment of protocols, Delphi articles, case reports, and other article types.

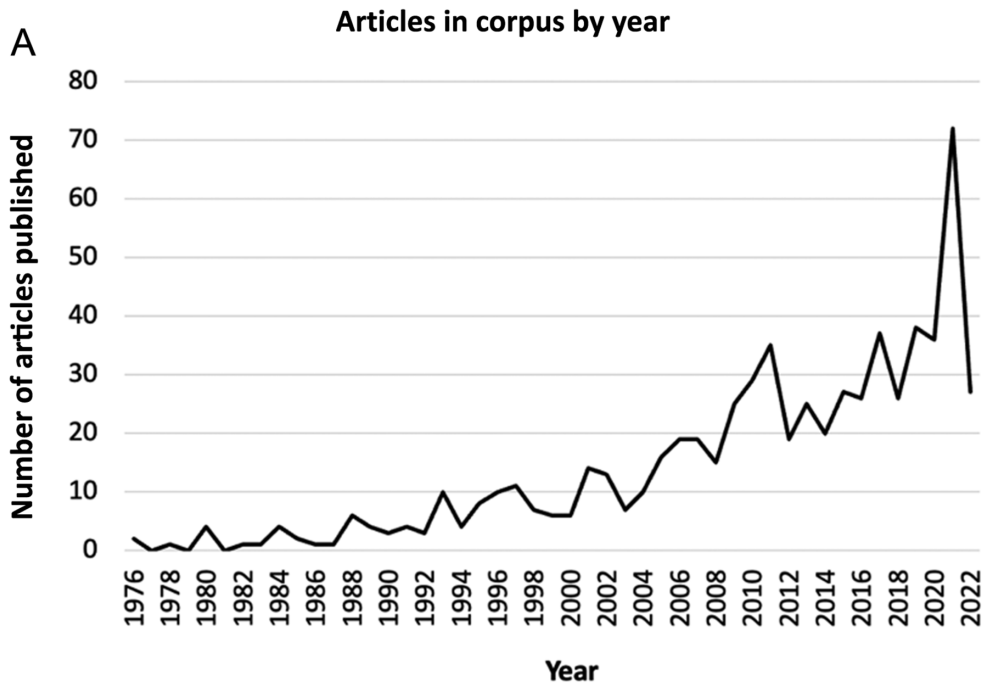
The Empirical Corpus

The empirical corpus consists of 547 articles that make up the bulk of the identified literature, indicating that the primary aim of most papers was to report quantitative findings from an experiment or observation. Forty-five different individual sports were represented, as were several articles addressing vision in referees, and even one addressing visual search strategies in swimming coaches (Moreno et al., 2006). As illustrated in Figure 3A, among the empirical studies, the most represented individual sports included baseball (74), soccer (55), basketball (41), cricket (30), golf (22), gymnastics (21), and tennis (21). Sixty-six articles reported on findings from athletes across multiple sports with many coming from Olympic combines, occurring at athletic training facilities, or undertaken in college athletic departments. There were 26 articles reporting on studies that were not specific to a sport. For example, several studies tested sports vision instruments in novice populations using drills not specific to a sport (e.g., throwing and catching balls).

As shown in Figure 3B, the empirical studies reported on athletes from all levels of competitive accomplishment. Notably, 150 articles reported on professional, elite, or Olympic athletes, indicating that research in this field has access to some of the most accomplished athletes in the world and pointing to an area of study in which expertise is routinely studied.

Assessment Studies

The most common type of article in the corpus was empirical studies that conducted vision-based assessments of athletes or sports vision technology. These studies sought to quantitatively measure aspects of vision including static and dynamic visual acuity, refractive error, ocular dominance, contrast sensitivity, and other foundational visual abilities. Other assessment studies aimed to quantify ocular motor skills including fixations, saccades, and pursuits, or visual-motor control skills such as eye–hand and eye–foot coordination. Yet other studies aimed to measure visual cognition including attention, working memory, and visual decision making. Many studies employed comprehensive test batteries that included many of these measures together to create multifaceted profiles in athletes (Wang et al., 2015; Ward & Williams, 2003). Tests of peripheral vision were particularly common, with over 40 papers including some test of the peripheral vision and/or useful-field-of-view. Proprioceptive abilities were also frequently studied in articles that either compared measures of vision with postural control or manipulated vision and tested proprioception.



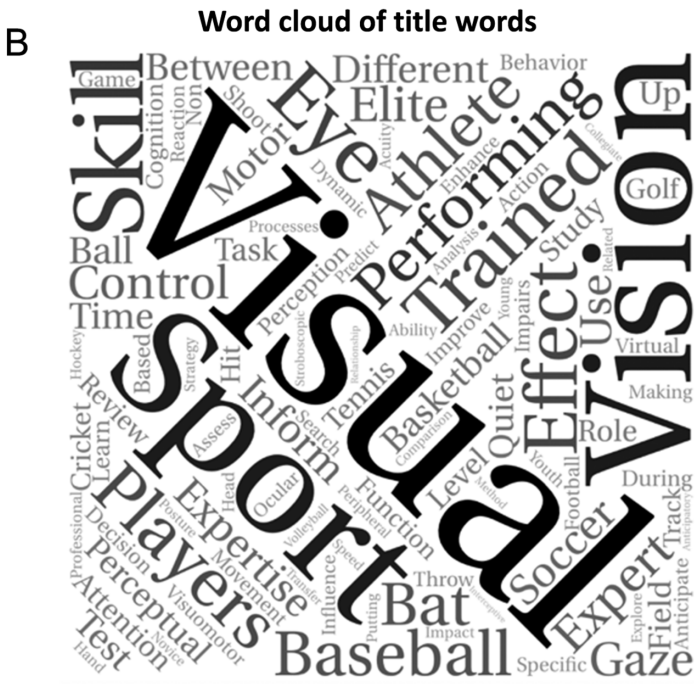


Figure 2 — (A) Graph of the number of publications by year. (B) Word cloud of the top 130 words occurring in the titles of all articles represented in the corpus, size by the frequency of occurrence.

Table 1 Journals With Highest Number of Studies Represented in Training Corpus and Scopus 2022 Journal and Field Metrics

Journal	Number of articles	CiteScore	CiteScore percentile	Field of study
Journal of Sports Sciences	44	6.5	89% (24/226)	PT, sports therapy and rehabilitation
Perceptual and Motor Skills	38	2.8	39% (93/152)	Experimental and cognitive psychology
Optometry and Vision Science	37	2.9	59% (5/11)	Optometry
Optometry: Journal of the American Optometric Association[a]	28			
Human Movement Science	18	4.3	72% (82/298)	Orthopedics and sports medicine
PLoS One	17	6	87% (17/134)	Multidisciplinary
European Journal of Sport Science	15	7	92% (17/226)	PT, sports therapy and rehabilitation
Journal of Sport and Exercise Psychology	14	3.2	69% (253/830)	General medicine
Research Quarterly for Exercise and Sport	14	4.3	75% (55/226)	PT, sports therapy and rehabilitation
Clinical and Experimental Optometry	13	4.5	77% (29/130)	Ophthalmology
Medicine and Science in Sports and Exercise	11	9.8	97% (9/298)	Orthopedics and sports medicine
Journal of Motor Behavior	10	2.7	53% (140/298)	Orthopedics and sports medicine
Eye and Contact Lens	10	3.9	71% (38/130)	Ophthalmology
Psychology of Sport and Exercise	10	7.5	83% (41/241)	Applied psychology

Note. Article counts between 10 and 44 indicate that sports vision is a frequent topic in these journals, while cite scores ranging from 2.7 to 9.8 show that the journals are mostly of medium to high impact, with 10 of the 13 journals ranked in the top third of their field of study. PT = physical therapy.
[a]Journal was discontinued in 2012.

Table 2 The 14 Most Frequently Occurring Authors, Their Number of Authorships, and the Primary Countries From Which They Publish

Author	Number of articles	Primary country
B. Abernethy	41	Australia
D.L. Mann	32	Netherlands
A.M. Williams	26	United States/United Kingdom
J.N. Vickers	21	Canada
D.M. Laby	19	United States
L.G. Appelbaum	19	United States
D.G. Kirschen	17	United States
D. Farrow	15	Australia
R. Gray	14	United States
S.J. Bennett	13	England
A. Mierau	13	Germany/Luxembourg
T. Hulsdunker	13	Germany/Luxembourg
P.M. Allen	12	United Kingdom
G.B. Erickson	10	United States

Table 3 Occurrence of Different Study Types for the Empirical and Descriptive Articles in the Corpus

Empirical studies, total	**547**
Assessment	411
Training	98
Survey	14
Retrospective analysis of athlete data	11
Other—modeling	7
Meta-analysis	4
Other—bibliometric analysis	2
Descriptive articles, total	**120**
Review	58
Commentary	20
Editorial	18
Protocol	7
Delphi	6
Other	6
Case report	5
Total	**667**

The methods of measurement used in the assessment studies were diverse. Eye tracking technology was common with several dozen papers using screen-mounted or head-mounted eye tracking systems to evaluate gaze patterns. Based on such approaches, approximately 30 articles addressed the "Quiet Eye" phenomenon which captures the final fixation at a task-relevant location prior to the initiation of a motor action (Vickers, 2007). Differences in the duration and stability of this fixation have been tied to expertise, and success in movement-based actions, with such effects widely reported in the assessment corpus (Causer et al., 2017; Dalton, 2021). Many other studies tested performance under differing visual conditions such as occlusion paradigms (Giblin et al., 2017), tachistoscopic visual presentations (Reichow et al., 2011), and blurred stimulus presentations (Czyz et al., 2015).

Neural measurements were implemented in a handful of studies with 11 articles utilizing electroencephalography (EEG) in athlete populations (Hulsdunker et al., 2023; Poltavski et al., 2021). Studies using virtual reality gained increasing prevalence with seven recent papers utilizing this technology (Kittel et al., 2019). Importantly, in a growing trend, several articles contrasted measures of visual function with game statistics to more directly link assessments of visual abilities to on-field performance (Laby

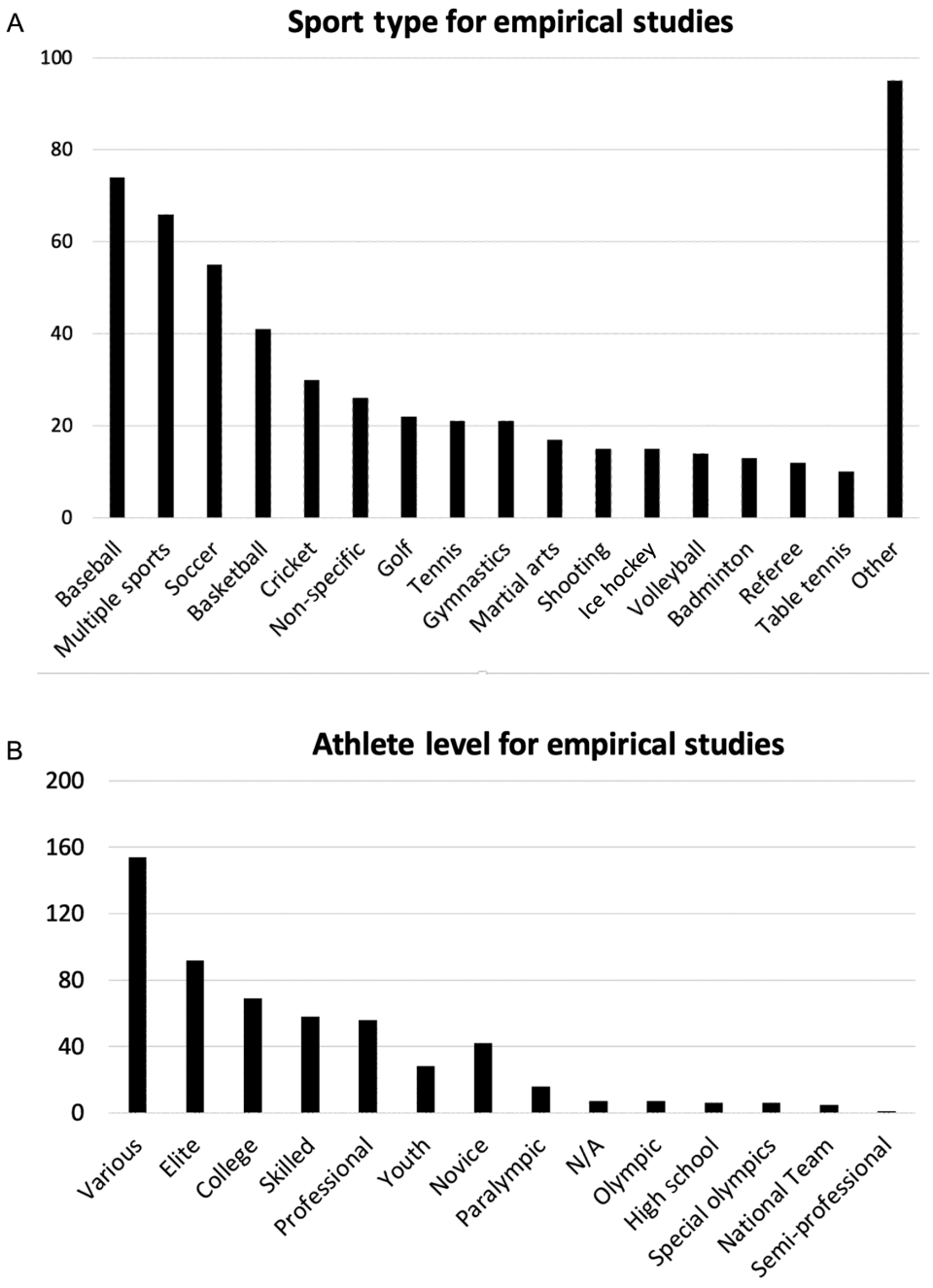


Figure 3 — Prevalence of empirical articles as a function of the (A) sport and (B) level of the athlete studied.

et al., 2019; Liu, Edmunds, et al., 2020). Ten articles reported studies with sports referees to evaluate visual functions that underlie visual decision making important for officiating.

Finally, when considering the content and methods of the studies, it was observed that many articles reported on the test/retest reliability of measures, with many finding a relatively high level of reliability, particularly in tasks that measured abilities like acuity and contrast sensitivity (Erickson et al., 2011; Krasich et al., 2016). Another notable characteristic of this literature was the extremely large variability in the number of individuals assessed in these studies. While many articles reported on very small sample sizes, with as few as three participants, the largest samples included 2,317 (Burris et al., 2020), 1,770 (Wang et al., 2018), 1,406 (D'Ath et al., 2013), and 1,352 (Ho et al., 2023) participants.

Training Studies

The second most common type of article was empirical studies that aimed to test vision-based training interventions to evaluate changes in either foundational visual abilities or changes in sports performance. The first of these articles was published in 1988, with the vast majority (57/73) coming since 2010. The most common types of interventions reported were occlusion training studies which appeared in 19 articles (Fadde, 2006; Farrow & Abernethy, 2002), followed by stroboscopic visual training using liquid-crystal eyewear which was tested in 16 articles (Appelbaum et al., 2011, 2012). Other common interventions included Quiet Eye training, convergence and divergence practice, multiple object tracking, and visual recognition programs. Multiweek training paradigms were

common, but the duration of these programs varied with most lasting 4–8 weeks, and one study training athletes for as long as 6 months.

The effects of training interventions were principally investigated through either near transfer to similar metrics like reaction times, eye movements, and anticipatory timing, or through far transfer to game performance metrics like batting statistics or shooting percentage. Some studies evaluated a combination of both. Several studies aimed to determine how long training effects lasted by testing athletes on the same task, minutes, days, or even months after the training program. Three studies investigated the neural effects of training by measuring changes in athletes' EEG recordings.

Overall, training programs were widely applied over many different sports. While baseball was the most common individual sport with 12 total articles, 28 different sports were represented. Training programs were also implemented across nearly all athlete levels. There was also a wide spectrum of sample sizes, with study populations ranging from as few as three athletes, up to as many as 240 participants (Vickers et al., 2017).

Of the 98 training studies, only 12 involved placebo control conditions to assess efficacy of active training versus performance on tasks with no known benefit. Other methods for comparing the benefits of training included no-contact controls in which some participants continued regular practices but did not receive a matched intervention to compare with the active training. Several studies compared measurements pre- and posttraining, without any reference group for comparison.

Findings from the training studies showed mixed efficacy with the strongest evidence pointing toward training of dynamic visual skills that rely on integration and rapid cognition, as well as the use of naturalistic tools that create less need for generalization and far transfer. While some studies reported positive training gains, others did not. Within individual studies, improvements were seen in anticipation skills, visual memory, attentional abilities, visual recognition speed and accuracy, and decision-making accuracy, all reflecting near transfer of learning (Appelbaum et al., 2012; Ryu et al., 2016; Smith & Mitroff, 2012; Williams et al., 2002). Some studies had conflicting results regarding the trainability of binocular functions, with some reporting improvements in convergence and accommodation, but not divergence (Gilliam et al., 2010; Jenerou et al., 2015; Zwierko et al., 2015). Twenty-one studies evaluated whether improvements in visual training skills transfer into game or practice settings, with some improvements seen in batting average, pitch recognition, runs scored, and gymnastics competitions (Clark et al., 2012; Deveau et al., 2014; Gray, 2017; Potgieter & Ferreira, 2009). Not all studies showed positive transfer, however, with no increases seen in studies of dribbling and shooting accuracy among soccer players who trained with multiple object tracking and Quiet Eye programs (Romeas et al., 2016; Wood & Wilson, 2011), possibly due to the lack of ecological validity of the training tasks for the transfer skills (Vater et al., 2021).

While this literature produced a mixed bag of findings, it is important to note that the vast majority of studies included small sample sizes were implemented in very different study groups with different sports and athlete levels, did not include follow-up assessments to determine the persistence of training effects, did not correct for multiple comparisons when testing multiple statistical tests, and infrequently used matched controls to rule out nonspecific training gains. In fact, only one identified study utilized preregistration along with a placebo control group. This study by Liu, Ferris, et al. (2020) reported modest gains in intermediate transfer including increases in hit distance and launch angle during structured baseball batting practice, but no far transfer to baseball game performance. Future studies will need to adopt more rigorous designs that include randomization of participants, placebo control, follow-up assessments, and preregistration, and larger sample sizes across more diverse study groups to improve the quality of inference that can be gained from sports vision training research. With such remaining gaps in need of exploration, the authors of this paper have also preregistered a systematic review of the 98 training studies, identified here, to include deeper coding and systematic review procedures that allow for a richer understanding of this literature (Open Science Framework project: osf.io/qx3w6; OSF, 2023).

Meta-Analyses

A meta-analysis is a statistical approach that combines the results of multiple published studies to pool effect sizes across separate study populations. There are several potential advantages of meta-analyses, including an improvement in precision and the ability to answer questions not posed in individual studies, and the opportunity to settle controversies arising from conflicting findings. Four meta-analyses were included in the empirical corpus that each addressed aspects of visual expertise in athletes. The first of these, authored by Mann et al. (2007), reported findings from 42 studies with 388 total effect sizes, with the aim of quantifying expertise differences in perceptual-cognitive abilities using sport-specific stimuli and tasks. Dependent measures included response accuracy, response time, the number of visual fixations, the duration of visual fixations, and the duration of the Quiet Eye period. Results indicated that athletic experts were roughly 31% more accurate and 35% faster in their decision making than nonexperts. Systematic differences in visual search behaviors were also observed with experts using fewer fixations of longer duration and prolonged Quiet Eye periods, compared with nonexperts. From these findings, the authors concluded that expert athletes are better able to extract and interpret visual information that is specific to their sport of expertise, thereby facilitating anticipation and better on-field performance.

A second, related meta-analysis was performed by Voss et al. (2010) to evaluate the relationship between athletic expertise and laboratory-based measures of cognition. Here, the authors sought to evaluate domain-general cognitive abilities to determine whether there was evidence that sporting expertise was supported by enhancements in general attentional and cognitive abilities, while also performing moderator analyses to assess whether the type of sport (static, interceptive, or strategic) and sex moderated the sport–cognition relationship. Meta-analytic results from the 20 included studies (198 total effect sizes) demonstrated small- to medium-sized effects favoring athletes who performed better on measures of attention and processing speed than nonathletes, with males and athletes from interceptive sports showing the largest effects. While these findings were not only limited to visual modalities, most included studies utilized visual paradigms, pointing toward enhancements in visual abilities that are not limited to contexts in which athletes are trained, but rather reflect generalized cognitive abilities.

The third meta-analysis authored by Gegenfurtner et al. (2011) evaluated expertise-based differences in eye movements. This meta-analysis included results from 53 data sources with a total of 296 effect sizes, with the authors compiling findings from multiple professional domains, including sports (team, one-on-one, and solo sports), medicine, and transportation and including a moderator for the complexity of the task. Dependent variables

included the number of fixations, fixation duration, saccade length, response accuracy, and response time. Results demonstrated that when compared with novices, experts had shorter overall fixation durations, more and longer fixations on task-relevant areas, and fewer fixations on task-redundant areas. Experts also had longer saccades and shorter times to first fixate relevant information owing to superiority in parafoveal processing and selective attention allocation. These effects were moderated by characteristics of the task and the domain of expertise, with larger moderator effects and faster response times for the sports domains. The authors interpreted these findings as likely resulting from task affordances in sport environments, pointing to specific visual skills that are prioritized in athletics over other professional domains.

The final meta-analysis by Lebeau et al. (2016) evaluated the duration of the Quiet Eye period in sports settings with the goals of assessing both noninterventional and interventional studies. In the first synthesis, they compiled 27 noninterventional studies with 38 effect sizes to find large effect sizes with expert athletes demonstrating longer Quiet Eye periods than novices, and moderate effect sizes wherein longer Quiet Eye periods were present for successful versus unsuccessful outcomes (such as successful dart throws or golf putts). In the second synthesis, from nine interventional articles with nine total effects, they observed very large effect sizes for both Quiet Eye durations and task performance for training groups over control groups, thereby demonstrating both near and far transfer gains from Quiet Eye training.

Together, these four meta-analyses included 153 total empirical studies with 929 effect sizes, to provide aggregate information about visual expertise in athletes. In all cases, athletes exhibited better visual function than nonathletes or lower level athletes. While these effects were largely moderated by the types of sports the athletes played (e.g., interceptive vs. strategic), and the gender of the athlete, there was generally evidence in support of both domain-specific and domain-general expertise, pointing to either the transfer of learned skills, or selection processes that are not constrained to just the visual contexts experienced within their given sport. Given the importance of these questions and the increase in available literature since the publication of the four meta-analyses, contemporary meta-analyses should be performed with improved sample sizes and greater resolution to tease apart important mediating and moderating factors.

The Descriptive Corpus

Sports Vision Review Articles

With nearly half a century of research activity and content filling over 500 empirical articles and four meta-analyses, it is natural that many review articles have also been published on topics related to sports vision. The descriptive corpus includes 58 review articles, published between 1982 and 2023. The first review, by Stine et al. (1982) in the *Journal of the American Optometric Association*, addressed the three foundational tenets of sports vision: (a) athletes possess superior visual abilities that scale with skill level, (b) visual abilities are trainable, and (c) vision training can transfer to improved athletic performance. Based on their review of the literature at that time, they concluded that there was support for the first two tenets, while little evidence existed to support the belief that gains from visual training transferred to sporting performance. This review sets the stage for ensuing studies that have attempted to identify the boundary conditions under which visual advantages exist for athletes, determine the optimal contexts for learning visual skills, and determine whether gains from vision-based training could transfer to improved athletic performance.

As described in dozens of subsequent review articles and underscored by the results of the four meta-analyses described above, the field has gained some measure of success toward the first tenet. For example, evidence for enhanced visual abilities was reviewed by Vickers (2012) who found support for superior Quiet Eye abilities in expert golfers, Vater et al. (2020) concluded that expert athletes exhibit better use of visual pivots and gaze anchors to scan the scene more efficiently than nonathletes, and Muller and Abernethy (2012) reported on findings showing enhanced anticipatory visual abilities in experts from striking sports. In recent years, there has been growing interest in understanding the neural underpinning of such expert advantages, with evidence of specific cortical processes contributing to faster visual-motor reactions (Hulsdunker et al., 2018), and modifications to the neural mechanisms underlying superior attention in athletes (Miller & Clapp, 2011).

Despite an abundance of evidence demonstrating superior foundational visual skills in athletes, reviews addressing vision-based training generally have not provided strong support for the third tenet that training gains transfer to sporting contexts. While some reviews advocate for the practical implementation of training programs (Clark et al., 2020) or optical dietary supplements (Hammond & Fletcher, 2012) that may hold the potential to improve performance or reduce injury, multiple other reviews describe limited and weak evidence for intermediate or far transfer gains from training contexts to improved athletic performance. This scarcity of evidence includes a range of perceptual-cognitive training programs (Zentgraf et al., 2017) and instruments meant to train specific abilities such as multiple object tracking (Vater et al., 2021). Moreover, in a recent review covering 16 studies that tested the effects of vision-based training for improving on-field performance, Laby and Appelbaum (2021) reported that the vast majority of studies failed to find strong support for training gains, and those that did were frequently underpowered, lacked preregistration, and implemented inadequate statistical rigor. One exception to this has been the growing evidence of training gains from Quiet Eye training, as evidenced by the Lebeau meta-analysis described above, and discussed in the review article (Vickers, 2016).

Despite these challenges, a recent framework proposed by Hadlow et al. (2018) may offer a path to improve the transfer of training gains in future studies. Under the "Modified Perceptual Training Framework," three interacting factors may influence the capacity to elicit transfer from training to on-field performance. By mapping the correspondence between the training scenario and the (a) targeted perceptual function, (b) stimulus presentation, and (c) response options, it is possible to identify the training applications that are most likely to lead to transfer of gains. Future work will benefit from the guidance of this representational learning design to improve training outcomes.

Finally, in addition to reviews that addressed visual abilities and training programs, several reviews focused on the technology that can be used for assessment and training. This includes reviews of eye tracking in soccer (McGuckian et al., 2018), virtual reality (Akbas et al., 2019; Miles et al., 2012), and stroboscopic eyewear (Wilkins & Appelbaum, 2019) that are used in sporting contexts.

Other Article Types

In addition to the assessment, intervention, meta-analysis, and review articles discussed above, there were a number of other article types identified in the corpus. These include several retrospective chart reviews demonstrating that while visual performance

of athletes was superior to the general population on measures such as gaze stability (Massingale et al., 2019), eyecare services were largely underutilized in athletic populations (Beckerman & Hitzeman, 2003). Several survey studies were identified that typically asked about attitudes toward visual correction in sports (Zeri et al., 2011) or the use of eyewear for protection (Eime et al., 2002). Commentaries addressed topics ranging from setting up a sports vision clinic (Gee, 2008) and how to drive revenue in such a clinic (Kirschen, 2006), to the pros and cons of elective eye surgery to enhance performance (Schwartz & Zagelbaum, 1999).

Para-Athletes and Visual Impairments

Sports provide opportunities for individuals from diverse backgrounds to come together to foster positive change and have increasingly become an important medium for celebrating and promoting inclusivity. Para-athletics are sports with participation of individuals with disabilities and are typically organized into three categories: physical, intellectual, and visual impairments. While para-athletic events have existed for >100 years, participation, promotion, and visibility of para-athletics have grown tremendously in the last several decades, spawning a growing number of research studies on this topic. A major aim of the research identified in this scoping review has been to understand the interaction of visual impairments and athletics, both for the purpose of developing better classification standards and improving performance.

Within the corpus, 44 articles addressed para-athletes. Of these, 36 reported on studies or topics related to athletes with visual impairments, while the remaining eight reported on topics related to visual skills or eyecare in athletes from other para-athletic categories. Among the studies focused on athletes with visual impairments, 27 of these were empirical studies. Many of these studies sought to test the minimum visual disability criteria for participation in para-sports of different classification levels and addressed a range of sports including skiing (Stalin & Dalton, 2021), judo (Krabben et al., 2022), shooting (Allen et al., 2021), and swimming (Le Toquin et al., 2022).

In support of these empirical studies, five Delphi studies were identified that drew on experts in the field to provide consensus statements that offer clear guidance on how classification of visual impairment should be addressed to remove barriers to properly classifying athletes for events and to minimize the impact of impairment on the outcomes of competition. In 2021, Chun et al. (2021) published a topical review on visual impairments and Paralympic classification that addressed the history, research, and current requirements for achieving a successful evidence-based, sport-specific classification system. Together, this research points toward the important commitment of researcher to address equity and inclusivity in athletics for athletes with visual impairments.

Summary

Vision plays a central role in sports for both fully sighted athletes and competitors who may have visual or other impairments. "Keep your eye on the ball," "you can't hit what you can't see," and other common visual metaphors tile the lexicon of sports; the interaction of vision and sports has long been an area of high interest for society. While sports are largely an empirical enterprise and produce a wealth of meaningful and objective outcome data, the ability to do research with athletes has historically been a major challenge because of limited access and insufficient tools to measure or train the visual skills thought to be essential for sports performance. In the last several years, these limitations have begun to dissolve. With the advent of digital assessments, wearable monitors, and the means to conduct interventions in more naturalistic settings, there has been a rapid shift toward greater access and more meaningful science. The aims of this scoping review are to capture the breadth of this emerging field, identify strengths and weaknesses, and provide a contemporary view of a discipline that is likely to continue to grow for the foreseeable future.

Through a broad search that included both systematic query of PubMed and Web of Science databases, and forward and backward bibliometric searches, a large and encompassing corpus of published articles was identified. To obtain a more complete mapping of the literature, the systematic, formulaic search was augmented with bibliometric searchers to account for the co-citation across literatures and better reveal the connections among the published works. The authors made judgments on some areas of inclusion that could be debated, such as the choice to exclude eSport athletes or to limit some physical activities that are typically not done in competitive contexts. Furthermore, during the vetting of the studies for this review it was concluded that including articles of a medical nature would obscure the goals of focusing on athletic performance. The epidemiology and pathology of ocular and neural injury in sports are areas of central concern (Haring et al., 2016; Register-Mihalik & Kay, 2017), but are beyond the scope of this review and may offer valuable information in a future synthesis. Additionally, despite attempting to identify all possible articles, some relevant works may have been missed because of the wide variety of potential search terms that could apply to articles in this domain. Nonetheless, the body of science captured should represent most of the peer-reviewed literature written on topics related to sports vision and may provide a valuable resource for the field going forward.

As illustrated in Figure 2, there has been considerable growth in this field over time, with a particularly rapid increase over the last 15 years. Despite restricting the search criteria to English language articles, the corpus included authors located all over the world, with most of the published works coming from Europe, North America, and Australia. As noted above, the articles came from nearly 200 different journals that span multiple fields including optometry, psychology, sports science, and sports medicine, among others. The majority of these journals were specialty journals that publish topical works related to their field-of-interest; however, some articles appeared in general interest journals such as *PLoS One*, *Scientific Reports*, and *Nature*. While a number of clinical journals were represented, most of the journals addressed basic science research.

Participants included in empirical studies reflect a wide range of sports with athletes at all levels of accomplishment. While the majority of articles reported on individual sports, 69 articles reported on athletes from multiple sports, typically offering contrasts in visual skills between athletes with different experience. Similarly, 154 of the articles presented empirical data from athletes with multiple levels of accomplishment. Interestingly, while in some cases there was subjectivity in the level of athletic achievement, a large number of articles addressed visual skills in very high-level athletes. This included over 150 studies with elite, professional, Olympic, and national teams, as well as 17 studies with Paralympic athletes, and six with Special Olympians. It is also notable that despite promising findings in nonathletic studies showing that nutritional supplements lead to faster visual

processing speeds (Bovier et al., 2014; Stringham et al., 2010), no studies were found that addressed this question in athletes, suggesting a gap that future research could fill.

In the 2011 special issue on sports vision, Kirschen and Laby (2011) noted,

> The sports vision literature is scattered among numerous specialties and is unknown to most sport vision practitioners. Many of the reports are only anecdotal, and few have any scientific basis. Some of the best research relating to sports vision occurs in other allied disciplines such as psychology or rehabilitative medicine and rarely reaches the eyes of the sports vision practitioner . . . . The discipline is young and is still finding its legs.

Twelve years later, this scoping review offers evidence that the field has evolved with studies appearing in more prominent journals largely known to practitioners. There has also been the creation of a specialty journal, *The Journal of Sports and Performance Vision*, devoted entirely to this discipline. Moreover, as reviewed in the sections above, there has been a transition toward greater rigor, with a number of placebo-controlled interventional studies, research employing larger and better powered samples of participants, and even the occasional occurrence of preregistered trials (Liu, Ferris, et al., 2020). The continued movement toward better experimental research standards will help foster more impactful findings and reduce biases that cloud interpretation of the results. Future research should incorporate more longitudinal measurements to assess the duration of training effects, in more sports and across more levels, while controlling for Type I errors by correcting for multiple comparisons to determine the significance of any changes in performance. While more recent studies have incorporated these precautions and indicate progress toward greater experimental rigor, they remain the exception and not the rule. The field will need to increase these trends to make further progress toward the goals of linking vision and sports performance. We anticipate that this will be the case and look forward what the future will hold.

The goal of this scoping review is to capture the current landscape of the literature making a map of what is currently investigated, not necessarily what is understood. The contours on the map seen here point toward areas of clear topography, like the robust observations of visual expertise in athletes, but also to areas where little is known about the landscape of knowledge. In particular, the central tenet of the transfer of training gains to athletic performance is still in great need of further exploration and discovery. To this end, the corpus of training studies has been preregistered for systematic review with deeper coding and scrutiny.

Acknowledgment

This research was supported by the Wu-Tsai Human Performance Alliance and the U.S. Army Research Office, award W911NF-15-1-0390.

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