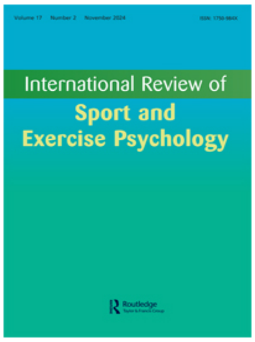

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Training vision in athletes to improve sports performance: a systematic review of the literature

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ABSTRACT

Sports vision training (SVT) refers to a training regimen designed to enhance visual skills that are essential for sports performance under the theory that such enhancement will lead to improved athletic performance. SVT regimens involve a variety of drills aimed at improving visual sensitivity, depth perception, tracking, reaction time, hand-eye coordination, and cognition important for success in sports. A growing body of empirical research has sought to develop and test SVT programs in athletes including training activities implemented in controlled, simulated, and naturalistic settings. This pre-registered, systematic review seeks to identify, describe, and evaluate the empirical literature addressing SVT. 126 articles were identified that tested SVT in athlete populations from many different sports and at all levels of achievement. While most studies reported improvements in generic and sports-specific visual abilities, and many also reported benefits in sports performance, the strongest evidence of performance improvements came from studies utilizing naturalistic training approaches where training activities were conducted with sports-specific stimuli or tasks. Despite this, relatively few studies used rigorous methods such as randomization, placebo-control, and blinding and therefore, while there is promising preliminary evidence in support of SVT, future studies will require improved methods and larger samples to move the field forward.

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Sports vision training; athletes; cognition; enhancement; learning; perception

Introduction

Vision plays a central role in the success of many sports. Whether spiking a volleyball, hitting a softball, or sinking a jump shot, precise and challenging athletic actions rely on vision for guidance and success. This connection between vision and action is frequently seen as a determining factor for sporting excellence (Erickson, 2007) and has opened the door for training approaches that seek to improve vision under the hypothesis that improved vision will lead to enhanced athletic performance. Over the past several decades, a growing body of empirical research has aimed to develop and test

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vision-based athletic training programs, so-called 'sports vision training' (SVT) (Erickson, 2020), leading to a diverse literature that spans many disciplines including optometry, ophthalmology, psychology, neuroscience, and athletic training.

While SVT interventions have been implemented in many different ways, they generally operate on three key assumptions: (1) that specific aspects of vision are crucial for sports performance, (2) these aspects of visual function can be enhanced through training, and (3) improvements in visual abilities can lead to better sports performance on the field of play (Hazel, 1995). Research across multiple sports disciplines provides compelling evidence in support of the first assumption, showing that visual-perceptual and visual-cognitive abilities are heightened in expert athletes relative to lower-achieving athletes or non-athletes. For example, professional and collegiate baseball players demonstrate superior visual acuity (Laby et al., 1996), enhanced contrast sensitivity (Hoffman et al., 1984), and improved visual tracking abilities (Uchida et al., 2013) compared to non-athletes. Moreover, two separate meta-analyses of the sports expertise literature quantifying 62 total studies (Mann et al., 2007; Voss et al., 2010) found that high-achieving athletes exhibit superior perceptual cue detection, more efficient eye movements, and enhanced performance in processing speed and attention tasks compared to less accomplished athletes. Furthermore, these advantages often correspond to the specific demands placed on athletes within their respective sports. For example, athletes engaged in interceptive sports display greater visual sensitivity and reaction speeds compared to athletes from strategic sports (Burris et al., 2018), while athletes from sports requiring attention to the horizontal plane, such as ice hockey, tend to exhibit wider horizontal attention spans compared to athletes in sports necessitating more vertical attention, such as volleyball, and vice versa (Hüttermann et al., 2014). As reviewed by Laby and Appelbaum (2021), several previous studies have attempted to link visual skill assessments to on-field performance, showing evidence that better assessment scores correlate with better in-game performance during competitive sports such as baseball (Burris et al., 2018; Liu et al., 2020; Müller & Fadde, 2016), hockey (Poltavski & Biberdorff, 2014), and basketball (Mangine et al., 2014). Despite this, not all athletes have a normal or supra-normal vision, with many reports of highly successful sighted athletes with visual deficits (Laby et al., 2011; Myint et al., 2016), as well as adaptive sports for low-vision athletes.

Extensive evidence supports the second SVT assumption that visual functions can be enhanced through training, with research showing that learning is enabled by the brain's neuroplastic ability to adapt and reorganize in response to practice and experiences (Castaldi et al., 2020). From developmental learning during childhood and adolescence, to skill-based learning that occurs in adulthood, studies have shown that people can improve perceptual sensitivity (Dosher & Lu, 2017), visual cognition (Anderson, 2013), and visual-motor control (Raymond, 1998). Moreover, growing research has shown that learning gains in certain domains can transfer to new, untrained contexts (Bavelier et al., 2012), opening the door for applications that promote generalized learning.

Together, evidence favoring the first and second assumptions, that better visual skills are associated with better sporting performance and that these abilities can be improved through training, offer a foundation for the third assumption, that improving vision may also lead to better athletic skills and competitive outcomes. SVT programs are, in turn, rooted in the belief that engaging in perceptual, cognitive, or oculomotor exercises can

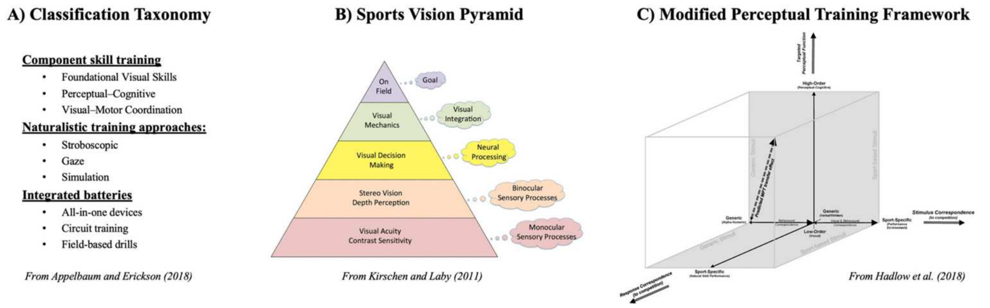

Figure 1. Conceptual frameworks. (A) classification taxonomy that parses training approaches into three classes, each with three subclasses. (B) Sports Vision Pyramid that illustrates the constructive nature of vision from monocular and binocular, to neural processes that can be optimized through training. (C) Modified Perceptual Training Framework illustrating correspondences between the desired goal of sports performance and the training contexts available to manipulate or recreate along three axes: stimulus, response, and perceptual function.

enhance the capacity to react to, and interpret, visual stimuli therefore providing an advantage for athletes in demanding sporting scenarios.

As described by Appelbaum and Erickson (2018) in their review of digitally-based SVT approaches, interventions can be categorized into different classes based on the intended mechanisms targeted by the intervention and the context in which the training manipulation is implemented. Within this classification taxonomy (Figure 1(A)), there are Component Skill Training, Naturalistic Training Approaches, and Integrated Training Batteries. Component skill training consists of three subclasses of training that aim to promote generalized learning, namely the transfer of learning from one context to another. The first subclass includes training of Foundational Visual Skills such as acuity, contrast sensitivity, depth perception, vergence, tracking, and other monocular and binocular processes that lie in the first two levels of the Sports Vision Pyramid proposed by Kirschen and Laby (2011); see Figure 1(B)). The second subclass is comprised of training that targets Perceptual-Cognitive functions emphasized in individual sports, such as attention, anticipation, and multiple object tracking. The third class of interventions focuses on Visual-Motor Coordination with the limbs, such as eye-hand and eye-foot coordination. Collectively, these component skill training approaches share the logic that enhancing foundational skills may remove bottlenecks and improve higher-level abilities that rely on these building blocks.

Naturalistic sports vision training approaches are a class of training approaches that attempt to embed training closely within the sport context by maximizing both stimulus and response correspondence, as illustrated in the *Modified Perceptual Training Framework* (MPTF; Figure 1(C)) of Hadlow and colleagues (2018). These approaches allow participants to engage in actual or simulated sporting activities with added elements that alter or augment the training experience. A first subclass of naturalistic approaches is Stroboscopic Training, which utilizes liquid crystal eyewear that can alternate between transparent and opaque states, thus occluding vision at programmable frequencies, typically used during athletic training activities. A second subclass is Gaze Training, which utilizes eye tracking and video interventions with sports-specific stimuli to train the optimal gaze patterns for success in each context. Finally, the emergence of virtual and augmented reality has opened the door for Simulation Training that is inherently visual and allows practice with actual or simulated sporting activities with fidelity to the real world. Collectively, these naturalistic approaches leverage digital opportunities to embed training with minimal need for transfer thereby potentially increasing the likelihood for performance optimization. A third class of interventions, *Integrated Batteries*, combines multiple individual elements into a wholistic training program, typically done through circuit training or using an all-in-one device.

With a large variety of skills and abilities targeted for training, an abundance of training tools available, and considerable value in successfully improving the performance of athletes, there has been a rapid growth in SVT applications and research. This systematic review seeks to identify and describe studies that have tested vision-based training interventions in athletes to improve performance, categorize them using the taxonomy of Appelbaum and Erickson (2018), and provide an evaluation of the state of this science. In doing so, this review will describe the interventions, the populations under study, positive and negative findings, and highlight gaps in knowledge that can be filled through improvements in future studies.

Methods

This review was pre-registered on the Open Science Framework (https://osf.io/3gvzr). Peer-reviewed articles that reported on empirical studies in which vision training was tested in athletes, with the goal of enhancing sport-relevant skills or in-game performance were considered for inclusion. The selection was limited to peer-reviewed empirical articles that tested non-novice athletes at any level of accomplishment, included pre- and post-training assessments, and addressed measures of performance (rather than injury prevention or recovery). As illustrated in Figure 2, the identification of included articles consisted of a systematic search of the PubMed database, as well as literature and bibliometric searches.

The PubMed database was searched between January 18 and February 30, 2024, using the terms, (‘athlet*’[MeSH Terms] OR ‘sport*’[MeSH Terms]) AND ‘vision’[Text Word] AND ‘training’[Text Word], (‘athlet*’[MeSH Terms] OR ‘sport*’[MeSH Terms]) AND ‘vision’[Text Word] AND ‘intervention’[Text Word], as well as (‘visual perception’[MeSH Major Topic] AND ‘sports’[MeSH Major Topic]) AND ((training) OR (intervention)) AND (fft[Filter]). Duplicates and non-English works were removed. The database search identified 4,756 articles that were rated independently by authors LL and LF on a three-point scale: likely inclusion, possible inclusion, and unlikely inclusion, with 89% inter-rater 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 amongst all authors, yielding an initial screening sample of 691 articles for further review.

During the subsequent screening, books, book chapters, and academic theses were not included in the corpus to focus on primary-source, peer-reviewed, empirical articles investigating performance effects resulting from deliberate visual training interventions. Assessment and observational studies were not included unless they also included an intervention. To focus on vision-based training that targets the hardware (eyes and extraocular muscles) and software (neural processing) of the visual system, several decisions were made about the boundary conditions for inclusion. For example,

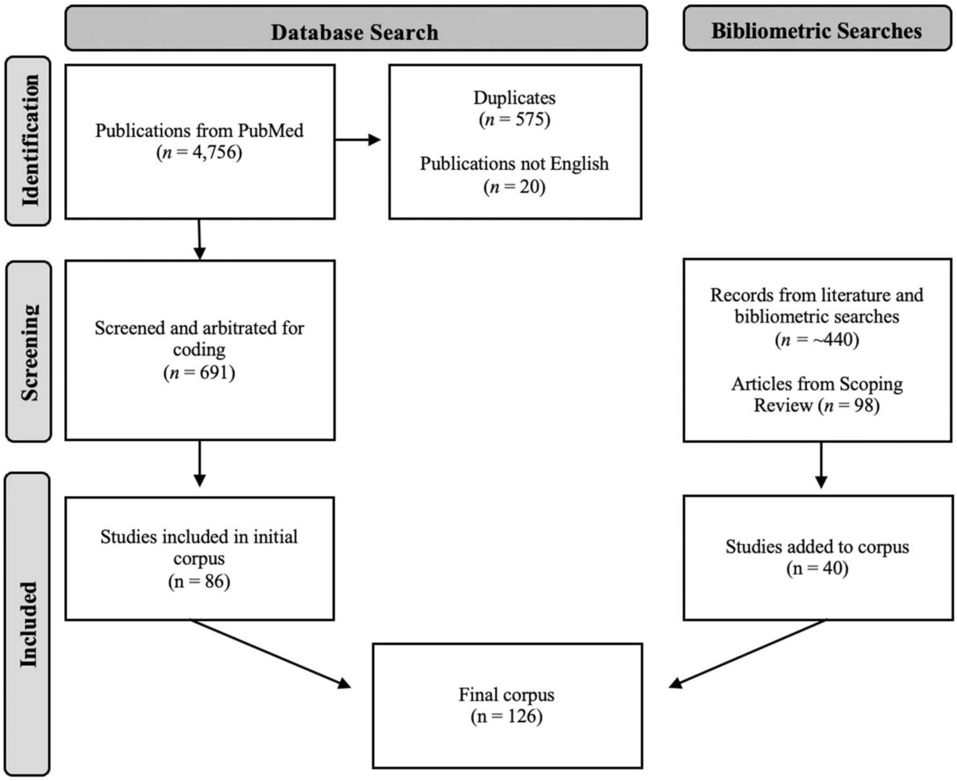

Figure 2. Flow chart of database and bibliometric search results.

studies involving mental imagery or balance (in the absence of visual stimuli) were not included. In addition, while there is a growing use of neurofeedback approaches for training athletes (Mirifar et al., 2017) and many of these studies utilize visual cues for feedback, studies that sought to modulate brain activity (rather than visual function) were not included. Furthermore, in five cases, the full article could not be accessed (three could not be accessed through the authors' library or online, and two were behind paywalls), and these articles were not considered further. Upon evaluation against the screening criteria, 86 articles were selected for inclusion and coded for their title, abstract, author, journal, publication year, classification of visual training intervention, summary of the intervention, total number of participants, number of participants in each group, the duration of training, a summary of the training groups or conditions, a description of the reported findings, a summary of statistical tests used, presence of retention or follow-up test, presence of subject or experimenter blinding, pre-registration, the primary sport under investigation, and competitive level of the athletes trained.

Literature and bibliometric searches were conducted between March 1 and May 15, 2024, to identify articles that may have met inclusion but were not retrieved in the initial database search. This included a review of training articles reported in the recent Lochhead et al scoping review (Lochhead et al., 2024), consultation with published reviews on topics related to sports vision training, notably (Carroll et al., 2021; Lebeau et al., 2016; Wilkins & Appelbaum, 2019; Zhao et al., 2022), and bibliometric searches conducted in Google Scholar. In each case, identified articles were compared against inclusion criteria and, if sufficient and not already in the corpus, were added. Additional bibliometric and database searches were conducted between September 22 and 29, 2024 in response to the manuscript peer-review to verify the inclusion of articles and obtain studies specifically investigating vision interventions in referees and officials. In total, literature and bibliometric searches yielded 40 articles that were added to the corpus leading to a final corpus of 126 articles that were included in this review.

Results

Summary of corpus

A total of 126 articles, published between 1997 and 2024, were identified for inclusion (see **Supplemental Materials** for full corpus). As illustrated in Figure 3(A), this literature grew from less than four articles per year before 2011, to over 10 new articles per year between 2019 and 2021. Articles in the corpus came from 72 different journals. These journals spanned fields including sports science, psychology, optometry, sports medicine, exercise science, and motor control, among others. Table 1 lists the top nine journals that were each represented three or more times in the corpus along with the 2023 Scopus journal and field metrics. Scopus CiteScores, calculated by dividing the number of citations received between 2019 and 2023 by the number of articles published during that time, range from 2.9 to 7.7 indicating that this is a relatively impactful literature. Furthermore, six of the nine journals ranked in the top quarter of their field of study (cite scores above 75%) according to the CiteScore Percentile, with several different specialties represented.

All studies in the corpus implemented vision training interventions, however, there was a wide range of applications with different approaches, sports, athlete groups, and skills targeted in these studies. Figure 3(B) shows a word cloud of the top 150 occurring words in the titles of all articles, with the size of the word reflecting its frequency of occurrence. The corpus was authored by roughly 300 individuals, with representation from numerous countries from across the globe. The authors with the greatest number of articles came from the United States, Australia, Canada, Germany, and England.

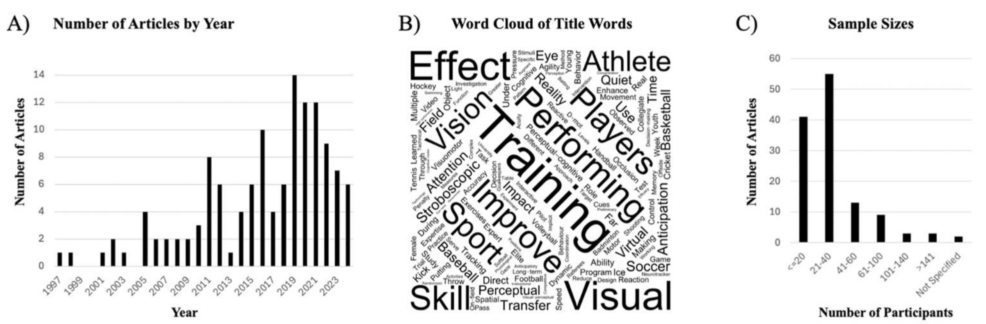

Figure 3. (A) Graph of the number of publications by year. (B) Word cloud of the top 110 terms occurring in the titles of all articles represented in the corpus, sized by the frequency of occurrence. (C) Histogram illustrating the frequency of sample sizes across studies.

Table 1. Nine most common journals appearing in the corpus along with 2023 Scopus journal and field metrics.

Journal	Number Articles	CiteScore	CiteScore Percentile	Field of Study
Journal of Sports Sciences	10	6.3	88% (30/247)	PT, Sports Therapy and Rehabilitation
Psychology of Sport and Exercise	8	6.4	74% (64/249)	Applied Psychology
Frontiers in Psychology	7	5.3	78% (47/216)	General Psychology
Perceptual and Motor Skills	5	2.9	40% (99/165)	Experimental and Cognitive Psychology
Journal of Sport and Exercise Psychology	4	3.6	54% (115/249)	Applied Psychology
Cognitive Processing	3	3.1	43% (93/165)	Experimental and Cognitive Psychology
International Journal of Sports Science and Coaching	3	3.5	80% (120/604)	Social Sciences
Medicine and Science in Sports and Exercise	3	7.7	94% (14/247)	PT, Sports Therapy and Rehabilitation
Scientific Reports	3	7.5	92% (14/171)	Multidisciplinary

Summary of participants

All studies recruited athlete participants to take part in the intervention activities. As illustrated in Figure 3(C), there was a large range in the number of participants in any given study, with most articles reporting samples with less than 40 participants. Six articles reported on training activities with over 100 participants, with the largest study consisting of 412 participants (Badau et al., 2023). Two studies did not report the specific number of participants but rather described the sample as consisting of all position players from collegiate baseball teams (Clark et al., 2012; Fadde, 2006).

Within the corpus, 26 individual sports were represented, along with six studies that reported on vision training in referees (Put et al., 2016). As listed in Table 2A, the most represented individual sports included soccer (22), baseball (11), basketball (8), tennis (8), badminton (7), and volleyball (7). In addition, 15 articles reported on studies with athletes from multiple sports, typically occurring at athletic training facilities or undertaken in college athletic departments with a wide representation of sports included.

As illustrated in Table 2B, studies in the corpus reported on athletes from all levels of competitive accomplishment. Notably, 61 articles reported on professional, semi-professional, elite, Olympic, or collegiate athletes, indicating that research in this field has

Table 2. Counts of the number of articles reporting on (A) each sport and (B) the level of accomplishment of the tested athletes.

A) Sport	Number of Articles	B) Athlete Level	Number of Articles
Soccer	22	Skilled	32
Multiple Sports	15	College	27
Baseball	11	Elite	25
Basketball	8	Youth	17
Tennis	8	Multiple	15
Badminton	7	Professional	6
Volleyball	7	Semi-professional	2
Other	48	Olympic	1
		High School	1
Total	**126**	**Total**	**126**

access to highly accomplished athletes and pointing to an area of study in which expertise is routinely studied.

Summary of interventions

Each study reported on an intervention with outcome measures collected at least before and after the intervention. The duration of the interventions and their frequency over time varied considerably. The shortest interventions occurred as a single session, with nine articles reporting on such single session, acute training programs. The remaining studies reported on longer, longitudinal training programs that lasted days or weeks, with the most common intervention schedules occurring two or three times per week, over multiple weeks, with approximately half of the total articles reporting on such bi- or tri-weekly schedules. The longest interventions unfold over many months, typically corresponding to a full season for a given sport with seven articles reporting on interventions that lasted at least three months (Arede et al., 2021; Bonato et al., 2020; Fadde, 2016; Hulsdunker et al., 2021; Leichtfried et al., 2016; Satyanarayana, 2020; Vasile & Stănescu, 2024), and the longest and most involved interventions occurring five days per week over 24 weeks (Theofilou et al., 2022) or lasting for two successive seasons (Harle & Vickers, 2001).

Regarding the interventional designs used in this literature, 98 of the 126 studies included at least one control group, or condition, as a comparator for the primary visual training intervention. These included a wide variety of different control and/or placebo groups ranging from matched control training interventions to no-contact controls who took part in regular training activities without additional matching of activities. In two cases, studies utilized crossover designs where the training groups each started on one intervention and switched to another intervention to compare the relative efficacy and sequencing of the training (Leichtfried et al., 2016; Poltavski et al., 2021). In the other 26 articles, no control was utilized. While many studies reported on efforts to blind the participants to their group assignment, this only occurred in approximately half of the studies. The occurrence of experimenter blinding was rare and only one article reported double blinding (Shekar et al., 2021). Among the 126 articles, only two listed pre-registration of their methods and hypotheses (Liu et al., 2020; Reneker et al., 2020). The most common statistical tests used in these studies included ANCOVA and ANOVA, with many studies reporting t-tests and change scores. Appropriate use of multiple comparison correction to adjust statistical criteria for multiple statistical tests was rare and most articles reported many different statistical tests without correction of their significance criteria (alpha level).

Summary of outcome measures

The primary aim of this literature was to test the effectiveness of vision-based training programs towards improving athlete performance. While the most direct and meaningful way to test such effects is through analysis of changes in in-game performance during competition, only 15 studies reported outcomes from competitive matches. These included individual athlete baseball and cricket batting statistics, basketball and hockey shooting statistics, as well as team batting and hockey statistics. The most common outcome measures were behaviors associated with sports-specific stimuli and tasks. 76 studies reported on primary outcome measures derived from a sports-specific physical action (e.g. free throw shooting, batting practice, small-sided soccer scrimmages) or outcomes derived from the perceptual decision on a sports-specific stimulus/task using screen-based methods (e.g. anticipating on-goal shots from video). Seventy studies utilized non-sports-specific generic stimuli and tasks, with most of these involving computer-based cognitive tasks using generic stimuli (e.g. multiple object tracking). In many cases, both sports-specific and generic stimuli were used as multiple outcome measures in the same study, while a small number of articles also reported on subjective outcomes such as questionnaires and surveys.

In addition to the pre- and post-training assessments which occurred in all the studies, 36 of the articles also reported on follow-up assessments that occurred after the primary endpoint was acquired. These studies included follow-up measures to test for retention of the training effects, with delay intervals ranging from one day to many months, while one study also included a five-year follow-up assessment in a subset of the participants (Gray, 2017).

Classification taxonomy and findings from sports vision interventions

Building on the previous taxonomy of Appelbaum and Erickson (2018), the interventions identified in this review can be categorized into three overarching classes; Component Skill Training, Naturalistic Training, and Integrated Batteries, each of which includes several sub-classes that center on certain psychological processes or technological approaches (Table 3). While this classification scheme is not meant to be absolute, it allows the grouping of interventions into a smaller number of descriptive categories. The following sections elaborate on the approaches and major findings within each of the three classes of interventions. While not an exhaustive catalogue of individual study results, these sections highlight the experimental designs, findings related to near and far-transfer of skills, and the strengths and weaknesses of evidence towards the efficacy of these classes of approaches. Where available, additional topical review articles are referenced.

Component skill training

Sporting activities, like catching a pass or kicking a penalty shot are the end-product of a cascade of subprocesses that build on each other to enable on-field success. Limitations in

Table 3. Counts of articles in each classification category and sub-category.

Component Skill Training	**59**
Foundational	5
Perceptual-Cognitive	47
Visual-Motor	6
Crossover	1
Naturalistic	**44**
Stroboscopic	15
Occlusion (eye patch)	2
Gaze	14
Simulation	13
Integrated Batteries	**21**
Circuit	19
All-in-One	1
Field-Based Drills	1
Other	**2**
Total	**126**

any single subcomponent may create bottlenecks that constrain overall performance (Welford, 1960). Component skill training approaches are a class of interventions aimed at improving foundational visual abilities important for sporting performance that may remove bottlenecks in processing and elevate on-field performance. Fifty-nine articles were classified as implementing component skill training approaches including five that primarily targeted foundational skills, 47 targeting perceptual-cognitive skills, six targeting visual-motor skills, and one that was a cross-over design.

Foundational Skills: Foundational skill training studies included several designs that aimed at improving oculomotor function or visual sensitivity. Oculomotor training techniques sought to improve the coordination and efficiency of eye movements through drills targeting saccades (rapid, voluntary eye movements between fixation points), smooth pursuit (tracking moving objects), and vergence eye movement (convergence and divergence of the eyes to focus on near or far objects). Studies seeking to improve visual sensitivity used perceptual learning designs to train aspects of dynamic and static vision, typically using adaptive procedures to encourage performance near the threshold of sensitivity. Together the studies targeting foundational skills used a combination of screen-based training and light rails to isolate processes that were the focus of training. These studies produced mixed evidence of efficacy, with most studies reporting improvements in sports-specific tasks, but only one (Deveau et al., 2014) reporting in-game performance improvements. Many of the individual techniques of foundational skill training are also present in integrated batteries, described in greater detail below.

Perceptual-Cognitive: Because of the challenging and dynamic visual conditions under which athletes practice and compete, sports are commonly seen as a domain in which perceptual–cognitive skills are enhanced. Over one-third of the corpus, 47 articles, reported interventions that targeted perceptual and cognitive processes thought to be essential in sports. These were grouped into studies that utilized occlusion paradigms, studies testing multiple object tracking (MOT), and the remainder that targeted other perceptual (e.g. sensitivity) or cognitive (e.g. attention) processes. This class of interventions was also used in all six of the articles that tested training approaches in sports referees (five soccer and one rugby).

Occlusion: Visual occlusion paradigms are techniques used to study perceptual and cognitive processes in activities requiring rapid decision-making and anticipation. These paradigms involve spatially or temporarily obscuring parts of a visual scene to understand how individuals process visual information and make predictions based on incomplete data. Based on the results of occlusion paradigms, it can be inferred that aspects of a scene are essential to performance and lead to an ‘expert advantage’ wherein the removal of these elements, but not others, reduces the superior performance of experts over novices (Farrow et al., 2005). These elements are then occluded in training paradigms to force participants to use information optimally with minimal exposure or to integrate information as early or late as possible under the theory that this will lead to more facile perception and cognition that enhances component abilities essential for sports performance (note: occlusion using stroboscopic eyewear is addressed separately below).

Twenty studies reported on occlusion training paradigms that utilized different video-based training, temporal and spatial occlusion, and guided discovery techniques to enhance athletes’ anticipatory skills, decision-making, and technical performance across various sports, including swimming, wheelchair basketball, handball, cricket, tennis, and soccer. Findings generally indicated that occlusion training improved athletes' sports-specific abilities to anticipate opponents' actions, make quicker and more accurate decisions, and execute technical skills more effectively. Improvements were noted in areas such as reduced exchange times between swimmers during relay events, improved shooting accuracy in wheelchair basketball, enhanced goalkeeping in handball, and better fielding performance in cricket. In most cases, analyses were done in relation to comparator control groups, such as training with the same video content, but absent occlusion, and several studies also reported positive retention effects after days or weeks following training. While two studies reported improvements in in-game performance due to occlusion training (Fadde, 2006; Hopwood et al., 2011), these were done with relatively small sample sizes, incomplete control conditions, and indirect game performance metrics. Collectively, this literature provides suggestive evidence in support of the ability of occlusion training to enhance foundational abilities that may lead to performance advantages in competitive settings, but limited evidence of far-transfer effects to enhance sporting performance.

Multiple Object Tracking (MOT): Dynamic sports like basketball, soccer, and hockey require athletes to simultaneously track and respond to movements in the field-of-play. These tracking abilities are vital for athletic success and research has shown that expert athletes generally have superior tracking skills than non-athletes (Faubert, 2013), though these abilities may be specific to the context of the athlete's sport (Styrkowiec et al., 2024). Based on the idea that visual tracking of movement patterns is important in sports and may be enhanced through training, there has been an effort towards developing and testing MOT training programs applied to athletes. In these programs, athletes typically view and track multiple simultaneously moving objects across the field-of-view over many seconds at a time, often while also performing other dual tasks (e.g. balance).

Ten studies in the corpus tested MOT training approaches in athletes. These studies examined the efficacy of MOT training for improving concentration, decision-making, and task-specific skills across different sports, including soccer, basketball, volleyball, and archery. In two cases, sports-specific athletic task transfer was tested using practice sporting activities like small-sided soccer drills (Romeas et al., 2016) and volleyball blocking tests (Fleddermann et al., 2019), while in two recent articles, far-transfer to in-game performance was tested in collegiate women's soccer (Phillips et al., 2023) and professional Japanese baseball (Furukado et al., 2024). In most cases active MOT training was compared with control training, however, this infrequently involved matched placebo training and often utilized passive controls who engaged in standard athletic training activities. No studies were pre-registered, and none involved follow-up retention tests.

Individual study findings indicated that MOT training was able to enhance generic cognitive abilities, such as improved sustained attention and processing speeds, as well as enhancements in the sports-specific volleyball and small-sided soccer tasks. Among the studies testing far-transfer effects on in-game performance, positive findings from Phillips and colleagues (2023) were limited to only one of several game outcome measures (in-game passing accuracy) and findings from Furukado and colleagues (2024) were derived from a small sample of athletes, used liberal statistical criteria ($p<0.1$), and were not corrected for multiple comparisons across the numerous outcome measures tested. As such, similar to conclusions drawn from a recent systematic review of MOT training conducted across athlete and non-athlete participants (Vater et al., 2021), the current sample of studies testing MOT training in athletes highlights the limited evidence of the transfer to in-game performance and methodological limitations including lack of preregistration, small sample sizes, and limited testing of ecologically valid athletic tasks.

Visual-Motor Training: Visual motor control refers to the ability to coordinate visual perception with motor actions, skills that are crucial for athletes to respond quickly and accurately during dynamic gameplay. Six studies tested visual-motor training programs, most typically using lightboards or light disc technology that also allows for embedded cognitive tasks during drills. These studies generally focused on near-transfer outcomes to generic tasks related to the training activities with five studies including control groups. In all cases, athletes who trained with visual-motor tasks improved at near-transfer abilities measured with generic tasks. In the one case where far-transfer to sports performance was tested, it was found that traditional volleyball training produced larger gains than visual-motor training, arguing against the utility of this approach (Formenti et al., 2019).

Naturalistic training

Naturalistic sports vision training approaches are techniques that allow participants to practice actual or simulated sporting activities with the addition of elements that alter or augment the training experience (Appelbaum & Erickson, 2018). These approaches do not reduce the training context to component skills but rather focus on training in the sports-specific performance environment. By maximizing stimulus and response correspondence between the training modality and targeted sports ability, these approaches create near-transfer learning opportunities (Hadlow et al., 2018). By enabling manipulations that can alter visual information processing, these approaches also seek to accelerate skill learning and improve athletic performance. As highlighted in this review, the three most common subclasses include the use of stroboscopic eyewear, training that utilizes feedback from eye tracking to train gaze behavior, and simulations that recreate the sporting environment in virtual contexts.

Stroboscopic Training: During stroboscopic visual training individuals practice athletic tasks under intermittent visual conditions with the intention of enhancing subsequent performance under normal visual conditions. The logic behind this approach is that by intermittently disrupting vision, individuals are only allowed to see brief snapshots of their environment and therefore must train under harder conditions than would otherwise be encountered – akin to resistance training. This then forces individuals to more effectively use the limited visual input that they do receive, leading to increased sensitization and better visual skills when they return to normal visual conditions. Stroboscopic training was greatly advanced by the introduction of light-weight digital eyewear that creates controllable strobe effects thorough the polarization of liquid crystal lenses. All articles identified here used such eyewear.

Fifteen articles, published between 2011 and 2024 were identified that tested strobe training in athletes. Five articles reported on multisport cohorts, three reported on badminton, two volleyball, three soccer, one ice hockey, and one sport climbing. All studies utilized control groups for comparison with most involving training with eyewear that remained transparent, though some studies also tested variable frequency protocols (Wilkins & Gray, 2015). The average sample size per study was 45, with samples ranging from 10 to 157 subjects. Fourteen studies involved longitudinal training with several training sessions per week over multiple weeks. Seven studies included retention tests.

Findings from these articles typically demonstrated that stroboscopic training improved component visual-motor and cognitive abilities, with some additional evidence of far-transfer to sports activities. Results indicate that strobe training improved short-term memory retention, central visual field motion sensitivity, and transient attention (Appelbaum et al., 2011; Appelbaum et al., 2012) as well as visual-motor reaction times (Hulsdunker et al., 2021; Wilkins et al., 2018). Given that the training and testing contexts were different, these findings point to some degree of transfer, improving foundational abilities that are important for sports. Evidence of far-transfer comes primarily from a pilot demonstration of improved puck placement in a small sample of 11 professional hockey players (Mitroff et al., 2013), significant improvement in volleyball-specific measures for strobe over control (Zwierko et al., 2023), as well as studies that utilized strobe training during circuit training, described below. As reviewed by Wilkins and Appelbaum (2019), these studies demonstrate preliminary evidence that stroboscopic training can improve visual and visual-motor skills with some limited evidence of transfer to athletic performance. Despite this, there is still a need for improved rigor, larger sample sizes, and more sufficient control conditions to advance this field.

Gaze Training and Quiet Eye: Gaze training protocols are techniques designed to improve an individual's ability to focus their gaze effectively during tasks. Gaze training most typically involves feedback to the trainee about the position and movement of their eyes through eye tracking or video technology, and often seeks to train the 'quiet eye' (QE) phenomena which is characterized by a prolonged fixation on a specific target just before executing a movement. Among the 14 identified articles that reported on gaze training approaches, 12 utilized QE training designs while the other two utilized visual focusing techniques.

In each case, sports-specific training stimuli were used that corresponded to the visual environment of the athletes, with golf (5) and basketball (3) the most frequently studied sports. Eleven of the articles reported on longitudinal interventions that lasted days or weeks, while three of the studies reported on the acute effects of a single session of training. These studies typically defined the QE period as the final fixation or tracking gaze at a location or object within three-degrees of visual angle for a minimum of 100 ms (Vickers, 1996) and provided real-time feedback to the user of their quality and quantity of QE during the training activities. Most studies made comparisons between gaze training programs and matched control groups, with four studies also including post-training retention assessments, though none utilized pre-registration.

All studies reported positive findings that Gaze or QE training led to improved outcomes with many demonstrating improved QE metrics and several offering evidence that QE training translated to improved sports performance in golf (He et al., 2024; Vine et al., 2011), basketball (Moeinirad et al., 2022), soccer (Wood & Wilson, 2012), and shotgun shooting (Causer et al., 2011). As reported in a meta-analysis of nine studies, conducted by Lebeau and colleagues (Lebeau et al., 2016), QE training produced large meta-analytic effects on QE duration with the intervention groups producing longer and more stable fixations and improved transfer task performance, while QE duration also demonstrated some ability to predict performance on some athletic tasks. Collectively, these findings from QE training present a compelling argument in support of the value of this approach and the potential to improve both foundational visual skills and in-game performance.

Simulations: Training with simulations offers athletes opportunities to recreate game scenarios, practice specific skills, and receive instant feedback. Because simulations mimic the playing context, they also reduce the transfer distance from the training context to the game context, in theory leading to more robust training gains. Twelve articles were identified that utilized virtual reality (10) or video simulations (2) to train athletes. The average sample size was 42 participants per study, with eight studies including control groups. Baseball (4) and karate (3) were the most frequently represented sports.

Findings generally demonstrated significant improvements in perceptual-cognitive skills such as pattern matching, anticipation, and decision-making that were tested on sports-specific measures. Importantly, three studies each found that baseball players using simulation-based training tools showed significant improvements in pitch recognition and decision-making, leading to better batting performance (Belling & Ward, 2015; Fadde, 2016; Gray, 2017). In these simulations, training methods often included embedded component training elements, such as occlusion techniques, to enhance athletes' anticipation and decision-making. As discussed in recent scoping (Faure et al., 2020) and systematic (Richlan et al., 2023) review articles, findings from the literature show that simulations can bridge the gap between laboratory research and practical application in sports, making them a valuable tool for coaches and athletes aiming to enhance performance. The use of simulations extends beyond just training, as they may also play a role in injury prevention, strategy development, and fan engagement, showcasing their broad applicability and potential in the sports domain.

Integrated batteries

As described in numerous cross-sectional studies, high-achieving athletes can be distinguished from lesser-achieving athletes on a diverse set of perceptual, cognitive, and visual-motor abilities (Mann et al., 2007; Voss et al., 2010). The most effective training approaches might, therefore, attempt to train skills across a battery of drills that capture this breadth of possible abilities to create a more holistic training experience. This diversity is at the core of the class of Integrated Batteries.

Twenty-one such studies were identified in the corpus, with 19 utilizing circuit training approaches in which athletes rotated over a set of training stations. These most typically involve short (<10 minutes), sequential drills in which athletes perform different component or naturalistic training activities. These often involve the combination of speed and agility exercises with the addition of visual elements, such as strobe glasses, as well as oculomotor (e.g. Brock string, Marsden ball) or eye-hand coordination (e.g. lightboards) drills. In the remaining studies, the training involved either an all-in-one digital training device (Shekar et al., 2021) or the fusion of cognitive exercises during physical practice (Casella et al., 2022).

Seventeen of the studies involved some form of control comparison, though the use of matched controls was relatively rare, and many studies compared intervention groups to standard athletic practice groups. The average sample size was 30 individuals per study, all interventions were longitudinal with typical schedules involving training two or three times per week for four to eight weeks, and six studies including retention tests. Five studies utilized in-game statistics as primary outcomes, three used sports-specific tasks, and the remainder utilized generalized task measures as the outcomes. Importantly, two of the studies utilized rigorous methods with pre-registration of hypotheses, randomization into active and placebo training groups, and experimenter blinding during analyses (Liu et al., 2020; Reneker et al., 2020).

Collectively, findings from these studies produced mixed results regarding the impact of training on athletes' visual skills and athletic performance. While many studies observed greater improvements in component visual and cognitive skills following active, versus control training (e.g. Appelbaum et al., 2016), many other studies found no significant improvements (e.g. Shekar et al., 2021), or the lack of transfer to non-trained tasks (Schwab & Memmert, 2012). Across the five studies where in-game performance was assessed, there was a positive improvement reported from vision training in four of the studies for individual (Balasaheb et al., 2008; Jenerou et al., 2015; Maman et al., 2011) or team (Clark et al., 2012) sports performance metrics. Despite this, two of the studies did not use matched controls (Clark et al., 2012; Jenerou et al., 2015) and one did not perform direct comparisons between the experimental and control groups (Maman et al., 2011). A fifth study by Liu and colleagues (2020) utilized a pre-registered, randomized and controlled design and reported that while in-game baseball batting performance did not significantly improve, intermediate transfer to batting practice resulted in significant gains in hit distance and launch angle. Collectively, these findings present mixed results regarding the efficacy of vision training through integrated batteries, with some evidence of both near and far-transfer effects but contain many methodological limitations and the need for greater experimental rigor to establish efficacy.

Other training modalities

Two studies included vision-based training but did not fall into the classification categories described above. These studies included interventions aimed at increasing morning light exposure (Leichtfried et al., 2016), and mirror training (Steinberg et al., 2016). In both cases, longitudinal training was employed, and sports-specific or generic outcomes were evaluated, but neither resulted in significant near or far-transfer learning.

Discussion

Over the last 25 years, researchers have begun investigating the possibility that training of visual abilities may lead to enhancements in sports performance. As identified in this review, at least 126 different peer-reviewed empirical articles have tested vision training approaches in athlete populations, leading to a diverse set of findings. As characterized by the classification taxonomy of Appelbaum and Erickson (2018), these articles primarily fell into three classes; Component Skill Training, Naturalistic Training, and Integrated Batteries. The characterization of these classes reflects a combination of theoretical, mechanistic, and technological influences on how sports vision interventions are designed and implemented, leading to clustering around several common approaches. This classification taxonomy also intersects with the Modified Perceptual Training Framework (Hadlow et al., 2018) which aims to capture the scope of training approaches along three theoretical dimensions allowing for testable predictions about the effects of any intervention towards improving athletic performance. Central to the MPTF is the prediction that stronger transfer effects will be seen in approaches that demonstrate maximal training-to-competition correspondence for the trained skill, the training stimulus, and the response required during the training, thereby minimizing the distance of transfer. In line with this prediction, the current review finds the strongest evidence of training gains from naturalistic studies that utilize training environments and tasks that maximize these correspondences. While past reviews have pointed out the lack of evidence for generalized, far-transfer (Harris et al., 2018; Smeeton et al., 2013), and other commentaries have cautioned about the possibility of exaggerated claims from companies seeking to market products based on far-transfer approaches (Fransen, 2024), the current review does find evidence of generalized learning in a number studies, particularly those employing naturalistic techniques, as discussed in more detail below. In the following sections, we discuss the evidence, strengths, and limitations of each class of studies, followed by recommendations for future improvements to this field.

Component Skill Training: In the last two decades, generalized learning has become pervasive, both as a research topic and through commercial product lines that market such products to the public. In the current review, 59 different articles were identified that applied component skill training approaches to athletes with the intent to improve skills inherent in sports performance and induce generalized learning that can improve on-field results. As noted above, near-transfer effects were commonly reported with improvements for the training groups, over control groups, leading to gains in virtually every domain of perception, cognition, and visual-motor control relevant to sports performance. Despite the widely reported near-transfer effects, there was relatively little evidence of robust far-transfer effects that led to improved sporting performance using rigorous methodologies. Contributing factors include infrequent far-transfer tests, lack of multiple comparison corrections for multiple statistical tests, small and moderate sample sizes, and rare attempts at replication.

Naturalistic Training: Naturalistic sports vision training refers to training methods designed to improve an athlete's visual and perceptual skills in conditions that closely mimic real-life sports scenarios. This approach emphasizes the integration of skills training within the context of actual sports activities, rather than isolated or artificial exercises. As articulated in the MPTF it is theorized that transfer occurs best if the training and transfer tasks engage highly overlapping processes and while such a proposition is clearly important, there is a fundamental challenge in recreating the context, stress, and pressure of live game situations. Through advancements in digital technology, these barriers have begun to come down with increasing ease and cost-effectiveness, though there is still a need to improve the fidelity to the true visual and motor tasks required to mimic real-life sports scenarios. As reviewed above, there is now strong evidence that gaze training approaches using sports-specific stimuli and tasks, particularly the Quiet Eye technique, show strong promise toward near, intermediate, and far-transfer. Studies showing gains in golf (He et al., 2024; Vine et al., 2011), basketball (Moeinirad et al., 2022), soccer (Wood & Wilson, 2012), and shooting (Causer et al., 2011) highlight the potential of gaze training, while the demonstration that QE duration correlates with performance suggests a causal link that may be exploited for scouting and selection purposes (Klostermann et al., 2013). While not as robust, promising evidence of far-transfer is also present in the studies testing stroboscopic training and simulation training, such as those reported by Mitroff et al. (2013), Zwierko et al. (2023), and Gray (2017), which each used randomized and placebo-controlled designs while showing evidence of on-field gains in athletes. These techniques promote the greatest training-competition correspondence as they can be done in the context of sports activities, as the case with strobe training; or try to replicate the sports context, as is the case with virtual reality simulations. As the price and complexity of these digital technologies continue to improve naturalistic training should continue to see increased use.

Integrated Batteries: By combining multiple visual and perceptual training techniques into a training circuit, integrated sports vision batteries seek to create a holistic program that can strengthen many simultaneous foundational abilities. The theory is that such integrated approaches ensure that various visual skills are developed in conjunction with each other, promoting better transfer of these skills to actual sports scenarios. Evidence from the reviewed articles paints a mixed picture, with many studies demonstrating gains in component skills and a few indicating transfer to sports-specific abilities and game performance. Despite this, several studies report null results, and many studies don't use rigorous methodologies to establish evidence of gains.

Limitations, improvements, and implications for practitioners

As with any scientific discipline, studies testing vision training should be guided by the best available evidence. However, conducting carefully controlled and sufficiently powered studies with athletes presents substantial challenges including logistical hurdles, limited available time, and the potential desire of athletes and teams to engage in certain activities over others while not revealing information that would compromise their competitive advantage. These factors may contribute to the relative scarcity of well-designed, sufficiently powered studies reviewed here. Despite these obstacles, the pursuit of rigorous and well-executed studies should remain the gold standard, and several steps can be taken to improve this rigor. First, while potentially challenging with athlete participants, it is important that studies implement randomized, blinded and placebo-controlled designs so that active and control interventions are matched, allowing isolation of training effects that aren't attributable to uncontrolled factors. Another area for methodological improvement is the use of more rigorous statistical tests that properly account for Type I and Type II errors. With multiple analyses, the chance of a false positive finding increases, creating the appearance of a significant finding when none exists leading to Type I errors. To mitigate this, it is necessary to adjust the significance level for multiple comparisons. Conversely, Type II errors occur when a null hypothesis that is false is accepted with insufficient sample sizes increasing the likelihood of Type II errors. To effectively reject the null hypothesis and avoid Type II errors, studies must have enough subjects. Given the challenges of obtaining large sample sizes and the desire to test various performance aspects simultaneously, studies in sports vision must take special precautions to avoid inflating these statistical errors. A central way to combat this, is through pre-registration of hypotheses and methods, though only two of the 126 reviewed studies used pre-registration, pointing to an important area of unmet need. Furthermore, it should be noted that among the 126 reviewed articles, there was not a single reported replication study presenting another major limitation that should be addressed with future studies.

Within the reviewed studies there was a large range of different intervention approaches performed in many different contexts. In most cases, the authors motivated their studies based on the theorized role of vision in sports and/or the interest in visual learning that might improve sports performance. At the same time, the options of what interventions are possible to test are not unlimited and are often constrained to both what is available to them (e.g. commercial products or research instruments) and what the athletes/teams/coaches are willing to do in a research study. The classification taxonomy used in this review is meant to capture and group the different approaches that are available, thereby offering a framework for further scrutiny and study. Nonetheless, researchers largely examine the impact of their own paradigms and outcome measures that often differ from those used by other research groups. One approach that may reduce such variability and strengthen future research is using standardized and reliable methods to capture psychometric data, such as the recently introduced PLFest platform (Jayakumar et al., 2024). Given the many challenges noted above, it is essential that future studies adopt more rigorous methods, move towards the collection of larger, better-powered sample sizes, and implement transparent, Open Science principles to advance the field. With these methodological advancements, the findings reviewed above may provide the basis for the next step, and lead towards greater adoption and impact of sports vision training on athlete performance.

As an applied discipline, it is important that information discovered, or rebuffed, through research be available to practitioners. Therefore, it is valuable for trainers, coaches, managers, and even athletes themselves to be informed about the current state-of-the-science so that they can make better-informed decisions about the technologies and approaches that they use in their activities. Because these groups are often at the forefront of newly emerging technologies, it is important that they look with a critical eye at both the opportunities and evidence that is available to them. Moreover, it is important that sports and athletics continue to trend towards a more multidisciplinary field with regular crosstalk between contributors. As it relates specifically to the visual instruments discussed in this article it is important to realize both the current state of the field and the future potential, wherein visual assessment and training techniques can both be used as baseline screening that can be used to personalize interventions that target weaknesses (or opportunities) and serve as reference information for skill improvement, injury recovery, and return-to-play decisions (particularly as it relates to concussion). Finally, it is important to also consider the real and perceived opportunity costs in money, time, and effort as these can differ considerably from context to context.

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Data availability statement

All data for this review comes from published articles and can be obtained from the citations in the Supplementary Materials.

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