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REVIEW

Sports vision training: A review of the state-of-the-art in digital training techniques

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ABSTRACT
Athletes need excellent vision to perform well in their sports, and many athletes have turned to vision training programs as a way to augment their traditional training regimen. The growing practice of 'sports vision training' relies on the notion that practice with demanding visual perceptual, cognitive, or oculomotor tasks can improve the ability to process and respond to what is seen, thereby improving sport performance. This enterprise is not necessarily new, but has been advanced greatly in the past few years by new digital technology that can be deployed during natural training activities, by perceptual-learning-inspired training programs, and by virtual reality simulations that can recreate and augment sporting contexts to promote certain sports-specific visual and cognitive abilities. These improved abilities may, in turn, instill a competitive advantage on the playing field, underscoring the potential value of these approaches. This article reviews emerging approaches, technologies and trends in sports vision training. Where available, critical review of supporting research is provided.

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1. Introduction

Competitive sports draw on a diverse set of physical and mental skills. Athletes, coaches and trainers are constantly searching for ways to enhance these abilities, and because of the perceptually demanding nature of sports, visual and visual–motor skills are often targeted in sports training programs. So-called 'sports vision training' (SVT) operates under the logic that practice with demanding visual perceptual and oculomotor tasks will improve vision, leading to quicker sensory processing, swifter and more accurate motor movements, and improved athletic performance while also potentially reducing injury (Erickson, 2007). Given the importance and interest in athletics, SVT programs have a relatively long history of use (Martin, 1984; Revien & Gabour, 1981; Seiderman & Schneider, 1983; Stine, Arterburn, & Stern, 1982); however, the past few years have seen a tremendous growth in new digital technologies that are used in sports vision training programs. The present review offers a brief overview of the motivation and historical use of traditional analog training approaches, followed by an in-depth review of the

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latest digital technologies and, where available, research supporting these new approaches.

1.1. Sports vision training philosophy and historical approaches

Familiar sporting expressions, such as 'the eyes lead the body,' 'keep your eye on the ball' and 'you can't hit what you can't see,' clearly underscore the key role that vision plays in athletics. Research across multiple domains of sports has provided empirical evidence in support of the notion that visual–perceptual and visual–cognitive abilities are enhanced in expert athletes (Starks & Ericsson, 2003; Williams, Davids, & Williams, 1999). For example, professional and collegiate baseball players have been reported to have superior visual acuity (Laby et al., 1996), enhanced contrast sensitivity (Hoffman, Polan, & Powell, 1984) and better visual tracking abilities (Uchida, Kudoh, Higuchi, Honda, & Kanosue, 2013; Vickers & Adolphe, 1997) than nonathlete controls. Further, as is captured in two separate meta-analyses of the sports expertise literature (Mann, Williams, Ward, & Janelle, 2007; Voss, Kramer, Basak, Parkash, & Roberts, 2010), higher achieving athletes are better able to detect perceptual cues, make more efficient eye movements and perform better on measures of processing speed and attention than less accomplished athletes or nonathletes. Moreover, these expert benefits are largely reflective of the demands required by the specific roles that athletes play. For example, response times, but not response accuracy, are better in athletes who play interceptive sports, suggesting that the inherent temporal constraints associated with hitting, catching and intercepting moving objects might engender faster responses (Davids, Salvelsbergh, Bennett, & Van der Kamp, 2002). Similarly, experts in sports that require a greater horizontal distribution of attention (e.g., ice hockey) demonstrate a greater horizontal breadth of attention than athletes whose sports require more vertical attention (e.g., volleyball), and vice versa (Huttermann, Memmert, & Simons, 2014). While there are certainly counter examples that have reported no difference in visual abilities between athletes and nonathletes (Eccles, 2006; Zwierko, 2007), and there are important questions about the balance of nature versus nurture that contribute to the development of these skills (Davids & Baker, 2007; Epstein, 2013), the studies noted above, as well as others from Olympic (Laby, Kirschen, & Pantall, 2011) and Junior Olympic (Beckerman & Hitzeman, 2003) cohorts, have demonstrated that high-level athletes are experts at processing some types of visual information. This visual expertise advantage, therefore, provides support for the notion that improving the underlying skills may lead to better athletic outcomes.

While there has been great heterogeneity in the way that SVT interventions have been implemented, the general philosophy behind these programs stems from three key assumptions: (a) Aspects of vision are important for particular sports, (b) these aspects of visual function can be modified through training, and (c) improvements in visual abilities can translate into improvements in on-field performance (Erickson, 2007). Despite the evidence described above linking better sensorimotor abilities to more accomplished athletes, research examining the extent to which these skills can be modified through training is less clear. Furthermore, there is a paucity of research linking visual learning to better sporting outcomes. As such, there is limited and mixed support for the notion that traditional analog SVT drills can improve sports-relevant vision, or manifests into better on-field performance.

Historically, early approaches to SVT entailed analog ‘eye fitness’ drills that imposed heavy oculomotor demands, forcing trainees to rapidly alter visual convergence, accommodation, saccadic and/or pursuit eye movements to visual targets. Research on such interventions has led to discrepant results. For example, research on club-level cricket batters found that a visual training regimen performed for 30 min, 3 days each week for 6 weeks led to improvements in fundamental visual abilities such as depth perception, accommodation, and saccadic eye movements, as well as improvements in batting statistics relative to both placebo and control groups (Balasaheb, Maman, & Sandhu, 2008). Using a similar set of analog vision training drills performed over five weeks, it was found that netball passing speed and accuracy were improved for individuals who underwent vision training, relative to controls (Bressan, 2003). Conversely, in a series of studies assessing multiweek SVT on different visual and oculomotor drills, little evidence was found indicating that these training interventions improved either visual or motor performance beyond that of control groups (Abernethy & Wood, 2001; Wood & Abernethy, 1997). Utilizing a hybrid training design that entailed both visual skill training and psychological training, greater enhancements in marksmanship performance were found for individuals who received training; however, these enhancements were not statistically significant above gains also seen for a no-contact control group (Quevedo, Sole, Palmi, Planas, & Soana, 1999).[1]

While such discrepant findings call into question the effectiveness of traditional analog vision training drills, the last decade has seen a paradigm change in the types of approaches that are being implemented. In particular, SVT approaches have been advanced greatly by perceptual-learning-inspired training programs that utilize information about the structure and function of the visual system to engender more specific and robust learning. SVT approaches have also been aided by new digital technologies that can be deployed during natural training activities and by virtual reality simulations that can recreate and augment sporting contexts to promote certain sports-specific visual–cognitive abilities. In the following section we provide a classification-taxonomy of these approaches and a framework for understanding the empirical research that has been undertaken. This is followed by a review of the theory, application and research surrounding the current marketplace of digital SVT techniques. As many of these digital tools are also gaining use in concussion evaluation and rehabilitation programs, we therefore note instances where training and concussion programs interact.

1.2. Sports vision training classification-taxonomy and research domains

SVT interventions are inherently designed to improve sporting outcomes. Different sports and/or positions, however, can have vastly different visual demands, and therefore there is a need for SVT approaches that target different skills. At the same time, the technological development of digital tools has progressed rapidly, with certain tools gaining increased adoption for training with particular athletic cohorts. For the purpose of this review, we have developed a classification-taxonomy with two overarching classes and several subclasses to characterize the diversity of approaches that have emerged around different skills-of-interest and technical innovations. Further, since the use of digital SVT tools is relatively new, there is a great amount of variability in the scope and intent of research that has been performed with these tools. In Section 1.2.2 we present a framework for understanding the types of evidence-based research that have been employed to study digital SVT techniques and describe the literature search and inclusion criteria of this review.

1.2.1. SVT classification taxonomy

1.2.1.1. Component skill training. Sporting activities like kicking a ball, blocking a shot or catching a pass are the end product of a cascade of many subprocesses that build on each other to enable on-field success. Limitations in any single subcomponent may create bottlenecks that constrain overall performance; thus, *component skill training* approaches are designed to target these fundamental subprocesses. Elements of the component skill training approach are highlighted in Figure 1, which illustrates two prominent models of sports vision. In both the Sports Vision Pyramid (Kirschen & Laby, 2011) and the Welford Processing Model (Welford, 1960) the critical sporting action results from the successful execution of lower level processes. Therefore, by training and improving elemental component skills it is possible to remove bottlenecks and improve overall performance. In this review we highlight four types of component skill training instruments: *low-level visual instruments* that target foundational visual skills, *perceptual–cognitive training instruments* that target generalizable visual–cognitive abilities, *visual–motor reaction training* that target neuromuscular function, and *integrated sensorimotor batteries* that bridge all these domains.

1.2.1.2. Naturalistic sports training. Many SVT interventions have implemented approaches that allow participants to practice actual or simulated sporting activities with the addition of specific elements that alter or augment the training experience. These *naturalistic sports training* approaches are in contrast to the component skill training approach, described above, in that they do not reduce the training context to elemental skills. Rather, these techniques focus holistically on the natural performance environment while enabling manipulations that can accelerate skill learning. In this review we highlight three types of naturalistic training approaches: *stroboscopic visual training* that uses eyewear to interrupt normal visual input, *eye tracking* interventions that train gaze behavior, and *simulations* that recreate the sporting environment in virtual reality contexts.

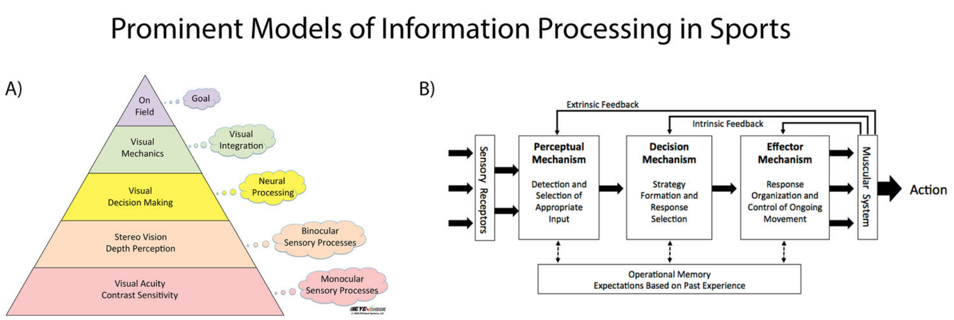

Figure 1. Two prominent models of sports vision and the processes that lead to successful on-field performance. (a) The Sports Vision Pyramid (©EYE Check Systems LLC. Reproduced with permission of Daniel Laby). (b) Modified depiction of the Welford information processing model. To view this figure in color, please visit the online version of this Journal.

1.2.2. Evidence-based research and the structure of this review

There is a rich history of evidence-based research in athletic training. When applied within the context of clinical care, evidence-based medicine is strongly guided by randomized clinical trials studies that test an intervention in relation to a carefully matched and randomly assigned control group to infer the effectiveness of the treatment. This type of design protects against threats to internal validity, allowing one to safely assume that the changes in performance occurring between measures collected before and after the intervention were caused by the experimental manipulation (Campbell & Stanley, 1963; Shipstead, Redick, & Engle, 2010). While this high-bar of research evidence is clearly desired, other types of prospective, observational, and noncontrolled studies can also offer valuable insight into the effectiveness of an intervention.

The use of digital sports vision training tools is new, and in many cases empirical research testing their effectiveness has followed closely behind. Nonetheless, due to the inherent challenges accessing and executing controlled designs with athlete populations, implementation of fully randomized and controlled experiments has been the exception rather than the rule. While several studies have endeavored (to greater or lesser success) to perform randomized and controlled designs (e.g., Appelbaum, Lu, Khanna, & Detwiler, 2016; Deveau, Lovcik, & Seitz, 2014), others have based comparisons on normative data drawn from other athletes or seasons (e.g., Clark, Ellis, Bench, Khoury, & Graman, 2012; Deveau, Ozer, & Seitz, 2014). Similarly, some studies have compared conditions/levels within the same intervention (e.g., Wilkins & Gray, 2015), while in other instances no control/comparison groups have been included. In yet other cases, researchers have inferred the effects of a SVT intervention through correlations with performance data (e.g., Mangine et al., 2014; Poltavski & Biberdorff, 2014). Further, a number of research studies have been reported in conference papers or proceedings, and not peer-reviewed articles, while other SVT interventions have not yet been tested in any manner and have no existing research support.

In light of this heterogeneity, and in an effort to be as comprehensive and inclusive as possible, the current article is structured as a mixed mapping and critical review (Grant & Booth, 2009). As a mapping review, our goal is to identify and categorize existing approaches from which to commission new research that will lead to profitable opportunities to fill gaps in knowledge. This includes descriptions of possible interventions, without regard to the scientific evidence. As a critical review, we endeavor to critically describe and evaluate the existing empirical evidence that is available in published research articles and conference proceedings. As such, where available we provide details of the methods, designs, and findings from the accompanying research studies. In order to achieve these goals, a search of the literature was performed using a combination of systematic searches in public databases (PubMed and Google Scholar) and bibliometric searches of backward and forward citations in the identified literature. Further correspondences with colleagues and practitioners aided in expanding in the scope of this review.

2. Component skill training

2.1. Low-level visual instruments

Over the last 20 years, the field of perceptual learning has demonstrated many examples of dramatic improvements in visual abilities from appropriately structured tasks. This line of research has shown that practice leads to substantial gains in sensitivity that can last for months or years (Crist, Li, & Gilbert, 2001). Most importantly, this research has shown that perceptual learning benefits can transfer to new, untrained contexts (Bavelier, Green, Pouget, & Schrater, 2012), making perceptual learning a powerful tool for generalized learning (Deveau, Jaeggi, Zordan, Phung, & Seitz, 2014). Following this renewed interest in the application of generalized perceptual learning, a number of groups have developed low-level instruments aimed at improving fundamental visual abilities important for sporting performance. In the following section we review recent digital visual training instruments based on principles of perceptual learning that have shown promising evidence for improving vision and sporting performance.

2.1.1. Ultimeyes®

Research in the realm of perceptual learning has highlighted a number of important factors that modulate the depth of learning and the degree of transfer. For example, it has been widely demonstrated that learning is improved when individuals are presented with information from multiple sensory modalities, leading to better encoding and retrieval of perceptual information (Shams & Seitz, 2008). Similarly, it has been shown that training on a diverse set of stimuli has the capacity to improve the extent to which learning generalizes to untrained conditions (Xiao et al., 2008). Furthermore, learning is improved when participants understand the accuracy of their responses (Ahissar & Hochstein, 1997), use highly motivating tasks (Shibata, Yamagishi, Ishii, & Kawato, 2009), and receive consistent reinforcement about the stimuli that are to be learned (Seitz & Watanabe, 2009). Taken together, these lines of research point to approaches that can be combined to substantially improve the effectiveness of perceptual learning.

From these multiple core principles of perceptual learning, Aaron Seitz and colleagues developed Ultimeyes® (ULTIMEYES, n.d.). This custom video application incorporates diverse stimuli, adaptive near-threshold training with learning-optimized flickering stimuli, and multisensory feedback in a digital training program designed to improve foundational aspects of visual sensitivity. In a series of studies, these authors have demonstrated improvements in visual acuity and contrast sensitivity in both nonathletes (Deveau, Lovcik, et al., 2014) and athletes (Deveau, Ozer, et al., 2014), as well as improved batting (Deveau, Ozer, et al., 2014) and pitching (Deveau, Thurman, & Seitz, 2016) performance in collegiate baseball players.

In the first of these studies (Deveau, Lovcik, et al., 2014), healthy nonathlete participants performed twenty-four 30-min training sessions along with tests of central and peripheral field visual acuity and contrast sensitivity before and after training. Results demonstrated significant improvements in central and peripheral acuity, and enhancements across the full contrast sensitivity function, relative to a control group who did not perform the training program. Following from this study, Deveau and colleagues tested the impact of Ultimeyes® training on visual abilities and athletic performance in a cohort of baseball players from the University of California, Riverside team. In this study 19 position players trained on Ultimeyes® for thirty 25-min sessions, while 18 pitchers from the team served as untrained controls (Deveau, Ozer, et al., 2014). Binocular acuity and contrast sensitivity were tested before and after the training program. Results demonstrated improvements in both visual acuity and contrast sensitivity, with seven of the trained players who already had above-normal visual acuity reaching an impressive 20/7.5 Snellen acuity.

While these results indicate potential training benefits for vision, the key tests in this study involved measures of on-field baseball performance. Analysis of batting performance before and after the training program demonstrated a significant reduction in strikeouts (4.4% improvement, *SE* = ±2.0) and a combined increase of 41.2 runs created. When calculated in relation to the prevailing conference statistics using Bill James's Pythagorean Theorem of Baseball, this led to an estimated 4–5 extra games won over the 54-game season. In a similar, yet unpublished, study (Deveau et al., 2016), Ultimeyes® training was evaluated on pitching performance, revealing significant improvements in pitching statistics including earned run average, walks, and hits per inning pitched for those who engaged in training compared to league-wide performance from the previous two seasons. Taken together these studies provide promising evidence that perceptual learning approaches can be used to improve sports-specific visual abilities, leading to better on-field performance.

2.1.2. GlassesOff and the CP3 application

Vision is inherently a spatial sense with lateral interactions underlying the neural processing that leads to visual perception. Based on the notion of 'collinear facilitation,' scientists have shown that it is possible to arrange stimuli such that weaker responses to subthreshold stimuli can be boosted by the placement of nearby suprathreshold stimuli. Further, by practicing detection and discrimination of these stimuli it is possible to improve visual acuity, contrast sensitivity and processing speeds in healthy (Sterkin, Yehezkel, & Polat, 2012), aging (Polat et al., 2012), and disordered eyes (Polat, 2009).

Based on this general platform of collinear facilitation, InnoVision Labs Inc. developed the GlassesOff mobile application aimed at improving visual function in a broad set of clinical and nonclinical domains. Of particular relevance to this review, in the first quarter of 2016, InnoVision Labs partnered with Chris Paul of the Los Angeles Clippers National Basketball Association (NBA) franchise to provide a sports-specific version of this application: the CP3 App (Take Your Sports Vision to the Next Level! n.d.). In this game, players identify flashing, near-threshold targets that vary in speed, size and contrast to progress through levels. The game tracks performance while providing feedback to users, giving them the opportunity to collect tokens that can be used to win prizes. A preliminary conference poster testing the prototype of this application with healthy nonathletes indicates improvements in a wide range of visual tasks and overall enhancement in visual processing speeds (Lev & Polat, 2015). As these individuals already had above-average vision, this research offers promise for improving sports-specific visual abilities in athletes.

2.2. Perceptual–cognitive training instruments

Because of the dynamic and challenging visual conditions under which athletes practice and compete, sports are commonly seen as a domain in which perceptual–cognitive skills are enhanced. As illustrated in a meta analysis of 42 studies investigating perceptual–cognitive abilities in athletes (Mann et al., 2007), athletic experts were roughly 35% faster and 31% more accurate in their decision making than their lesser skilled counterparts. These findings suggest that experts are better able to extract and interpret visual information facilitating anticipation and better on-field performance (Ericcson, 2003).

Given the strong evidence that perceptual–cognitive processes play an important role in sport performance, a number of different groups have developed training instruments that target aspects of sports-related cognition to improve athletic performance.

2.2.1. Cognisense NeuroTracker

Dynamic sports such as basketball, soccer and football involve the simultaneous movement and tracking of teammates and opponents alike. In these sports, athletes must correctly and efficiently extract the most important visual information to respond appropriately, usually when confronted with multiple choices and costly consequences. These abilities are critical to athletic success, and previous research has indicated that visual tracking skills are enhanced in expert athletes (Faubert, 2013; Romeas & Faubert, 2015; Zhang, Yan, & Yangang, 2009). Based on this notion that context-specific movement patterns are essential to sports, training programs that target multiple object tracking (MOT) abilities have recently been developed.

One such digital training program that has received considerable interest from athletes, trainers and sports science researchers alike is the CogniSense NeuroTracker (CogniSens, n.d.). This training platform entails an immersive three-dimensional MOT intervention with added dual-task functions to increase cognitive load. During this program participants view a virtual, 3-D volume space and are shown an initial set of identical yellow balls with a random subset of balls briefly illuminated at the start of a trial to indicate the objects to be tracked. Once this tracking set is established, all of the balls move simultaneously throughout the volume of the cube. At the conclusion of each trial (usually eight seconds) the balls freeze in place, and a number is displayed over each one. Participants are instructed to identify the balls that were originally illuminated as the tracking set at the beginning of that trial. The speed at which the balls move on the next trial is then adjusted according to a staircase procedure in which the speed is increased if all of the balls are correctly identified on the previous trial, and reduced otherwise. At the end of a block of trials, visual tracking speeds are calculated as the fastest speed at which the player could correctly identify the tracking set with 100% accuracy.

In a typical training program, participants start out sitting then progress to standing or performing sports-specific movements while at the same time tracking targets. Over time, the objects speed up, more targets are added, and the user is asked to perform more complex movements. Additional dual-task modes have also been added such that participants are asked to perform tracking while also simultaneously performing secondary tasks such as reacting to complex sports-specific elements (e.g., a quarterback reporting a defensive formation).

Research with the NeuroTracker system has entailed a number of studies carried out with groups including healthy young adults (Parsons et al., 2016), young adults with learning and attention difficulties (Parsons, Bates, & Faubert, 2013), healthy older adults (Legault, Allard, & Faubert, 2013; Legault & Faubert, 2012), and athletes across several sports and skill levels. In one such study (Faubert, 2013), groups of professional athletes, high-level amateur athletes, and nonathletes each performed 15 training sessions with NeuroTracker. As compared to the other two groups, the professional athletes began with higher scores and improved at a faster rate. Relative to the nonathlete group, the high-level amateur group started at a similar level, but improved at a faster rate. This experiment therefore demonstrates that NeuroTracker performance can effectively discriminate high-level from lower-level athletes and provides evidence that a brief training regimen with the program can produce improvements in this important sports-related ability.

Building on these findings, other studies have contributed preliminary evidence that NeuroTracker performance is correlated with actual game performance in professional basketball players (Mangine et al., 2014), and that training with this program can selectively transfer to improved small-sided game performance in university-level soccer players (Romeas, Guldner, & Faubert, 2016). To elaborate, Mangine and colleagues (2014) tested a sample of 12 professional NBA basketball players and found that motion speed thresholds measured in the preseason were correlated with a number of in-game statistics, including assists, steals and assist-to-turnover ratios during the following season. Other types of assessments such as reaction times and eye–hand coordination were not. While correlational in nature and stemming from a relatively small sample, this study provides preliminary evidence that MOT abilities are fundamental properties for optimal sports performance.

To assess the transferability of NeuroTracker training from a laboratory setting to a soccer field, Romeas et al. (2016) compared passing, dribbling, and shooting accuracy during small-sided games in university level soccer players. Experimental participants ($n = 9$) trained for 10 sessions on NeuroTracker, an active control group ($n = 7$) trained for 10 sessions with 3-D soccer videos, and a passive control group ($n = 7$) did not receive any training. Results from this study indicated that decision-making accuracy improved for passing, but not dribbling and shooting, between pre and posttraining sessions for the NeuroTracker group, compared to the control groups. This improvement was correlated with the players' subjective decision-making accuracy, rated through a visual analog scale questionnaire. Taken together, these results indicate that training exercise in the NeuroTracker protocol can selectively transfer to dynamic performance abilities important for sport performance.

2.2.2. Neurotrainer

The use of multiple object tracking has also been incorporated into a new device called NeuroTrainer (NeuroTrainer VR | Develop Mental Control and Cognitive Advantages. n.d.). In this training program, athletes are given a series of dual tasks that simultaneously challenge attention and peripheral vision. This training program includes tasks developed from visual training research in youth with low vision that has shown promise for improving vision in the far periphery persisting for 12 months (Nyquist, Lappin, Zhang, & Tadin, 2016). This battery includes a number of visual tasks such as MOT, visual discrimination, visual search, visual crowding and go/no-go. These tasks are often performed in parallel and presented in a virtual reality environment that requires the user to deploy resources to extremely large fields of view.

2.2.3. Brain training games

Brain training games have become ubiquitous in today's society. This big business includes a number of companies that have developed products targeting a range of individuals looking to use digital training approaches to sharpen their minds. Common applications include those tailored to older adults looking to enhance memory and to children with attention difficulties who might benefit from structured games that have the capacity to improve executive function. While the preponderance of these applications fall outside the realm of athletics, there is growing traction with athletes and teams using these games.

Brain HQ (Posit Science), for example, has partnered with TB12 (Tom Brady's training program, TB12, 2015) to promote a sports-specific cognitive training module (Brain Training that works, n.d.) that targets four areas of cognition: reaction time, useful field of view, visual processing speed, and multiple object tracking, with an assortment of brief digital training games. In a similar vein, CogMed is promoting the use of their working memory training modules for athletes (Cogmed Working Memory Training | Executives and Athletes, n.d.). Another recently developed digital training application that has been specifically tailored for athletes is HeadTrainer (Creative, n.d.). This application targets five areas of mental function – focus/concentration, visual–spatial awareness, decision making, memory, and processing speed – through games that are played for several minutes each day. Collectively, these digital brain-training games represent a new realm of SVT, and while there is considerable promise that these approaches might translate to better athletic performance, there is not yet any research evaluating the effectiveness of these techniques.

2.3. Visual–motor reaction training

Many sport situations require an athlete to quickly make motor responses to visual information. Thus, rapid and accurate visual and neuromuscular processing is a valuable skill for an athlete, and several instruments have been created to evaluate and improve visual–motor reaction speed. Wayne Saccadic Fixator (Follow us. n.d.), Dynavision D2^{TM} (International, n.d.), Vision Coach^{TM} (Vision Coach, n.d.), SVT^{TM} (Sports Vision, n.d.), Batak^{TM} (Welcome to the Official BATAK Website! n.d.), Sanet Vision Integrator (Channel Islands Design | Robert Gray | 805.382.4243 | www.cid.cc, n.d.), and FITLIGHT Trainer^{TM} (Speed & Agility Training | FitLight Trainer™ n.d.) are examples of commercially available instruments that feature programs for training visual–motor reaction times. These instruments each consist of a two-dimensional panel or setup with an array of illuminated 'buttons.' The athlete is required to press a randomly lit button as rapidly as possible; then, another button is lit in a random position on the instrument, with this cycle repeated for an established period. FITLIGHT^{TM} is unique in that it employs wireless LED powered lights that are controlled by a computer and can be flexibly placed at distances up to 50 yards from the controller, rather than embedded in a fixed board as is customary in other devices.

Typically, the athlete repeats a specific training program on the instrument in an attempt to improve their score. The instruments have programs in two primary modes: *Proaction* refers to a self-paced mode for a set period in which each light stays lit until the button is pressed, while *reaction* refers to an instrument-paced stimuli presentation in which each light stays lit for a preset amount of time before automatically switching to another light, whether the button is pressed or not. As performance improves, the speed of the reaction training programs is increased to keep the athlete working at the threshold of their ability. Previous research with these tools has varied considerably in scope and intent, with some devices compiling a number of peer-reviewed studies, while others have little-to-no available research. Further, a number of these devices have been used as benchmarks in studies assessing improvements from other interventions, rather than as interventions themselves.

The Wayne Saccadic Fixator was the first instrument to be marketed for use in training visual–motor reaction speed. While we can find no published studies testing this instrument as an effective training method, reference was made to a research presentation that found significant improvement in eye-hand reaction and response speed following 10-min training periods over 15 days (Coffee & Reichow, 1995). Further, this device was used as an assessment benchmark in SVT studies testing both athletes (Vanttinen, Blomqvist, Luhtanen, & Hakkinen, 2010) and nonathletes (Gallaway, Aimino, & Scheiman, 1986; Wood & Abernethy, 1997), indicating that it is viewed as a valuable measure of sports-specific abilities.

For the past two decades, Dynavision International has produced and sold light board systems that have gained use in the athletic, medical, and tactical communities. Two primary visual–motor training devices, the Dynavision 2000™ and the Dynavision D2™, have been used as part of SVT programs and concussion management protocols. Previous studies have demonstrated the test–retest reliabilities of these devices (Klavora, Gaskovski, & Forsyth, 1994, 1995; Wells et al., 2014) and have correlated performance on the Dynavision apparatus to other conventional psychomotor tasks (Vesia, Esposito, Prime, & Klavora, 2008).

Of relevance to the current review, several studies have utilized the Dynavision tools in SVT programs. In these studies, multiweek training programs included a number of training devices in addition to the Dynavision light boards. In a first study performed with collegiate baseball players, training sessions began six weeks prior to the season and occurred three times per week throughout the season. In conjunction with seven other SVT drills (Nike strobe glasses, saccade training, near–far training, rotary, tachistoscope, Brock string, Eyeport), a 1-min Dynavision program was completed twice each session. From this training it was found that batting averages, slugging percentage, and on-base percentage were all improved as compared to the previous season when no vision training was performed (Clark et al., 2012).

In a second study, members of this same research group evaluated the influence of a similar SVT program on concussion incidences in a collegiate football team (Clark, Graman, et al., 2015). This program was conducted during the two weeks of preseason camp for each of four years (2010–2013) and consisted of Dynavision D2™ training, Nike strobe glasses, and several other customized drills. Evaluation revealed that concussion incidences during these four years were reduced relative to the four years prior to the implementation of the training programs. Despite this possible benefit, no control group was included, and therefore it is not possible to discount secondary factors such as raised awareness of concussions or changed coaching philosophies accounting for the reduction in concussion incidences.

In a third study, the Dynavision device was used as part of a 6-week training study with youth field hockey players (Schwab & Memmert, 2012). In this study, Dynavision was used both as an assessment tool and as one of five training stations (along with Eyeport®, Hart charts, P-Rotator, and the Vision Performance Enhancement Program). While performance on the Dynavision assessment task and a functional field of view assessment task both improved compared to a control group, there was no difference in the MOT assessment (a transfer task). As such, this study shows evidence of specific learning, but does not provide support for transfer of this learning to other tasks or generalization to on-field performance. While these studies collectively provide evidence that programs utilizing the Dynavision tools produce some benefits, it is important to note that all of these studies also involved training with other activities, so the precise contribution of the Dynavision training has yet to be clearly determined.

Beyond the Wayne Saccadic Fixator and Dynavision lightboards, there are several other instruments on the market, including the Vision Coach™, SVT™, Batak™, and FITLIGHT™, and while there is evidence that many of these instruments are useful for evaluation of visual–motor performance (Zwierko, Florkiewicz, Fogtman, & Kszak-Krzyżanowska, 2014), there is scant research evidence regarding their efficacy as a training tool.

The instruments discussed in this section are most often used to train eye–hand reaction, but there are some instruments that provide a method to train eye–foot response. The HD Sensor Board developed by The Quick Board (QuickBoard - What the pros use, n.d.) consists of a rubber mat positioned on the ground with sensor pads in five locations. The mat is connected to a control device that provides visual stimulus and feedback information about the movement responses. Galpin, Li, Lohnes, and Schilling (2008) found that four weeks of training with the Quick Board produced significant improvements in foot speed, choice reaction and change-of-direction in moderately active adults. The FITLIGHT™ units can be configured similar to the Quick Board for this type of training as well as a host of other arrangements that can be tailored for certain kinematic skill development.

2.4. Integrated sensorimotor batteries

As described above, high-achieving athletes can be distinguished from nonathletes or lower achieving athletes on a diverse set of perceptual, cognitive and motor abilities. Reasonably, the most effective training approaches might attempt to train skills across a battery of tasks that capture this breadth of possible abilities. Based on this notion, computerized assessment and training devices, such as the Senaptec Sensory Station (Senaptec, n.d.), Sports Vision Performance from M&S® (Sports Vision Performance | M&S Technologies, n.d.) and Vizual Edge Performance Trainer® (Sports Vision Performance Training - Visual Fitness by Vizual Edge, n.d.), have been developed to measure and train a broad set of interrelated visual, cognitive and sensorimotor skills for the purpose of improving athletic outcomes.

The Senaptec Sensory Station is a successor to the Sensory Station device originally developed by Nike Inc. This digital assessment device is equipped with a battery of behavioral tasks that are administered with standardized instructions in about 30 min. The interactive battery includes 10 sensorimotor tasks (nine in the original Nike device with a MOT task added to the Senaptec device) that have been identified as important for sports performance (Erickson, 2012; Hitzeman & Beckerman, 1993). These tasks include visual clarity (akin to static visual acuity), contrast sensitivity, depth perception, and multiple object tracking, and tasks that rely on ocular–motor coordination such as near–far quickness, target capture (akin to dynamic visual acuity), perception span, eye–hand coordination, go/no-go and hand reaction/response times.

In addition to the behavioral tasks, descriptive questions are registered about the participant (name, date of birth, gender, age, height, hand/foot preference, etc.), their sporting groups and activities (level, primary/secondary sport, position), vision correction, and concussion history. Measurements of eye dominance (using the Miles Test) and the near point of binocular convergence are performed with brief manual assessments and entered into the report. Importantly, assessments acquired on this device are registered in a central database to provide feedback for each individual about their performance relative to both their athletic peer group and previous individual assessments.

Research with the Nike iteration of this device has demonstrated that certain tasks in the battery are reliable (Erickson et al., 2011; Gilrein, 2014) and cross-validated (Wang et al., 2015) measures that can be used to investigate sensorimotor abilities in relation to performance in athletic endeavors. For example, using logistic regression techniques, Poltavski and Biberdorff (2014) found that better performance on measures of dynamic visual acuity and visual motor control accounted for nearly 70% of the variability in goals scored over two seasons in a sample of 19 men's and 19 women's collegiate hockey players assessed over two seasons. Furthermore, worse performance on the Sensory Station has been associated with an increased likelihood of sustaining head impacts during practices and games for American collegiate football players (Harpham, Mihalik, Littleton, Frank, & Guskiewicz, 2014), indicating a link between collision avoidance and visual–motor skills and suggesting that this tool might be useful in proactively assessing concussion risk. Recently, it was also demonstrated in a sample of 28 recreationally active students that performance on the near–far quickness, eye–hand coordination, and go/no-go tasks correlated with King–Devick scores and other self-paced saccade tasks (Asken et al., 2016). This finding, therefore suggests links between established clinical tests that are sensitive to dysfunction following concussion and digital sports vision tools such as the Sensory Station, a topic we return to in Section 4, Takeaways and Future Directions.

In order to evaluate the influence of practice on this battery, Krasich and colleagues (Krasich et al., 2016) measured performance over 10 practice sessions spaced across three days. Significant learning was found in tasks with high visual–motor control demands, with up to 60% improvement in these abilities. The Sensory Station was also recently used as both a training tool and an evaluation benchmark in an applied program conducted by the University of Texas varsity softball team (Appelbaum et al., 2016). This intervention involved multiple weeks of SVT drills including practice with Strobe Eyewear, Marsden Balls, Brock Strings, and Near Far Charts, as well as the Depth Perception, Eye-Hand Coordination, and Go/No-Go tasks on the Sensory Station, which were completed in conjunction with typical softball activities. Results from 15 athletes who underwent SVT and 10 teammates who did not indicate significant relative improvements for the SVT group in three Sensory Station tasks (Near–Far Quickness, Target Capture, and Go/No-Go), although these did not relate to the number of drills practiced. Collectively, these studies suggest that the sensorimotor skills measured by the Sensory Stations may be directly related to athletic performance and that training programs targeting these skills may lead to more optimal performance outcomes.

The Vizual Edge Performance Trainer® (VEPT; Sports Vision Performance Training - Visual Fitness by Vizual Edge, n.d.) is a 3-D, computer-based visual skills training program designed to assess and train six visual skills: eye alignment, depth perception, convergence, divergence, visual recognition, and visual tracking. VEPT provides quantitative scores for each skill and a combined performance score for the complete battery. This battery can be completed on a tablet or computer in about 20 min with four of the exercises using 3-D glasses.

Previous research with the VEPT has evaluated this application as both an assessment tool and an intervention tool. For example, in evaluating Brazilian soccer players, Alves and colleagues (Alves, Spaniol, & Erichsen, 2015) found that while eye alignment, depth perception, convergence, divergence and visual recognition did not differ as a function of soccer experience, visual tracking was greatest for the most experienced athletes. In a presentation delivered at the National Strength and Conditioning Association annual conference, Spaniol and colleagues (Spaniol et al., 2014) observed that in a sample of 352 minor league baseball players, individuals who performed better on the VEPT convergence, divergence visual recognition and visual tracking tasks had better batting statistics in a number of measures including on-base percentages, slugging percentages, and strikeouts. While this research suggests that the VEPT has some sensitivity towards differentiating athletic achievement, other research has indicated this tool might be effective for training. For example, in a study presented by Spaniol and colleagues at the 2008 National Strength and Conditioning conference (Spaniol et al., 2008), D1 baseball players who trained with the VEPT for five weeks were able to hit balls pitched from a pitching machine at a higher velocity than control subjects who did not have training. It should be noted, however, that this study utilized a statistical threshold of $p < .1$, indicating that more research is needed to substantiate these findings. Other studies have found that VEPT training might benefit pitch recognition in baseball (Gilliam et al., 2010) and softball (Szymanski et al., 2011).

Sports Vision Performance by M&S® technologies provides a digital assessment of several visual factors similar to the previous instruments. Subscribers have the ability to compare performance to an established database of athletes, including visual acuity, contrast sensitivity, eye alignment, depth perception, fusional ability, and developmental eye movement. There is no research evidence regarding the reliability or validity of this system; however, many of these measures employ standard psychophysical protocols, so it is reasonable to expect reliability of the measurements.

3. Naturalistic sports training

Athletic training focuses on the transfer of learned skills from the practice field back to live game situations. A common hypothesis from the learning literature proposes that transfer occurs best if the training and transfer tasks engage highly overlapping cognitive processes (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008). While such a proposition is clearly important, there is a fundamental challenge in recreating the context, stress, and pressure of live game situations. As a result, one could argue that training situations that most closely resemble game situations might have the highest values in training practical athletic skills. It is this notion that underlies the importance of naturalistic sports vision training approaches.

In recent years, a number of important technological innovations have occurred that allow participants to practice actual or simulated sporting activities with altered or augmented visual information. These approaches attempt to replicate or perturb the natural performance context, allowing trainees to practice drills with the addition or removal of critical information. In the following sections, we describe three types of naturalistic training approaches: stroboscopic visual training, training that utilizes eye tracking to train gaze behavior, and simulations that recreate the sporting environment in virtual contexts.

3.1. Stroboscopic visual training

Sports place great demands on vision, and there is no doubt that athletic performance is better when an athlete has an uninterrupted flow of accurate and reliable visual information. While peak performance is usually reliant on optimal conditions, there is a long history of athletes purposefully training under suboptimal conditions. Quintessential examples such as altitude training for runners and drag suits for swimmers adhere to the notion that training under more difficult conditions will lead to better performance when athletes return to normal competition conditions. This 'resistance training' is fundamental to stroboscopic visual training.

Stroboscopic training has taken different forms (Figure 2), from the use of strobe lights in otherwise dark settings to digitally controlled eyewear that can be used in natural practice situations. The basic idea behind these approaches is that by intermittently disrupting vision, individuals are only allowed to see brief snapshots of their environment and therefore have to train under harder conditions than would otherwise be encountered. The underlying theory is that the stroboscopic effect 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.

In practice, the most common device used for stroboscopic athletic training has been the Nike Vapor Strobe® (Nike Inc., Beaverton, OR) eyewear, which uses battery-powered liquid crystal filtered lenses that alternate between transparent and opaque states and are under the control of the user through two side-mounted buttons. The strobe effect is defined by a 100-ms fixed-duration transparent state with complete visibility and a variable-duration opaque state consisting of a medium gray neutral density filter that reduces light transmission to the eyes. The opaque states can be changed through eight durations, ranging from 25-900 ms of visual occlusion. As such, the visible duration is constant, and difficulty is increased by lengthening the duration of the opaque state. While Nike has stopped producing and selling these devices, a new version has recently been released through Senaptec LLC (SENAPTEC STROBE, n.d.) that includes programmable control of the alternation sequence and a more opaque lens for use in higher light environments. Similar in design to the Nike and Senaptec eyewear, the Visionup Strobe glasses (Appreciate Co, Ltd. Kyoto Japan, Primary Shop – the specialty shop of Strobe Glasses Blinking LCD

Figure 2. Four types of stroboscopic training instruments: (a) Strobe light; (b) Senaptec Strobe eyewear; (c) VisionUp strobe glasses; (d) MJ Impulse eyewear. To view this figure in color, please visit the online version of this Journal.

lenses improve sport visions, visual skills, and athletic performances, n.d.) and the MJ Impulse eyewear (Impulse, n.d.) both also allow for flexible control of the transition frequency and dynamic control of the opaque/transparent duty ratio. All existing research that we were able to identify with these tools utilized the Nike Vapor Strobe® eyewear, with some studies addressing sensorimotor and others investigating potential improvements in sport performance.

In the realm of general visual perceptual learning, studies by Appelbaum and colleagues have compared psychometric performance on various visual–cognitive tasks for groups of individuals who underwent multiday sports training programs with the Nike Vapor Strobe® eyewear (e.g., varsity collegiate football, soccer, and basketball drills or throwing and catching drills), versus individuals who participated in the same training activities using identical eyewear with only transparent lenses. In the first of these studies (Appelbaum, Schroeder, Cain, & Mitroff, 2011), Strobe training participants produced significantly better posttest performance in measures of central visual field motion sensitivity and transient attention than the control participants. No differences were seen in measures of peripheral motion sensitivity or sustained MOT performance. Using a similar design, a second study from this group found improved short-term memory performance for the strobe group relative to that for controls, with this effect being maintained for at least 24 hours after training (Appelbaum, Cain, Schroeder, Darling, & Mitroff, 2012).

In an effort to understand the influence of stroboscopic training on anticipatory timing – the ability to predict where a moving stimulus will be at a specific point in time – Smith and Mitroff (2012) compared participants' performance before and after training using a Bassin Anticipation Timer. In this study, the intervention group practiced with the Bassin Timer while wearing the Nike Vapor Strobes® set to Level 3 (100 ms visible/150 ms opaque), while a control group practiced with normal vision. Posttraining assessments were administered immediately after training, 10 min after training, and 10 days after training. Results indicate that compared to the control group, the intervention group was significantly more accurate immediately after training, was more likely to respond early-than-late immediately after training and 10 min later, and was more consistent in their timing estimates immediately after training and 10 min later.

Dynamic visual acuity (DVA) is the ability to track a moving object while one's head is also in motion. This ability is critical in a multitude of different sports and as a part of his Masters thesis, Joshua Holliday tested the influence of strobe training on DVA (Holliday, 2013). In this study, DVA measured with the NeuroCom® inVision system and ball-catching abilities were compared in college football players at various points during and after a multiweek strobe training program. Results demonstrate that the strobe-trained group improved significantly relative to the controls at several of the assessment points right after training, but not at longer delays. Both groups had significant improvements in ball-catching performance. As such, this study indicates that while ball catching did not differ between the two groups, strobe training might be a practical tool for improving DVA. In a similar vein, Wilkins and Gray (Wilkins & Gray, 2015) tested the influence of strobe training on ball catching and two different visual perceptual tasks: a useful-field-of-view task and a motion-in-depth task. The intervention group trained with a variable strobe rate in which the off-time of the glasses was systematically increased and a constant strobe rate for which the glasses were always set at the shortest off-time (i.e., the easiest setting). In this study there were no significant differences between the groups in any of the measures, but the amount of improvement in the perceptual tasks correlated with improvements in ball catching.

While these studies provide some evidence for the benefits of stroboscopic training on visual–perceptual abilities, its influence on simple motor tasks is unclear. Other studies, however, have directly evaluated the influence of strobe training on sport performance. For example, in a pilot study comparing on-ice performance in a cohort of professional NHL hockey players, a two-week course of stroboscopic training during hockey drills was found to improve puck placement accuracy relative to the performance of individuals who did the same training without stroboscopic eyewear (Mitroff, Friesen, Bennett, Yoo, & Reichow, 2013). While this constituted an impressive 18% improvement, it should be noted that this study was conducted with a rather small sample size (11 total) and without any active control for the nonintervention group. In a separate in-season training study utilizing strobe eyewear in conjunction with other vision training methods it was found that batting averages, slugging percentage, and on-base percentage in university baseball players were improved as compared to the previous season when no vision training was performed (Clark et al., 2012, discussed also in Section 2.3). Similarly, stroboscopic training with batting and fielding drills, in combination with other training methods, led to improved sensorimotor performance on several tasks in the Sensory Station battery (Appelbaum et al., 2016, discussed also in Section 2.4).

In conclusion, there are a number of independent peer-reviewed studies indicating that stroboscopic training leads to enhancement in sensory and motor skills, with some evidence that these translate to on-field performance. Additionally, there have been propositions that strobe training might be a useful tool for lower extremity (e.g., anterior cruciate ligament, ACL) injury recovery (Grooms, Appelbaum, & Onate, 2015), suggesting roles for this intervention in both performance enhancement and rehabilitation.

3.2. Eye tracking and quiet eye (QE) training

In fast-paced activities like sports there is a premium placed on executing optimal eye movements, and the gaze patterns of expert athletes have become an important area of study in the field of sports vision. In particular, the advent of lightweight portable eye tracking technology has allowed for evaluation and feedback of eye movements in sporting activities that are carried out in natural settings. These systems typically consist of two cameras mounted on an eyeglass-type frame – one to monitor eye position and one to monitor the scene (point-of-view) with an external camera that is positioned to monitor motor performance characteristics. The data collected by the mobile eye tracker are then synchronized with elements of motor performance using software programs that can operate in real time.

Studies with such mobile eye trackers have typically found that experts have a lower number of fixations that occur for longer durations than do novices during the viewing of specific sport situations, especially when the subjects are required to move while gaze behaviors are recorded (Land, 2009; Wilson, Causer, & Vickers, 2015). Across a variety of aiming and interceptive tasks, experts typically demonstrate longer fixation durations before initiation of the motor performance. Similarly, these patterns are also found on successful relative to unsuccessful trials. This long-duration fixation that occurs just prior to motor response has been called the quiet eye (QE) period (Vickers, 1996) and is the basis for QE training. The exact neural mechanisms that direct gaze behavior during QE are still under investigation; however, it appears to show an advantageous period of cognitive processing allowing for computation of force, direction and velocity that guide and fine-tune the motor response (Vickers, 2016).

Quiet eye training typically involves the use of feedback to educate athletes about the importance of maintaining a longer QE duration (Wilson et al., 2015). Understanding the optimal visual search pattern, fixation location, attentional control, and onset of the QE fixation for specific sport tasks is a critical element of the training. In addition, training of attentional control is typically accomplished by developing a preperformance routine (Wilson & Richards, 2011).

Previous research provides support for QE training in several sport applications, with many studies reporting benefits that persist for days or weeks. For example, studies have found that QE training can improve accuracy in golf putting performance, even under simulated pressure (Moore, Vine, Cooke, Ring, & Wilson, 2012; Vickers, 2007; Vine, Moore, & Wilson, 2011; Vine & Wilson, 2010). In basketball, QE training has demonstrated improvements in free throw shooting percentage (Harle & Vickers, 2001; Vine & Wilson, 2011) and jump shot performance in game situations (Oudejans, Koedijker, Bleijendaal, & Bakker, 2005). QE training has resulted in improved accuracy and ability to cope with pressure when taking penalty kicks in soccer (Wood & Wilson, 2012). International-level skeet shooters demonstrated better shooting accuracy following three QE training sessions (Causer, Holmes, & Williams, 2011). Further, there is evidence that QE training has a positive effect on development of ball throwing and catching in children with typical development, and also those with developmental coordination disorder (Miles, Vine, Wood, Vickers, & Wilson, 2014). Collectively, these studies support the contention that the use of eye tracking technology can facilitate development of improved visuomotor behaviors and control of attention and anxiety under pressure.

There are several companies that market complete mobile eye tracking systems for use with sport applications, such as SensoMotoric Instruments (Sports, Professional Training, n.d.), Tobii Pro (Human Performance – Tobii Pro, n.d.) and Arrington Research (Arrington Research Eye Tracker, n.d.), but these systems tend to be quite expensive. There are also some recent eye tracking systems that are computer based rather than eyeglass based, such as RightEye (Home, n.d.), Tobii EyeX (Nilsson, 2016) and the Eye Tribe Tracker Pro (AFFORDABLE EYE TRACKING JUST GOT BETTER! n.d.), which offer more affordable options. These platforms, however, limit the natural environment applications of eyeglass-based systems and have not typically been used for sport-related research.

Collectively, there is abundant research utilizing mobile eye tracking to determine optimal visual search and fixation behavior in a variety of sports. This platform affords an objective means to provide feedback to athletes in natural training conditions to improve visual behaviors. Many aspects of performance can be trained using this paradigm, including the ability to cope with performance pressure.

3.3. Sports simulations and virtual reality platforms

Team practices have historically been viewed as the best approach to simulate actual game situations; however, these require athletes and coaches to collectively engage in drills that hold a high potential for injury. Over the past several years, computerized simulations and virtual reality (VR) platforms have gained substantial use as alternate means by which to simulate game action. Such simulation platforms allow for the design of complex training protocols, which can mimic real game activities, allowing athletes to gain 'mental repetitions' that mimic actual plays being run in the first person. Simulations can be customized to desired scenarios, such as plays derived from game footage, and can yield quantitative information about performance under pressure, with little to no risk of injury. As such, sports simulations and VR platforms have garnered increasing use in sports training and comprise the last class of digital tools addressed in this review.

In practice, the use of VR and related sports simulation technologies include off-the-shelf sports-themed computer games (e.g., Nintendo Wii and Microsoft Kinect for Xbox), customized academic research projects, and sports-related commercial systems. While the current review focuses on sports-specific applications primarily developed as standalone commercial systems, it is worth noting that off-the-shelf sports-themed computer games have played a pivotal role in the development and cost reduction of technology used in the commercial products. Further, the rapid growth of VR simulations in academic research has moved towards the validation of these training techniques for the learning of transferable skills in domains such as surgery (John, 2008) and navigation (Roupe, Bosch-Sijtsema, & Johansson, 2014). Other research has addressed the effectiveness of VR methods for introducing competitive anxiety and stress (Argelaguet Sanz, Multon, & Lécuyer, 2015; Wellner, Sigrist, von Zitzewitz, Wolf, & Riener, 2010), as well as learning of general physical skills (Bailenson et al., 2008). Academic research with customized applications has also started to evaluate the capacity to implement realistic sports-specific simulations of tennis (Xu et al., 2009), ping pong (Knorlein, Szekely, & Harders, 2007), billiards (Gourishankar, Srimathveeravalli, & Kesavadas, 2007), archery (Gobel, Geiger, Heinze, & Marinos, 2010), handball (Bolte et al., 2010), baseball (Fink, Foo, & Warren, 2009; Gray, 2002; Zaal & RJ, 2011), and rugby (Miles, Pop, Watt, Lawrence, & John, 2012).

For the purpose of this review, we focus on several emerging commercial applications that have gained substantial traction as sports-specific training tools. These applications have received notable coverage in the popular media including features on major media outlets such as ESPN, CBS, Sports Illustrated, CNN, and Fox Sports, among other venues. Three companies in particular, Eon Sports VR, StriVR Labs, and Axon Sports, have recently developed suites of digital training simulations that are marketed towards athletes, coaches and trainers. While these tools and products are rapidly evolving to include new sports, new modules, and new technologies, we briefly highlight a few of the core tools and capabilities currently available from these companies.

Eon Sports VR (n.d.) offers simulations for both baseball and football that function in real time, include live action video capture, and allow for flexible programming so that users can customize plays to be simulated or can utilize a host of preprogrammed options. Recently, Eon Sports began using rotoscoped video footage (a form of video editing that allows a 2-D image from a video to be incorporated into a virtual reality simulation) into their baseball software, allowing hitters to see the exact motion of opposing pitchers to gain mental repetitions before games. Members of the Eon Sports VR development team recently conducted a user study with 17 football players ranging in age from 7th grade to college (Huang, Churches, & Reilly, 2015). Over a 3-day period, these athletes performed multiple repetitions on the SIDEKIQ™ football simulation, making presnap reads to identify the optimal receiver to throw the ball to on each play. Over the course of the evaluation, individuals improved in their ability to make the correct passing decision by an average of 30% while also reporting subjective enjoyment and ease in performing the simulations. Though this case study did not address important questions about transfer to actual game performance, it does reflect a preliminary step towards validation of these tools.

StriVR Labs (STRIVR | Immersive Training Solutions, n.d.) has developed a series of VR sports simulations that include applications for football, basketball, baseball, and hockey. These simulations utilize head mounted displays and incorporate real film footage, recorded in 360°, with actual audio from teammates and coaches. This immersive, multisensory platform allows players to relive practice from inside a virtual reality headset and to study the experience from the same vantage point from which they play.

Axon Sport (THE LEADER IN ATHLETIC COGNITIVE TRAINING. n.d.) has partnered with a number of US and international training facilities to implement both baseball and football simulations. These simulations are presented on large 2-D flat panel displays, and do not incorporate VR technology, but do add elements of cognitive assessment that allow for evaluation and training of core component skills. This so-called 'digital skills training' is tailored to athletes for their specific sport and position to provide modules that are directly relevant for the sporting activities that they engage in.

In addition to these broad commercial platforms that have applications for many different sports, there is a growing number of products that target specific individual sports. For example, Zwift (Zwift, n.d.), ErgVideo (ErgVideo™ Virtual Reality Cycling. Indoor Cycling Videos for Power-based training for cyclists and triathletes, n.d.), Widerun (Widerun, n.d.), CycleOps (Indoor Bike Trainers, Rollers and Indoor Cycles, n.d.), Bkool (Bkool Indoor, n.d.) and Virzoom (VirZOOM, n.d.) have each developed VR cycling programs that can be used in conjunction with indoor cycles or bike stands to create virtual training routes. For soccer training, Beyond Sports (Beyond Sports. n.d.) has developed a VR simulation that can be used to create custom training scenarios in consultation with individual clubs, allowing athletes to learn tactical concepts of a specific team or coach. Visual Sports (Visual Sports Systems, n.d.) offers a number of golf training simulators, such as the SwingTrack™, which includes high-speed cameras to capture and analyze club motion and ball flight. This system utilizes GPS data to render a selection of actual golf courses, while also allowing for simulations in different weather conditions and at different times of day. Finally, for runners, RunVirtual360 (Runvirtual, n.d.) has developed VR training for distance runners that uses 360° video capture to provide trainees with immersive experiences of actual racecourses that can be viewed to prepare a runner for the terrain that they will encounter during competition. Outside Interactive (Home – Outside-interactive, n.d.) has come up with a filming apparatus that films 2-D simulations of courses during races and is designed to help runners train for the next year's race.

Collectively, these sports simulations allow users to practice in realistic contexts without the need to gather a large number of players and coaches for on-field practice, and without the potential exposure to inclement weather or physical injury. These simulations permit athletes to efficiently experience a large number of repetitions that do not count against regulations that limit the number or duration of on-field practices. It is important to note, however, that sports simulations are a new technology with relatively little supporting evidence. While previous sections of this review article provide more instances of research speaking to the effectiveness of other techniques, there are currently very few studies that have evaluated the capacity of simulations to improve performance. Therefore, further research is needed to determine the true value of these programs. Lastly, while the cost of head mounted displays has dropped substantially, with prices ranging from under $100 to several hundred dollars, larger projection displays and more immersive CAVE-like environments can cost several thousands to tens of thousands of dollars. As such, it is important to weigh these limitations in the evaluation of simulation technologies.

4. Takeaways and future directions

The current review has highlighted a number of contemporary tools and techniques that comprise the current landscape of SVT approaches. Throughout this review we have tried to highlight existing research, particularly independent peer-reviewed studies that speak to the strengths and limitations of the various approaches. In many cases, however, there is paucity of research, and in these instances such limitations have been noted. Sports vision training is a rapidly evolving field, and it is likely that some relevant techniques and tools were not included here. Nonetheless, the current review offers a broad view of the types of approaches and many specific instances of tools and products that are available to train vision and cognition for the purpose of improving sporting proficiency.

As noted in several places, SVT techniques have also gained traction as a means to assess and rehabilitate sports-related concussions. There is ample evidence that in addition to reduced visual processing speeds (Fimreite, Ciuffreda, & Yadav, 2015), concussions lead to binocular vision deficits, oculomotor dysfunctions, and visual field deficits (Suchoff, Kapoor, Waxman, & Ference, 1999). Vision therapy, and by extension SVT approaches that addresses the component skill deficits, may therefore provide important therapeutic benefits as part of a comprehensive multidisciplinary approach to manage concussion. For example, previous research has supported the application of vision therapy to treat deficits in component vision skills (CITT, 2008; Ciuffreda, 2002), and there are some studies that demonstrate that vision therapy can improve outcomes in postconcussion vision disorders (Clark, Colosimo, et al., 2015; Gallaway, Scheiman, & Mitchell, 2016). As such, prospective clinical trials that assess the natural history of concussion-related vision disorders, and intervention studies designed to determine specific aspects of treatment efficacy, are needed to better understand the role of vision in sport-related concussion. Future research with the digital SVT tools described in this review paper may therefore pave the way for the increased application of vision treatments to mitigate the sequelae of deficits resulting from concussions.

Given the scope of this article there are a number of domains related to SVT that were not included, such as the use of biofeedback or neurofeedback (Moss & Werthner, 2015), sleep monitoring (e.g., SenseLabs | The Leading Innovator in Brain Training, n.d.), and brain stimulation (e.g., Halo Neuroscience, n.d.) to improve sports performance. Further, new innovations are constantly arising, and the landscape of SVT approaches will undoubtedly change in the coming years. It is therefore exciting to consider the possibilities that lie on the horizon. In the future, continued research will be necessary to establish the capacity of SVT approaches to train sports-relevant abilities and for these enhanced abilities to translate to improved performance on the field.

Note

1. Though it is beyond the scope of this article to discuss all of the historical approaches to SVT, the reader may wish to see Ciuffreda and Wang (2004) for an elaborated review of the training of component visual skills for sports, as well as West and Bressan (1996), Hopwood, Mann, Farrow, and Nielsen (2011), Jenerou, Morgan, and Buckingham (2015), and Schwab and Memmert (2012) for more examples of SVT intervention studies.

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