

Stroboscopic Visual Training for Coaching Practitioners: A Comprehensive Literature Review

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ABSTRACT

Background: The importance of vision and its impact upon an athlete's performance has long been recognized by elite athletic communities. In recent decades, stroboscopic training methods have been developed to help train athletes from a visual, perceptual, and cognitive perspective using strobe glasses. **Objective:** Herein a comprehensive literature review was conducted to investigate the effectiveness of strobe glasses in training collegiate and professional athletes. **Methods:** This comprehensive literature review investigates the origins, attention influences, tasks, practitioner takeaways, and cost feasibility of stroboscopic visual training. **Results:** The findings from this review show promise of benefits from utilizing strobe glasses during training scenarios, particularly for improving fast or impulsive tasks. Strobe glasses can be accommodated into varying sporting environments and training regimens while being affordable to athletic, coaching, and training departments or centers. Studies investigating the direct influence of stroboscopic training on subsequent performance demonstrate viable methods for strengthening fundamental visual abilities. Notably, these fundamental abilities have been shown to correlate with improved game performance. Though early results are promising, there are still significant areas for further research and more comprehensive designs of stroboscopic training studies. **Conclusion:** This review highlights potential benefits and existing research gaps concerning the use of stroboscopic eyewear as an intervention method in sports. The delineation of optimal applications for strobe glasses is undetermined; however, information presented in this review can be meaningfully applied by coaching practitioners who are considering adopting the technology.

Key words: Stroboscopy, Motion Perception, Cognition, Motor Skills, Vision, Memory

INTRODUCTION

Stroboscopic visual training (SVT) is best defined by Wilkins et al. in that it "is the practice of placing individuals under conditions of intermittent vision, often using specialized eyewear, in an attempt to enhance visual and perceptual skills" (Wilkins, Nelson, & Tweddle, 2018). In theory, these visual improvements brought about by SVT will transfer to improved motor performance, especially from a sporting task perspective (Wilkins et al., 2018). Stroboscopic training has been utilized to study visual, cognitive, and perceptual

skills for almost 30 years, and researchers have examined the importance of eyes and vision with respect to sports since as early as the 1960's (Erickson, 2018; Wilkins & Appelbaum, 2020). Early stroboscopic research focused on visually guided locomotion and understanding visual integration with little attention paid to athletic applications (Elliott, 1990). Furthermore, training devices were immobile or not practical for use outside of an experimental setting (Wilkins & Appelbaum, 2020). A shift in the types of approaches implemented for vision training has occurred over the past decade

due to advancements in understanding of functions of the visual system, allowing more discrete and rich learning (Appelbaum & Erickson, 2018). More recent research continues to be divided on the lasting benefits of such training (Appelbaum & Erickson, 2018).

Appelbaum & Erickson (2018) completed a review that covers more of the recent approaches to digital training exercises for sports vision training. As part of that review, Appelbaum and Erickson developed a framework to split the many variations of digital sports vision training techniques into two main groups, *component skill training* and *naturalistic training*, with subgroups under each. Component skill training focuses on the fundamental processes needed to complete a task, with the idea being that as each sub task improves, the trainee's ability to complete the overall task will improve as well. Naturalistic training has a more holistic focus rather than breaking larger tasks down into the elemental skill components. For more details regarding the specific training techniques for component or naturalistic trainings, see Appelbaum & Erickson (2018). Beyond grouping training techniques by component level training or naturalistic methods, research further indicates the need to define the appropriate training for each sport and each position within the sport (Wilkins & Gray, 2015).

The aim of strobe glasses technology is to provide an athlete or coach with a tool that can be used in a natural training environment to "enhance an athlete's visual, perceptual, and cognitive skills" (Wilkins & Appelbaum, 2020). Strobe glasses work by quickly transitioning between transparent to opaque to limit the user's vision, forcing the wearer to become more efficient in processing the limited images they see. The level and duration of opacity as well as the transition speed can be adjusted to increase the level of difficulty as training progresses and the wearer becomes more accustomed to limited vision.

Research indicates that training with reduced vision through the use of strobe glasses can result in improved task performance (Appelbaum, Schroeder, Cain, & Mitroff, 2011; Holliday, 2013; Wilkins & Gray, 2015). Wilkins & Appelbaum (2020) theorize that training with strobe glasses has been linked to some positive outcomes, namely (1) increased attention vigilance, (2) forced attention to external objects, (3) increased ability to extrapolate trajectories and speed of moving objects when performing catching or hitting skills, and (4) increased perception. Users also note that tasks feel easier when the strobe glasses are removed after having used the strobe glasses for training (Wilkins & Appelbaum, 2020).

The purpose of this comprehensive review is to identify all previously peer-reviewed research regarding the study of stroboscopic training using strobe glasses as applied to training athletes at all sporting levels with a focus on National Collegiate Athlete Association (NCAA) Division 1 and professional sports. The review aims to inform practitioners in their use or consideration of stroboscopic glasses. Strength and conditioning coach practitioners at the collegiate and professional levels across numerous sports were included in this study as coauthors to provide guidance during the literature search as well as to present an autoethnographic

frame of strobe glasses application during athlete training regimens.

METHODS

Study Design

To begin this study, the authors partnered with strength and conditioning coaches from multiple collegiate and professional basketball teams to gain a comprehensive understanding for how strobe glasses can be used in a sports context. These training and information sharing sessions helped guide the research team's establishment of five questions that would be used to guide the literature search for academic work relevant to the topic of strobe glasses usage in sports training. The five research questions the team developed were:

- (Q1) What are the origins of stroboscopic training and how effective were historical methods?
- (Q2) Do strobe glasses influence focused attention, and if so, what is the effect?
- (Q3) What types of tasks can stroboscopic training be used for, and what value does it add to those tasks?
- (Q4) What could coach practitioners looking to use this technology take away from existing studies and literature?
- (Q5) Is the technology used for stroboscopic training practical and affordable for athletics organizations?

Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 research methodology, and guided by these five research questions, a systematic literature review was conducted. Searching a variety of terms, including strobe glasses, athletics-focused attentiveness, focused attention, cognitive training, eye-hand coordination, skill acquisition, sport vision training, and stroboscopic visual training resulted in the discovery of 16 studies include in this research. Once these studies had been identified, the team proceeded with qualitative analysis of the body of work and drew conclusions based on this analysis. Recommendations for future work were also developed and provided end of the study.

Literature Search

The team generated search terms utilizing brainstorming discussions based on insights from the practitioner information sharing sessions. A comprehensive list of key terms regarding stroboscopic visual training was compiled with terms being separated based on their application to each research question. The researchers concluded that information concerning Question 5 would be derived from research into the other study questions as well as through research into the different prices and varieties of stroboscopic training tools from non-peer-reviewed related sources. Minimal research has been completed through studies of any kind to address this question, and therefore the team decided against the use of key words. A literature search was subsequently conducted for digitally available resources. Key terms included in the EBSCO and Google Scholar database search are presented in Table 1.

Table 1. Key terms used in EBSCO and Google Scholar literature search

Question 1
“strobe glasses; cognitive training”
“strobe glasses; eye hand coordination”
“strobe glasses; skill acquisition”
“strobe glasses; sports vision training”
“stroboscopic visual training; information; basketball”
Question 2
“strobe glasses; cognitive training”
“strobe glasses; eye hand coordination”
“strobe glasses; skill acquisition”
“strobe glasses; sports vision training”
“strobe glasses; stroboscopic visual training”
Question 3
“stroboscopic training NOT voice”
“stroboscopic training NOT vocal”
Question 4
“stroboscopic; sports training”
“strobe glasses; skill acquisition”
“stroboscopic visual training; information encoding”
“strobe glasses; sports vision training”

The literature search was conducted from September 2020 through October 2020 via the EBSCO and Google Scholar databases as primary sources. The EBSCO is a search engine available through Academic Libraries and is available at most research institutions. This search engine enables researchers to search all academic literature-based databases using keywords. EBSCO includes Google Scholar, IEEE, and PubMed allowing with 536 other, commonly known as well as lesser used databases. Utilization of EBSCO ensures exclusion of predatory journals and inclusion of most scholarly research. Mendeley resource management software was used to house, organize, and allow all team members access and review all articles. The resources found through the literature search mostly consisted of peer-reviewed articles published between the years 2002-2020.

Data Extraction and Analysis

The PRISMA method was utilized for discovering relevant literature in the stroboscopic eyewear domain investigated for this study. Based on the research questions, retrieved literature was evaluated with respect to relevance and standardized inclusion and exclusion criteria to maintain a consistent process. Search results were chosen upon fulfillment of the following requirements:

1. Full-text article available.
3. Available in English
4. Found in a peer-reviewed source.
5. Not an exact duplicate.
6. Fit within the context of the research questions:
 - a. Stroboscopic training origins
 - b. Assessment of stroboscopic eyewear on focused attention
 - c. Application of stroboscopic training and added value to users/organizations

- d. Limitations of available stroboscopic eyewear
- e. Discussion of practitioner considerations for adoption of stroboscopic eyewear.

Upon reviewing the literature, anecdotal and empirical assessments of stroboscopic eyewear utilized for improving athlete performance were identified and evaluated. An examination of the technology based on the research questions was conducted. Figure 1 shows the literature review process and notes how many articles were found and excluded during the process such that findings from this study can be replicated and future studies can expand upon this review as more stroboscopic technologies and evaluations become available.

RESULTS

Study Selection

The literature search revealed 410 articles, identified through EBSCO and Google Scholar as primary databases, to meet the aim of the project. 321 articles were initially excluded according to the defined exclusion criteria; that is, the articles were written in a non-English language, were published in a non-peer-reviewed journal, were duplicates, had an unavailable full text, or did not address the five research questions as they were not sports related and/or did not make a clear statement on the influence the technology had on the wearer. The remaining 89 articles were assessed for relevance according to Eligibility Criteria 1-5, and a total of 16 articles were identified as suitable given the context of the research questions. The inclusion/exclusion process is described in Figure 1. The 16 articles were subsequently assessed for alignment to one or multiple research questions. Of the 16 identified articles, four contained information concerning the historical use and effectiveness of stroboscopic eyewear (Q1). Eight fully or partially answered the influence of strobe glasses on focused attention (Q2). All sixteen articles described tasks in which stroboscopic lenses may be worn (Q3). Fourteen contained relevant information for coaching practitioners considering adoption of the technology (Q4). In the subsequent sections of this review, research of particular importance or notability is reviewed in detail. Finally, a summary of financial information common to many collegiate athletic programs is presented for discussion about practicality and affordability.

Synthesis of Results

Q1: What are the origins of stroboscopic training and how effective were historical methods?

Sports vision training has been a subject of research as early as the 1960's when famed Cleveland Browns coach, Blanton Collier, recognized the importance of the eyes and vision with respect to sports (Erickson, 2018). Michael Jordan of the Chicago Bulls is credited with being one of the first athletes to incorporate strobe glasses into a training regimen (Haberstroh, 2017). In the 1990's during Jordan's zenith, strobe lights had been installed in the ceilings of most NBA stadiums for photographers to get better images so Jordan wanted strobe lights installed in his practice gyms, allowing him to replicate the game environment for his practices

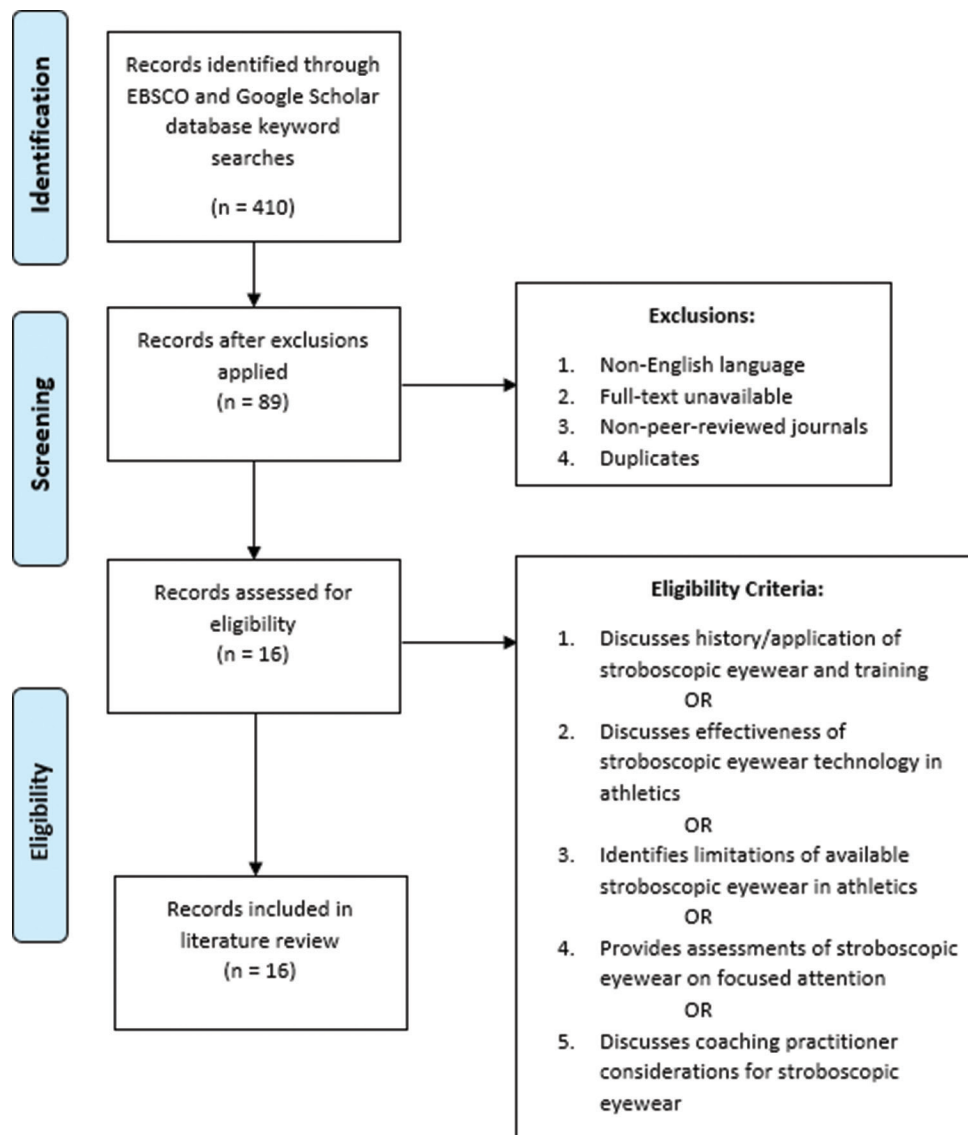


Figure 1. PRISMA diagram representing article selection flow

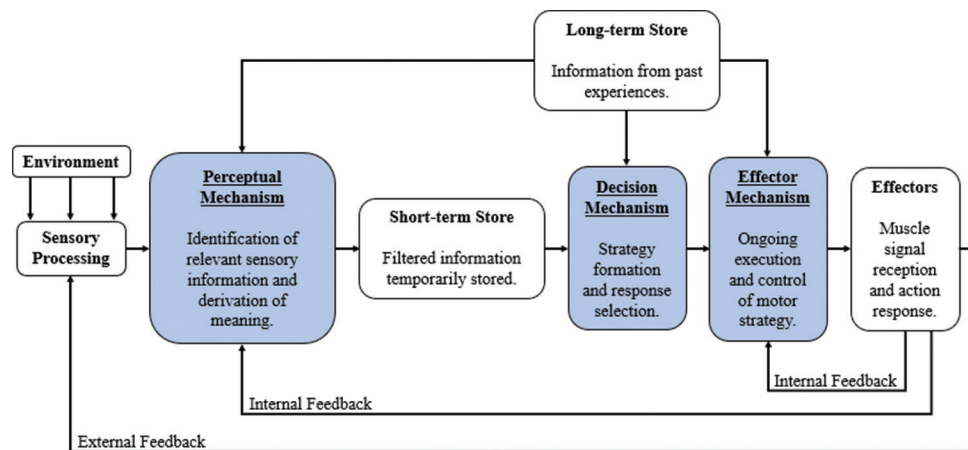


Figure 2. Modified Welford's Processing Model. (Recreated from Erickson, 2018)

(Haberstroh, 2017). Jordan's trainer, Tim Grover, eventually found the Strobe Spex glasses that could be worn during training. By the late 1990's the Strobe Spex were discontinued, but other companies, namely Nike, Vima, Senaptec, and

Sensory Performance technology, recognized the opportunity to jump into the market and each created their own versions of strobe glasses geared towards various sports training activities (Haberstroh, 2017)

Many of the early methods of visual training focused on the fitness of the eye and consisted of drills to strengthen eye muscles (Appelbaum & Erickson, 2018). These methods were mostly analog, used tethered devices, and were not focused on usage in the sports world (Wilkins & Appelbaum, 2020). According to Appelbaum and Erickson (2018), the effects of the interventions were also inconsistent.

Q2: Do strobe glasses influence focused attention, and if so, what is the effect?

In general, stroboscopic visual training (SVT) appears to be applicable to the improvement of tasks which are fast or impulsive and occur in the foveal field of vision, and not those which require extended periods of vigilance or occur in the peripheral vision (Wilkins & Appelbaum, 2020). Based on this finding in previous research, inclusion criteria for studies that demonstrate (or do not demonstrate) efficacy of strobe glasses will be centered around sport and/or drill performance rather than focused attention. In addition to spatial vision assessments, several studies are reviewed herein that have sought to evaluate the influence of stroboscopic training on a variety of other vision factors, including visual acuity, visual information-retention, and reaction time.

In a study conducted by Holliday (2013), 16 NCAA football athletes participated in several catching drills over a period of two weeks. Half of the players performed the drills while wearing strobe glasses, while the rest of athletes practiced as normal. Over the two-week period, each athlete's catching success rate and visual acuity were evaluated. Visual acuity refers to the ability of a person to extract information from a moving object. Results showed that practicing with strobe glasses improved athletes' dynamic visual acuity, extracting object information while oneself moving. The research also highlighted a positive correlation between the level of dynamic visual acuity and catching success rate during practice.

Wilkins & Gray (2015) conducted a similar study to Holliday (2013) by using tennis ball catching drills as the mechanism of training. However, the goal of the study was to investigate the effectiveness of varying strobe patterns, rather than comparison to a control group. Usable field of view (UFOV) and motion in depth sensitivity (MIDS) were used to evaluate strobe pattern effectiveness. Wilkins & Gray (2015) showed that improvement of UFOV and MIDS correlate positively with improved catching performance.

In Appelbaum et al. (2012), the effect of strobe glasses on visual information-retention ability was investigated. Participants were asked to complete a series of visual memory-training exercises with and without strobe glasses. The group wearing strobe glasses showed greater performance improvement than the control group. Some participants were retested after a 24-hour period to determine whether the enhancement caused by the training was persistent or simply a temporary effect. Results showed that the training benefits can translate to other visual activities and the effects persist for at least one day.

Research performed by Appelbaum et al. (2011) in a different study aimed to determine properties of certain tasks

make them responsive to SVT. As previously discussed, tasks which are fast, impulsive, and occur in the foveal field of vision have been shown to be improved by SVT. These results show that peripheral motion tracking and visual memory do not see any significant improvement from training with stroboscopic training. Additionally, the researchers saw no significant improvement in sustained attention or vigilance tasks because of SVT.

Mitroff et al. (2013) designed an experiment to study whether SVT with strobe glasses translated to significant performance improvement when playing the sport. Eleven professional ice hockey players of varying defensive and offensive positions were recruited and assigned to either a control or an experimental group. The athletes participated in the same practice exercises over a 16-day period; practice activities consisted primarily of shooting and defensive drills and scrimmage. At the end of the training period, the athletes who practiced with strobe glasses showed improved shooting/blocking performance by 18%, while the athletes who did not wear strobe glasses saw no change.

Finally, Hülzdünker et al. (2019) studied elite German badminton athletes in a similar experiment to Mitroff et al. (2013) where both research teams reported a significant performance increase in the experimental group of players after a 4-week training period. The athletes who trained with strobe glasses were able to block incoming shots more effectively and react more quickly to the situation than the control group.

The results and scope of these studies in terms of sport, task, field of vision, and sporting improvement are summarized in Table 5 in Section 4.1.

Q3: What types of tasks can stroboscopic training be used for, and what value does it add to those tasks?

Visual abilities can be enhanced through training, but to what extent utilizing stroboscopic eyewear as an intervention method is difficult to conclude. Ambiguous empirical evidence concerning the effects of stroboscopic visual training can be attributed to stroboscopic tools recently becoming available to a wider margin of users but is largely due to difficulties surrounding study and experiment methodologies in applied contexts (Wilkins & Appelbaum, 2020). Indeed, SVT interventions can be implemented across a wide variety of contexts, and extant literature reflects this variability—sports played across studies vary considerably, along with athlete populations and training/testing protocols (Wilkins & Appelbaum, 2020). Though stroboscopic visual training can be easily adapted to different sports, findings suggest that SVT does not improve all aspects on visual attention and perception (Appelbaum et al., 2011). As stated earlier in this review, studies suggest SVT can increase dynamic visual acuity as well as fast, foveal vision, or skills which require interpretation of information in the central field of vision (Wilkins et al., 2018). Skills relying on more peripheral vision or sustained visual attention have not seen much benefit across literature (Wilkins & Appelbaum, 2020).

A primary advantage of SVT compared to other visual training tools is its easy adaptability to natural contexts.

While wearing glasses, athletes can practice within their specific domain while practicing their sports-specific task whereas with other tools athletes may have to train elsewhere (Wilkins & Appelbaum, 2020). This capability is particularly important since practice benefits depend upon the similarities in practice and later-game context (Henry, 1958). There is a link between practicing and performing in conditions with many elemental overlaps. Since SVT can organically fit into many training methods, athletes can take advantage of the opportunity to maximize near-transfer learning, or transfer between very similar contexts (Perkins & Solomon, 1992; Wilkins & Appelbaum, 2020). However, due to the high variability of training regimes to which SVT can be adapted, no standard practices for implementation have been delineated. As such, protocols vary between and within interventions. Wilkins & Appelbaum (2020) point out three main aspects of studies where variability is present: (1) training length across intervention and by session, (2) exact activities performed, and (3) frequency of strobe rate applied. More recent literature does not elucidate a protocol. One study suggests that training benefits can be realized through interruption of visual input alone regardless of whether that interruption is constant (e.g., a set frequency of the strobe rate) or variable (Wilkins & Gray, 2015).

Q4: What could coach practitioners looking to use this technology take away from existing studies and literature?

Sports vision training interventions lack homogeneity across the literature, but Abernethy and Wood (2001) identified three key assumptions from which a general philosophy concerning sport vision training stems. They stated that (1) certain “aspects of vision are important for particular sports,” (2) “these aspects can be modified through training,” and (3) “improvements in visual abilities can translate into improvements in on-field performance” (Abernethy & Wood, 2001; Appelbaum & Erickson, 2018). Vastly different visual skills are necessary for different sports and/or positions. Demands are quite variable across the broad array of sports, and visual and cognitive development depend on these demands. Erickson (2018) cites stereopsis, the perception of depth produced by the brain’s reception of visual stimuli from both eyes, as an example of a vision factor important to many sports but not as essential to other sports like shooting, which intend the use of one eye (Howard & Rogers, 1995). There is therefore a need for a visual task analysis for sport and sport position to help determine where enhancement of visual factors may provide the most benefit. An effective analysis ends with sports vision training approaches following accordingly (Erickson, 2018).

Literature across multiple sporting domains demonstrates the enhanced visual-perceptual and visual-cognitive abilities of elite athletes compared to lower achieving or non-athletes (Appelbaum & Erickson, 2018). These abilities translate to on-field performance, but performance is largely reflective of the specific roles that an athlete plays since the role demands vary so widely. For example, athletes who participate in interceptive sports like cricket, hockey, and tennis require better response times but not response accuracy. This may

derive from inherent temporal constraints imposed by hitting, catching, and intercepting. Further, sports like ice hockey necessitate a greater horizontal attention (to look across the rink) than a sport like volleyball which requires more vertical attention. Two separate sports literature meta-analyses additionally provide information concluding that more successful athletes are better at detecting perceptual cues and are more efficient with their eye movements when compared to non-athletes (Appelbaum & Erickson, 2018; Erickson, 2018). These apparent expert visual qualities bolster the argument for task analysis when implementing visual training in sports and provide some support that better athletic outcomes can result from an enhancement of visual skills (Appelbaum & Erickson, 2018).

Erickson (2018) helpfully classifies assessment areas to more fully understand how factors can affect performance using a modified version of Welford’s Processing Model (Figure 2) that incorporates vision factors.

Using the model, an example of vision factor classification into relevant mechanisms is presented:

1. “Perceptual mechanism
 - a. Visual acuity
 - b. Contrast sensitivity
 - c. Dynamic visual acuity
 - d. Ocular alignment
 - e. Stereopsis
 - f. Accommodative function
 - g. Vergence function
 - h. Oculomotor function
 - i. Peripheral vision.
2. Decision mechanism
 - a. Speed or span of recognition
 - b. Visual attention or visualization
 - c. Multiple object tracking.
3. Effector mechanism
 - a. Visual motor reaction speed (eye-hand, eye-foot)
 - b. Vision and balance
 - c. Peripheral vision response speed
 - d. Coincidence-anticipation” (Erickson, 2018; Welford, 1960).

Two studies reference user perception of stroboscopic eyewear. In a study with elite youth soccer players, Wilkins et al. (2018) found three themes from interview data concerning players who wore stroboscopic glasses: (1) players perceived SVT to improve their visual and perceptual skills, notably “reactions”, “judgement”, and “focus”, (2) players believed that SVT improved on-field goalkeeping performance, and (3) players found SVT to be both effortful and enjoyable. Wilkins & Gray (2015), in a study with non-athletes, discovered via unstructured interviews that participants found SVT to be “highly enjoyable and motivating.”

Q5: Is the technology used for stroboscopic training practical and affordable for athletics organizations?

In an effort to gauge the affordability of strobe glasses for NCAA athletic programs, an American Institute for Research study into the average spending for NCAA Division 1 athletic departments was used (Desrochers, 2013). In

Table 2, data from the study shows the median spending per athlete, as well as the amount allocated towards facilities and equipment spending.

Research was also conducted into the pricing of some of the common strobe glasses currently on the market. Table 3 shows some of these glasses and their respective prices.

Table 4 describes the percent of the per athlete budget for each of the different pairs of strobe glasses.

As the data shows, the percent of the equipment budget a pair of strobe glasses would consume varies across Division 1 athletic departments, from 0.9% to 10.5%, which depends on both the price of the glasses as well as the funds available.

The work done by the American Institute for Research helps shed light on the financial feasibility of strobe glasses for Division 1 athletic programs (Desrochers, 2013). As shown in Table 4, the percentage of the equipment budget for a student athlete that a pair of strobe glasses would consume varies, depending on the size of the athletic department as well as the pair of strobe glasses that is purchased (Desrochers, 2013). The decision lies with an athletic department to decide what it is capable of spending on equipment such as strobe glasses for its athletes and will depend on spending priorities of that athletic department. Another factor to consider is how many pairs of strobe glasses a team might need to use them effectively. The analysis conducted in Table 4 is operating under the assumption that every athlete would have a pair of strobe glasses (Desrochers, 2013). However, if all the athletes were not using the glasses at the same time, having a pair for every athlete may be unnecessary. This analysis also assumes there is not a deal in place between an athletic department and a strobe glasses supplier, as there often are deals between universities and athletic equipment suppliers which may reduce the cost associated with the strobe glasses.

DISCUSSION

Summary of Evidence

The empirical results are variable and point to opportunities for conducting further research to answer questions that may help provide more precise information on the benefits of strobe eyewear. Most of the studies surrounding strobe eyewear have been completed within the last ten to fifteen years, making this a relatively new area of study. As with any new research area, there are some opportunities to further the body of knowledge. Gray (2017) makes mention and Wilkins and Appelbaum (2018) reiterate that “the need for research designs in sports training to include both an assessment of far transfer (i.e., performance in the sport) and an assessment of the mechanisms which are intended to positively

impact this transfer.” Wilkins and Appelbaum (2018) also identify that SVT research could benefit from studies that “include measures of visual/perceptual/cognitive skills and measures of the sporting performance captured by specific motor skills.” In general, more systematic, and comprehensive design of sports studies would help to improve the area of research surrounding SVT. To date, the studies completed have varied widely in training duration, number of athletes, use of other technologies, and type of sport.

Another area of interest is the foveal improvements compared to lack of improvements in peripheral vision. This would include research into what physiological or cognitive mechanisms related to foveal vision are triggered using stroboscopic vision training and how can similar mechanisms be triggered or trained to improve peripheral vision. Table 5 summarizes relevant work focused on the effects of SVT presented throughout this research study along with basic information about each study shown in the right-side columns.

Applications for Coaching Practitioners

Sensory/neurocognitive training has been researched for decades; however, it has not reached mass adoption in the field of athletic performance training. Using an autoethnographic frame (Davarzani et al., 2020; Luczak et al., 2020; Reid et al., 2020), the strength and training coach practitioner authors of this comprehensive review believe there are a few specific challenges and barriers to implementing vision training in cohesion with the other key areas of a training regimen. There is not a lack of research on the benefits of vision training, but currently there is no system in place for its application. In modern training circles, sensory/neurocognitive training is perceived by some head coaching staff to be “wasting valuable time that can be spent training other athletic qualities” (e.g., strength, speed, power, etc.). For this reason, there is a need to create a blueprint for how to educate coaches on the benefits and application of sensory training. Another challenge that many coaching practitioners may struggle with is building buy-in with their student and professional athletes. The sensory/neurocognitive type of training is very different from the physically driven regimens typically seen and performed. First, coaching practitioners must educate the athletes on why it’s necessary to add this extra layer to their training. Then, practitioners must practice the importance of utilizing aspects of reciprocal determinism—an understanding that there is a dynamic relationship between an individual, their environment, and their behavior (Collings & Eaton, 2021). All these attributes influence each other. For example, during the process of rolling out unique training protocols

Table 2. Median spending per athlete (desrochers, 2010)

Spending Quartile	Median Athletic Spending per Athlete	Facilities and Equipment Budget	Facilities and Equipment Spending per Athlete
Quartile 1	\$ 149,711.00	23.3%	\$ 34,882.66
Quartile 2	\$ 108,911.00	19.0%	\$ 20,693.09
Quartile 3	\$ 77,535.00	15.7%	\$ 12,173.00
Quartile 4	\$ 51,532.00	14.7%	\$ 7,575.20

such as sensory/neurocognitive-based tasks, coaching practitioners may gravitate toward athletes that are more likely to buy in to vision training and may serve as cultural evangelists of change. Over time, the other athletes' perception of this type of training may shift to acceptance because of peer acceptance. This leads to an environment that is conducive to positively influencing incoming athletes' perception of various training modalities.

The key with vision-based training is to find reliable and validated tools that can be effectively added into a training session or sport-specific practice. The coaching practitioner authors for this comprehensive review have identified stroboscopic eyewear as a tool that meets these criteria. Strobe eyewear is a sensory training tool designed to improve movement, balance, and reaction time by removing visual information to train processing visual stimuli more efficiently. This technology can be used independently or as a part of existing training drills. Some of the authors have experience using stroboscopic eyewear as a part of pre-practice stationary and dynamic warm-ups in both collegiate and professional sports environments. The athletes training with strobe eyewear have reported that improved perception and faster

reactions after using the eyewear pre-practice; however, this has not been validated scientifically. The pre-practice warm-up is necessary to help athletes mentally and physically prepare for practice and while these coaching authors believe that stroboscopic eyewear adds an additional benefit to an existing warm-up, there is a lot of research needed to validate these assumptions of benefits.

Comfort and Adoption

As Herz & Rauschnabel (2019) report, a critical variable of wearable technology adoption is end-user comfort. The integration of fashion-related concepts into wearable technology is not new, however remains a critical supplement to overall adoption. Rauschnabel et al. (2016) coined the term *fashnology* to address these factors in current research. Kalantari (2017) review of wearable technology adoption identifies two key areas of adoption: wearable aspects and technology aspects. The wearable aspects include utilitarian factors of comfort, durability, fit as well as the aesthetic factors of design and perceived style. Wearable comfort, a key factor affecting end-user adoption, is the overall subjective assessment by the end-user on the physical attributes when wearing the product (Herz & Rauschnabel, 2019; Knight & Baber, 2005). Increases in wearable comfort led to higher levels of perceived use enjoyment and eventually overall technology adoption (Eisenmann, Barley, & Kind, 2014; Herz & Rauschnabel, 2019; Kalantari, 2017; Rauschnabel et al., 2016). Conversely, low ratings on wearable comfort, to the extreme of discomfort, significantly override technological benefits of the wearable device, thereby stifling end-user adoption. These critical

Table 3. Common strobe glasses price points

Strobe Glasses	Price per Unit
Senaptec Strobe	\$ 299.00
Senaptec Quad	\$ 799.00
Vima REV Sport	\$ 399.00
Vima REV Tactical	\$ 499.00
Nike Vapor Strobe	\$ 300.00

Table 4. Strobe glasses budget breakdown (Desrochers, 2013)

FBS Spending Quartile	Q1	Q2	Q3	Q4
Facilities and Equipment Spending per Athlete	\$ 34,882.66	\$ 20,693.09	\$ 12,173.00	\$ 7,575.20
Senaptec Strobe % Budget	0.9%	1.4%	2.5%	3.9%
Senaptec Quad % Budget	2.3%	3.9%	6.6%	10.5%
Vima REV Sport % Budget	1.1%	1.9%	3.3%	5.3%
Vima REV Tactical % Budget	1.4%	2.4%	4.1%	6.6%
Nike Vapor Strobe % Budget	0.9%	1.4%	2.5%	4.0%

Table 5. Stroboscopic Training Influence Summary

Article	Sport	Type of Task	Field of Vision	Sport Improvement
Holliday (2013)	Football	Catching/Motion Tracking	Foveal	Yes
Wilkins & Gray (2015)	General	Catching/Motion Tracking	Foveal	N/A
Appelbaum et al. (2012)	General	Motion Tracking	Foveal	N/A
Appelbaum et al. (2011)	General	Multiple	Foveal/Peripheral	N/A
Mitroff et al. (2013)	Ice Hockey	Blocking/Shooting	Foveal	Yes
Hülsdünker et al. (2019)	Badminton	Blocking/Hitting	Foveal	Yes
Schootemeijer & Visch (2017)	Tennis	Hitting	Foveal	Yes
Madsen & Blair (2017)	Softball	Hitting	Foveal	No
Ellison et al. (2020)	General	Reaction Time	Foveal/Peripheral	N/A
Edgerton et al. (2018)	Softball	Catching	Foveal	Yes

factors cannot be overlooked when assessing technological adoption of wearables.

Limitations

The limitations of this literature review are the reliance on the availability and validity of previously published stroboscopic visual training research utilizing the outlined search methodology. Further, the appropriateness of these studies was considered with respect to the defined inclusion/exclusion criteria as determined by the research team. Some variability may exist between researchers as to which articles fall under the purview of the inclusion/exclusion criteria. Limitations in extant stroboscopic training research present additional challenges for accurately answering the research questions, namely Questions 2, 3 and 4 and delineating the optimal applications of strobe glasses. The limitations are identified as several areas in stroboscopic vision training research that remain open. For example, a lack of systematic and repeatable training/testing protocols specific to applied sporting context represents a challenge to coaching practitioners considering implementation or buy-in of the technology. A contributing factor here is both a limitation and benefit of the technology: the ability of the strobe glasses to be easily integrated into a wide variety of sporting contexts. Study designs also lack assessments of both far transfer (sporting performance) and the mechanisms intended to positively impact this transfer, instead evaluating one or the other. The study by Liu et al. (2020a) reported a pre-registered, randomized, placebo-controlled sports vision training trial involving multiple university baseball teams. The training protocol includes strobe glasses as a main training tool. This work echoes with this noted review point that the reviewed studies lack the test of far transfer (Sicong Liu et al., 2020).

Clarity concerning how long the effects of stroboscopic training last, which sports benefit most from training, how long training must last to be effective, which tasks provide the most transfer of training, and what external factors may influence the effectiveness of strobe glasses in an athletic contest further contribute to research limitations and mainly affect this review's assessment of optimal stroboscopic eyewear applications.

Limitations of the technology itself include safety risks for athletes with a history of seizures or epilepsy. Wilkins and Appelbaum (2020) note that strobe glasses' frequencies are below levels considered sensitive by the World Health Organization, but careful monitoring of athletes can mitigate the risk, nonetheless. Since strobe glasses also disrupt the wearer's vision during a physical or intense activity, some potential physical hazards are introduced during training. Finally, due to the unfamiliar nature of sensory training in athletics, some organizations may have trouble achieving user buy-in.

Future Research Applications in NCAA Division 1 Baseball

While this research team largely has experience with strobe glasses use within the sport of basketball, the sport of base-

Table 6. NCAA Division 1 baseball task training incorporating strobe glasses and the different strobe patterns for direct transfer of skills into competitions

Baseball Training Skill	Training Task Scenario with Strobe Glasses and Patterns
<i>Hitting Warmups</i>	<ul style="list-style-type: none"> • Hitting off a batting tee. • Hitting off a coach standing in front of the hitter tossing the baseball underhanded.
<i>Catching Drills</i>	<ul style="list-style-type: none"> • Tossing baseballs underhanded to a student-athlete in a squatted catcher's position. • Tossing different size balls (golf balls, whiffle golf balls, baseballs, whiffle baseballs, heavy 15-ounce plyo balls, 3-ounce plyo balls, foam balls, etc.) underhanded to a student-athlete in a squatted catcher's position. • Tossing red and blue racket balls underhanded to a player in a squatted catcher's position while having the student-athlete call out the color of the ball during the task.
<i>Fielding Drills</i>	<ul style="list-style-type: none"> • Hitting and throwing baseballs to both in- and outfielders at their respective positions during different times of the day to account for sun positioning in the sky.

ball presents opportunities to wear this technology during task training that is directly transferrable to task elements during competition. For example, Liu et al. (2020b) is an exploratory study investigating the most important visual variables correlating with professional baseball players' plate discipline performance (S. Liu, Edmunds, Burris, & Appelbaum, 2020). The findings from this study may help future mechanism research focus on those visual variables more likely to explain the SVT benefit. With the help of studies like these (S. Liu et al., 2020; Sicong Liu et al., 2020), and the information aggregated within this narrative, this team of researchers and coaching practitioners intend to incorporate the use of strobe glasses into the following baseball practice scenarios (Table 6) for an NCAA Division 1 baseball program:

CONCLUSION

The purpose of this comprehensive review is to investigate the effectiveness of stroboscopic eyewear as an athletic training tool through a review of scientific research regarding SVT interventions. The goal of SVT in athletics is to improve athletes' visual and perceptual performance under normal visual conditions by intermittently reducing their vision during training activities. Studies exploring the direct influence of stroboscopic eyewear interventions on sporting performance present a reasonable method for enhancing fun-

damental visual abilities. However, visual skill requirements vary vastly across the sporting domain, and SVT research protocols demonstrate this variance, hindering the realization of a firm conclusion on optimal applications and consequently SVT effectiveness. Despite the presented study limitations and areas for further research, the limited number of studies available are promising and practitioners should not rule out the potential benefits of stroboscopic visual training for athletes. The inference from this comprehensive literature review agrees with previous studies: SVT is considered to effect spatiotemporal dynamics of vision and that pre-registered and more highly powered studies are still needed. Skills requiring the use of foveal vision during fast movement activities have shown improvement when utilizing stroboscopic eyewear as an intervention method, as opposed to skills requiring vision to be more peripheral or sustained. As studies have shown that the main purpose for training with SVT is to improve fast, foveal vision, more research is needed to understand additional impacts while considering comfort both in the wearable sense as well as for the strength coaches interested in prescribing their use.

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