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An early review of stroboscopic visual training: insights, challenges and accomplishments to guide future studies

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ABSTRACT
Stroboscopic visual training (SVT) is a form of training in which an individual practices a task under intermittent visual conditions with the intention of enhancing subsequent performance under normal visual conditions. Training with stroboscopic devices is theorized to improve important visual, perceptual, and cognitive skills, which in turn transfers to enhanced sporting performance. Indeed, while there is an abundance of anecdotal evidence suggesting benefits of strobe training, empirical evidence is rarer and less conclusive. This lack of clarity is due, in part, to the challenging methodological issues faced when conducting experimental vision training studies in applied contexts. The present paper is an early review of the research to date with a focus on the key methodological decisions, such as the training and testing protocols employed, participant samples and control groups used, and practical considerations that enable such training in applied settings. Whilst still at an early stage, the existing studies point to SVT enhancing some aspects of foveal visual sensitivity and visual motor control, with notable benefits for some athletic tasks. Such improvements could have implications not just in sport, but in domains such as rehabilitation, education, and motor vehicle safety.

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Stroboscopic visual training; sport; athletes; vision; eyewear

Introduction
In 2011, Nike released the SPARQ Vapor Strobes: eyewear with liquid-crystal technology in the lenses to produce a stroboscopic effect. The aim was to provide a sports training tool which could enhance an athlete’s visual, perceptual, and cognitive skills, and therefore improve their athletic performance. This type of training has been around for over 20 years – albeit not in the public eye – and was inspired by the experiences of Michael Jordan, who would often have to cope with performing whilst numerous cameras flashed from the crowd all around him (Haberstroh, 2016). Though there had been stroboscopic research prior to this, it used tethered devices, attached to computers, and tended to focus on understanding the mechanism of visual integration (see Elliott, 1990, for a review), with less emphasis on the applied use for activities such as sports. With the
advent of light, portable eyewear that could create a stroboscopic vision, new avenues became available for applied use in sports, creating a new opportunity for academic research. In this qualitative review, we will introduce studies that have attempted to test the efficacy of stroboscopic visual training (SVT) in athletic contexts, by addressing the theoretical mechanisms, training and testing protocols, and findings that have been made in this relatively new field.

It is important to note that this review will predominantly focus on studies and papers that explore the training effects of stroboscopic vision, rather than the acute influence that stroboscopic vision has on performance. That is, the focus will be on research that examines the extent to which training under strobe conditions affects performance under normal visual conditions. Whilst research has been conducted investigating the direct impact of stroboscopic vision, it lacks the practical application that is important in the sporting domain; athletes rarely compete with the intermittent vision of the scale experienced during SVT. As a consequence of this, notable stroboscopic research such as that by Bennett, Ashford, Rioja, and Elliott (2004), Ballester, Huertas, Uji, and Bennett (2017), Fransen et al. (2017), Lyons, Fontaine, and Elliott (1997), and Rhodes, Mihalik, Franz, and Wikstrom (2017) will not be discussed in detail. In addition, this review will focus on studies in which SVT is the sole intervention method, as opposed to work in which SVT forms part of a larger vision training protocol (such as in the studies by Appelbaum, Lu, Khanna, & Detwiler, 2016; Clarke, Ellis, Bench, Khoury, & Graman, 2012). Finally, whilst this paper will predominantly focus on SVT from a sporting perspective, it should be stated that SVT has the potential to be applied in a wide range of domains, such as in health care as a rehabilitation tool or in education for children with attention deficits.

To date, there are seven sports-specific peer-reviewed articles addressing SVT, though there also exists some work that has been presented at conferences (Jones, Carnegie, & Ellison, 2016) or produced as graduate projects (Holliday, 2013; Janssen, Burger, & Mann, 2016). This review will explore this early stage of SVT work by first briefly introducing the theoretical premise underpinning its use and the devices that are available to create this experience. Next, each of the seven studies will be briefly reviewed. Following this, we will highlight the training protocols, testing protocols, and experimental design considerations that shape this literature. Finally, we will consider the future directions of SVT research and provide some concluding remarks. It is our intention that this early review will help guide practitioners in their use of SVT, whilst aiding researchers in addressing areas of need in this potentially fruitful area of sports science.

**Theoretical mechanisms**

Though research on this nascent approach has yet to arrive at strong conclusions regarding the mechanisms of action driving SVT, the underlying premise is twofold. Namely, that when experiencing a rapid and repeated interruption of visual input, an individual is forced to (1) utilise the limited visual samples they receive more efficiently, and/or (2) utilise other facilities, such as kinaesthetic awareness and auditory cues, more effectively. In both instances, the individual is engaging in potentially advantageous strategies that they otherwise wouldn’t were they to experience full vision.

These two theoretical mechanisms underpin other potential benefits of SVT, such as the forced practice of extrapolating speeds and trajectories when aiming to intercept a
moving object. Other positive outcomes of SVT may relate to the need to maintain higher attentional vigilance or to change the focus of attention in a manner that promotes the visual-motor engagement being practiced. With regards to the latter point, it is logical that interrupting the visual scene of an individual would result in an increase in attention to external aspects of the primary task at hand, due reductions in the sensory input available and increased difficulty. For instance, a baseball hitter may increase their attentional resources to the ball (an external object), and reduce their attentional resources to their swing mechanics or body position (internal foci). Considerable research has found external attention to be superior to internal attention in skilled performance and learning, particularly for intermediate and elite athletes (Wulf, 2013). Finally, it is possible that SVT may create conditions where temporal integration of information is more efficient, leading to a perceptual advantage once normal vision is restored. Considerable past research has addressed the temporal dependencies of visual integration including during optic flow (Burr & Santoro, 2001), the detection and tracking of moving objects (Irani, Rousso, & Peleg, 1992), and across saccadic eye movements (Melcher & Morrone, 2003), each of which are utilized in sporting contexts and may be affected by the intermittent conditions induced during SVT. It has been suggested that the imposed overload of effort on the visual system caused by SVT is such that tasks feel easier (or moving objects feel bigger/slower) once the glasses are removed (Smith & Mitroff, 2012), akin to jogging with ankle weights or swimming in a drag suit. This increased effort may also serve to function as a pseudo-psychological warm-up, with the glasses ensuring that typically basic skills are honed with focus and without complacency.

**Stroboscopic eyewear**

Whilst the premise underpinning stroboscopic effects is similar across different eyewear products, the specific details of each piece of eyewear do vary from company to company. The now discontinued Nike SPARQ Vapor Strobe glasses consist of liquid crystal lenses that alternate between transparent and semi-transparent states when an electrical current is either passed through the lens or withheld, respectively. This eyewear has a duty cycle consisting of a fixed 100 ms ‘open’ state, in which the lenses are fully transparent, and a ‘closed’ state that ranges from 67 to 900 ms, at eight set increments. In the closed state, the Nike glasses are semi-transparent and have been shown to allow for luminance of 128 lux under ambient room lighting (Ballester et al., 2017), conditions almost equivalent to that of a ‘very dark overcast day’ (Schlyter, 2015). Furthermore, through a button on the temple of the eyewear, it is possible to alternate between binocular viewing with strobing in both lenses, and monocular viewing with one or the other lens held in the opaque state.

Following the discontinuation of the Nike eyewear, Senaptec LLC began manufacturing eyewear that utilized the same basic form factor, but improved upon the design of the lenses to create a semi-transparent state that blocked nearly all light. In addition, Senaptec introduced a digital application that allowed for remote control of their eyewear through Bluetooth connectivity. More recently, the company has introduced the ‘Senpatec Quad Strobe’ eyewear with segmented lenses, allowing each quadrant to be controlled separately so that specific parts of the visual field could be manipulated individually.
In addition to the Senaptec eyewear, three additional companies produce commercial products intended for applied activities such as sports. Vima produces both the Rev Sport and the Rev Tactical, each of which comes with 11 levels and digital control through a Bluetooth connected application. MJ Impulse and Vision up Store have also produced lightweight battery powered strobe eyewear that has gained use in both sports and research (e.g. Hülsdünker et al., 2018). Whilst the ‘closed’ state in all of these products consists of semi-transparent lenses, the degree of opacity differs to some extent within each set of glasses.

Finally, while not typically used in sporting settings, the PLATO Visual Occlusion Spectacles (Milgram, 1987) were employed in much of the early work testing intermittent vision by Digby Elliott and colleagues. The ‘closed’ state of the lenses in these spectacles are translucent such that light is permissible, but due to the scattering of light all local contrasts are destroyed and no vision of objects or movement is perceptible. The duty cycle is customisable and limited only by the transition time between open and closed states (approximately 7 ms), whilst users can also implement non-periodic series of cycles; thus, the spectacles allow for the greatest amount of variation in the stroboscopic conditions induced. As these spectacles are large, fragile and require the individual to wear either a wallet-sized battery pack or remain tethered to an external power supply their use in sporting contexts (particularly excessively active or contact sports) has been limited.

Primary research literature

As noted, there are currently seven published peer-reviewed articles testing the efficacy of SVT. In the following section, we briefly describe the primary application and findings from these studies in order to provide an overview of the nascent literature. This is not intended to be an exhaustive account of all the studies, but rather background information for subsequent sections that detail the methodological considerations used in each study.

The first published SVT study using the Nike glasses was carried out by Appelbaum, Schroeder, Cain, and Mitroff (2011). University students and athletes were assigned to either an SVT group or a control group that wore altered versions of the eyewear that remained transparent, with measures of motion coherence (experiment 1), divided attention (experiment 2), and multiple-object tracking (experiment 3) compared before and after the intervention period. The authors found that, compared to the control group, SVT led to (1) significantly improved detection of centrally presented, but not peripherally presented, motion coherence, and (2) significantly improved divided attention in terms of central field processing, but not peripheral field processing. SVT did not, however, lead to improvements in multiple-object tracking.

Using a similar design and population, Appelbaum, Cain, Schroeder, Darling, and Mitroff (2012) carried out two experiments to examine the effect of SVT on short-term visual memory. In the first, they found that SVT led to significantly greater improvement in memory compared to a control group. In the second, with a new group of individuals, the study found that these improvements in memory were retained 24 h following training.

The effect of SVT on anticipation (as assessed by a Bassin Anticipation Timer – a 4-m long track of light-emitting diodes and response button used to test coincidence anticipation) was examined by Smith and Mitroff (2012). Here, participants completed 5–7
min of training which consisted of practice with the anticipation timer, either whilst wearing the Nike Strobe eyewear (experimental group) or whilst not wearing any eyewear (control). The study included an immediate post-test, 10-min retention test, and 10-day retention test. It was found that the experimental group had (1) significantly better anticipation in the post-test, but not in either retention condition, (2) significantly greater bias towards reporting early responses in the post-test and the 10-min retention, but not in the 10-day retention (though significant pre-training differences make inferences about any real changes difficult), and (3) significantly more consistent anticipation errors in the post-test and the 10-min retention, but not the 10-day retention.

Mitroff, Friesen, Bennett, Yoo, and Reichow (2013) conducted a pilot study with elite ice-hockey players. Despite a small sample size (six participants in the experimental group and five in the control group), and the lack of intervention blinding, it was found that the players who undertook SVT significantly improved their precision in either an on-ice shooting task (forwards) or an on-ice passing task (defensemen), whilst the control group of players showed no such improvement.

The fifth solely-SVT study published was by Wilkins and Gray (2015). Here, university students were assigned to either an experimental group undertaking variable SVT (i.e. the frequency of the strobe varied during training) or a pseudo-control group undertaking constant SVT (i.e. the frequency of the strobe remained at the lowest/easiest setting during training). No significant group differences emerged following the 5-week training intervention in either motion sensitivity, processing speed, divided attention, or tennis ball-catching performance. However, for both groups, it was found that motion sensitivity did improve in the post-test, whilst there were significant correlations between changes in catching performance and both changes in motion sensitivity and changes in processing speed.

A case-study approach was taken by Wilkins, Nelson, and Tweddle (2017) to explore the outcomes of SVT with three elite youth soccer goalkeepers. In this study, the players underwent seven weeks of SVT and conducted a number of visual-perceptual tests pre- and post-training, as well as engaging in semi-structured interviews post-training. This study highlighted three themes with regards to SVT: (1) the belief that it improved their visual and perceptual skills, (2) the belief that it improved their on-field goalkeeping performance, and (3) the opinion that SVT was both effortful and enjoyable.

Finally, Hülsdünker et al. (2018) recently conducted the first SVT study utilising neurophysiological measures (electroencephalography indicative of cortical visual processing) alongside a sport-specific performance task. Here, five elite badminton players who underwent a four-week SVT intervention were compared against a control group of five, age and ability matched, players completing the same training intervention, but without the strobing eyewear. Post-test performance in the badminton task (when controlled for pre-test scores) were significantly higher for the SVT group compared to the control group, though there were no group differences for the neurophysiological measure (N2 latency). A significant negative relationship between change in N2 latency and change in badminton performance was reported, however, this was based on all 10 participants (both SVT and controls) and any interpretation of the mechanisms-of-action are not specific to the strobe training. Nevertheless, the research provides promising evidence for the benefits of SVT in applied contexts.
Training protocols

A major strength of SVT compared to many visual, perceptual, and cognitive training tools used by athletes is that it allows for training to take place in natural contexts. Athletes can practice their regular sports-specific drills within their sports-specific domain whilst wearing the stroboscopic eyewear, rather than performing tasks outside of the sports field/court/pitch. It is widely acknowledged that the benefits of practice are dependent upon the similarity between the practiced-context and the later performed-context (Henry, 1968), with a strong push in recent years to adopt high levels of task representativeness (Krause, Farrow, Reid, Buszard, & Pinder, 2018). Because SVT can be adapted to the natural contexts of a training regime, it offers the opportunity to maximize near-transfer learning. At the same time, this variability means that training protocols do not follow a regulated format, which leads to variability between and within interventions. Specifically, this variability manifests itself in three forms: (1) the length of the training (both per session and across the whole intervention), (2) the exact activities performed by the individuals, and (3) the frequency of the strobe rate experienced by the individuals.

In terms of training length, SVT not only varies between studies, but within-studies as well. For instance, in Appelbaum et al. (2011) participants completed between 2 and 10 SVT sessions of between 15 and 30 min, with the resultant total training between 54 and 300 total minutes. Table 1 highlights the between-study variance, with interventions lasting as little as 5–7 min (Smith & Mitroff, 2012), or as long as 635 min (Wilkins et al., 2017).

With the release of the SPARQ Vapor Strobes, Nike produced a series of videos which recommended an assortment of training drills with which to use the eyewear. These videos mostly comprised variations on simple ball catching tasks, such as a ‘wall catch’, ‘power ball drop’, and ‘turn and catch’, but also included some agility and strength based drills (Athletic Republic, 2011a). These are practiced on the easiest (fastest) strobe frequency rate, before being made progressively harder (strobe frequency rate slows) at a certain time- or performance-based intervals (i.e. every 5 min or every 5 successful catches). Much of the existing literature adopts this ‘levelling up’ approach while utilizing adaptations of these drills within sport-specific activities. While training protocols generally start on the fastest/easiest level and get progressively harder, the reporting of the precise details are understandably vague within current literature. Specifically, none of the studies listed in Table 1 specify the exact duration with which participants trained on each strobe level, making inference on this dimension challenging at this point. More generally, while levelling up is understandable and appealing due to its simplicity, it may not prove best practice for SVT. It is certainly possible that the effects of SVT may be greater (or indeed reduced) if participants remain on just one strobe frequency. Wilkins and Gray (2015) discuss this possibility and suggest that it may be that the ‘mere interruption of visual input, regardless of whether it is constant or variable … is sufficient to produce advantageous training effects’ (p. 75).

Much of the variance seen in SVT protocols is due to the logistical constraints imposed by using athlete populations (e.g. limited time, impracticable matching control participants, and changeable training schedules). Yet these issues do not take away from the fact that the lack of clearly identified structure makes understanding of optimal interventions challenging. The work by Appelbaum et al. (2011, 2012) usefully included ‘cohort’ –
the athletic sample by which the training protocol typically varied – as a factor in their analyses and found no significant differences in the effect of SVT. Whilst this may indicate that the differing protocols all had the same effect, it remains possible that length of training, activities performed, frequency of strobe rate, or something else entirely may all contribute to an as-yet undetermined optimal SVT intervention.

**Testing protocols – timing**

Testing protocols entails both assessments that are designed to measure constructs that might change due to SVT, as well as temporal structure that dictates the timing of pre- and post-tests relative to training activities. Across the seven studies reviewed here, five post-tests occurred immediately after the final training session, ensuring minimal interference of learning that may lessen any potential effects. Indeed, in both studies by Wilkins and Gray (2015), Wilkins et al. (2017), the experimental procedure was specifically designed such that a shortened training session could be undertaken prior to the post-tests.

While immediate post-tests provide the best opportunity to observe SVT effects, it is also of fundamental interest to assess whether training effects persist for any period of

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**Table 1. Synopsis of training protocols used in the seven solely-stroboscopic training studies published in the literature.**

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<tr>
<th>Length of training</th>
<th>Activities performed</th>
<th>Frequency of strobe rate</th>
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<tr>
<td><strong>Appelbaum et al. (2011)</strong></td>
<td>Dependent upon cohort. Recommended training drills from Nike. Specifically, the ‘forward-facing and turn-and-catch drills’. ‘Typical soccer activities, such as passing and dribbling drills’. ‘Warm-up and agility drills’.</td>
<td>Ranged from 1 to 6 Hz, though ‘participants primarily experienced levels 2–4 (5–3 Hz)’</td>
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<tr>
<td><strong>Appelbaum et al. (2012)</strong></td>
<td>Dependent upon cohort. Recommended training drills from Nike. Specifically, the ‘forward-facing and turn-and-catch drills’. ‘Typical Ultimate Frisbee activities involving passing and throwing drills in both stationary and running situations’. ‘Warm-up and agility drills’.</td>
<td>Ranged from 1 to 6 Hz, though ‘participants primarily experienced levels 2–4 (5–3 Hz)’</td>
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<td><strong>Smith and Mitroff (2012)</strong></td>
<td>5 blocks of 10 trials, whereby a trial consisted of participants practicing their anticipation using a 200-light Bassin Anticipation Timer. Note: this was the same as the pre- and post-test task.</td>
<td>4 Hz</td>
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<tr>
<td><strong>Mitroff et al. (2013)</strong></td>
<td>‘a range of natural activities in which the professional hockey players engage, such as on-ice skills (eg, skating, passing) and off-ice skills (eg, balance and conditioning drills).’</td>
<td>Ranged from 1 to 6 Hz</td>
</tr>
<tr>
<td><strong>Wilkins and Gray (2015)</strong></td>
<td>Recommended training drills from Nike. Specifically, the ‘wall catch’, the ‘front catch’, the ‘turn and catch’, and the ‘power ball drop’ (all using a tennis ball).</td>
<td>Ranged from 1 to 6 Hz</td>
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<tr>
<td><strong>Wilkins et al. (2017)</strong></td>
<td>‘simple catching-based drills using a tennis ball … and goalkeeper-specific drills using a football’.</td>
<td>Ranged from 1 to 6 Hz</td>
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<td><strong>Hülsdünker et al. (2018)</strong></td>
<td>‘badminton-specific training protocols … integrated into regular training … midcourt longline drives, two forms of midcourt cross drives as well as net drives … defend long drives as well as different forms of cross drive’.</td>
<td>Ranged from 5 to 6 Hz and 50–70% duty cycle</td>
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time following training. As such, retention-test data has been collected in a number of studies. These included delays of 10 min (Jones et al., 2016; Smith & Mitroff, 2012), 24 h (Appelbaum et al., 2012), 10 days (Smith & Mitroff, 2012), two weeks (Holliday, 2013), and four weeks (Wilkins et al., 2017). Complicating matters slightly is that, in some instances, what was termed by the researchers as a ‘post-test’ session did not occur immediately after training, and therefore may be better classified as retention tests. For example, Mitroff et al. (2013) conducted post-tests 24 h after their last training session.

Interestingly, in the only qualitative data to date regarding athlete perceptions of SVT, a key theme identified by researchers was that participants found the training intervention ‘effortful’ (Wilkins et al., 2017). This opens questions about the interpretation of post-tests which occur immediately after an SVT session and might be underweighting potential effects of athlete fatigue. Further research should investigate this point.

Testing protocols – assessed measures

Gray (2017) highlights 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. For SVT research, it would be beneficial for studies to include measures of visual/perceptual/cognitive skills and measures of the sporting performance captured by specific motor skills. Within the seven published studies considered here, four report only visual/perceptual assessments, one reports only sporting performance, and just two report assessments for both markers of visual/perceptual skill and motor performance (see Table 2). It should be noted that assessment of motor skills in the form of ball-catching (Appelbaum et al., 2011) and free-throw shooting (Appelbaum et al., 2012) were obtained in the

<table>
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<th>Table 2. List of dependent variables measures in the seven solely stroboscopic training studies published in the literature.</th>
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<td><strong>Visual/perceptual/cognitive measures</strong></td>
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<td><strong>Hülsdünker et al. (2018)</strong></td>
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studies by Appelbaum and colleagues, though they were not reported due to ceiling effects within the data.

Across the extant literature, studies have generally found good evidence supporting a positive effect of SVT on a variety of visual, perceptual, and cognitive skills. In particular, findings point towards a beneficial effect of SVT on fast, foveal vision. That is, visual and perceptual skills which are reliant on interpreting visual information in the central field and/or with transient stimuli can be improved by undergoing a period of SVT. By contrast, SVT does not appear to enhance skills that are based on more sustained visual stimuli or stimuli appearing in the peripheral field. For instance, SVT has been shown to improve centrally presented motion coherence and central field processing (Appelbaum et al., 2011), visual memory of rapidly presented stimuli (Appelbaum et al., 2012), anticipation of the sequence of rapidly illuminated lights (Smith & Mitroff, 2012), and motion sensitivity of fast-flowing 3-D stimuli (Wilkins & Gray, 2015). Conversely, SVT has been found to have no effect on peripherally presented motion coherence, peripheral field processing, multiple object tracking (Appelbaum et al., 2011), or divided attention (Wilkins & Gray, 2015). It should be noted, however, that processing speed (a fast, foveal skill) was not improved in Wilkins and Gray’s (2015) work, whilst the anticipation task in Smith and Mitroff’s (2012) study may have involved peripheral field detection depending upon the strategy employed by participants.

As noted above, since SVT has the overall goal of enhancing sporting performance, it is beneficial for studies to include measures of physical skill that are inherent to sporting performance. Of the seven studies discussed, three include such measures.

Wilkins and Gray had participants complete a tennis ball catching task under normal visual conditions, before and after five weeks of SVT. Importantly, in the study, two SVT groups were compared: a variable strobe rate group (akin to traditional levelling up) and a constant strobe rate group (easiest level; proposed to act as a pseudo-control). Various visual measures were also recorded. With regards to the effects of SVT, no group differences were elicited though motion-in-depth sensitivity increased post-training for both groups. The authors suggest that the stroboscopic eyewear used in the study (PLATO occlusion spectacles as opposed to the Nike or Senaptec glasses used in much of the other SVT work) could explain the lack of findings. It should also be noted that unlike in the work of Mitroff et al. (2013) and Hülsdünker et al. (2018) – where positive effects of SVT on motor performance were found – the participants here were not of an elite sporting level.

The pilot work by Mitroff et al. (2013) had NHL ice-hockey players perform pre- and post-tests of passing (for defensemen) and shooting (for forwards) in between which an experimental group underwent 16 days of SVT. Despite the small sample size (six in the SVT group and five in the control group), a significant and substantial positive effect of SVT on performance was found. When comparing pre-to-post measures of hockey puck placement, it was observed that the SVT group significantly improved precision by 18% whilst the control group did not change. Although the performance measures nicely reflected the contextual demands of the athletes (i.e. has good far transfer), this study is limited due to the relatively small sample size and the possibility that placebo, or Hawthorne, effects may have contributed to some extent. These results should rightly be considered a pilot study warranting follow up research.
The badminton task devised by Hülsdünker et al. (2018) required players to defend a ball played by the coach to the opposite side of the back of the court, with the player beginning 2 m from the net. Like the work by Mitroff et al. (2013), the test accurately represented the true sporting demands of these athletes, but the small sample size and possible placebo effect are justifiable caveats. The scoring system devised could also have allowed for greater sensitivity, with trial performance rated purely on whether the ball was successfully hit, hit with the frame of the racket, or missed.

Finally, as mentioned previously, there has been one paper which collected qualitative data regarding SVT. Thematic analysis of the semi-structured interviews from Wilkins et al. (2017) revealed three consistent themes; (1) players believed that their visual and perceptual skills (particularly ‘focus’, ‘reactions’, and ‘judgement’) improved due to SVT, (2) players believed that their on-field goalkeeping performance improved due to SVT, and (3) players found the SVT both effortful and enjoyable. This last theme is an interesting one, and supports data collected in the study by Wilkins and Gray (2015) indicating participants’ beliefs regarding their perceived improvement in focus, reactions, and judgement. Of course, it should be noted that it is possible, or perhaps even likely, that the subjective data collected in these studies is prone to biases such as the placebo effect and experimenter effect.

Collectively, it can be inferred from the testing protocols and assessed measures described above that SVT is broadly thought to influence specific aspects of the spatio-temporal dynamics of vision. While the preliminary conclusion of this review is that the main effect of SVT is to improve fast foveal vision, more research, utilizing pre-registered and sufficiently powered samples will be needed to draw stronger conclusions.

**Control groups and participant samples**

Perhaps the greatest challenge in SVT research relates to the identification of appropriate control groups. In traditional controlled designs (e.g. drug trials), it is possible to create a placebo intervention to balance the experience, and importantly motivation, of the participants. In the case of stroboscopic vision, it is not possible to introduce a placebo, nor is it possible to blind one to the experience of the intervention, so motivational effects may exist. The most common solutions among stroboscopic research studies have been to either (1) have control group participants wear the eyewear, but have the lenses remain transparent throughout, or (2) have the control group participants not wear the eyewear at all (Table 1, right). In the first case, participants are typically instructed to press the buttons on the side of the glasses in the same manner as the experimental groups, in an attempt to balance the procedure. While it is not possible to validate the efficacy of this approach, consistent patterns of task-level effects provide anecdotal evidence that training effects were not due to motivation, which would have been equivalent across tasks for individuals in either group. Another approach taken by Wilkins and Gray (2015), involved the use of contrasts across different stroboscopic conditions. This was done to combat the potential for differing motivation, enjoyment, and effort levels between SVT and control group participants (subjective data collected post-training indicated no group differences in these metrics). In their study, the fastest strobe setting acted as a pseudo-control, based on previous research showing that catching performance under such conditions did not significantly differ from normal visual conditions (Bennett
et al., 2004). Thus, rather than compare an intermittent vision SVT group with a continuous vision control group, they compared a variable strobe rate group and a constant strobe rate group.

The participant sample tested in a given study is another important area to consider within SVT research. It has been suggested that SVT may have greater efficacy for elite athletes compared to intermediate or novice athletes, given that the visual abilities of the latter are less likely to be limiting factors to their performance (Wilkins et al., 2017). Conversely, it could also be argued that the benefits may be larger for novice athletes given that they have more room for improvement. Of the seven solely-SVT studies published to date, four contained data from participants classified as university students, three contained data from participants classified as university athletes, and three contained data from elite-level athletes; thus, the early literature has managed to explore a range of sporting abilities. Despite this, no studies have yet to empirically test for differences in strobe effects as a function of athlete experience. Furthermore, all the studies referred to in the previous paragraph demonstrate significant findings (to varying extents), so identifying whether SVT is more or less effective for particular individuals is challenging.

Within the athlete populations studied, the sports played have also varied considerably. Soccer, given its popularity, has been studied on a number of occasions, whilst predominantly-American sports have received the majority of interest. One of the difficulties in conducting research with athletes, as opposed to the general public, is in the recruitment of large enough samples. The three published papers using only elite-level sportsmen consisted of a total of 11 (Mitroff et al., 2013), six (Wilkins et al., 2017) and 10 (Hülsdünker, et al. 2018) participants. Such small sample sizes make reliable statistical analyses difficult, yet are often an inescapable fact in elite sport settings. It should be noted that the participant sample used in the work by Appelbaum and colleagues (2011, 2012) did contain a reasonably large number of Division 1 varsity athletes (67 total), though the data was eventually collapsed across all cohorts, including non-athlete students, as no cohort difference was observed for any of the statistical tests. Sufficient recruitment of student populations, such as those in Appelbaum et al. (2011), Appelbaum et al. (2012) and Smith and Mitroff (2012) may be easier, but they bring with them issues of generalizability if the intention of a strobe intervention is to improve elite athletes.

Applications of SVT

Visual training has become a popular tool in the arsenal of sports teams and coaches in recent years. The fact that SVT allows athletes to train in-situ is a significant advantage over many traditional programmes, and is in line with optimal approaches according to representative learning designs and the recently devised Modified Perceptual Training Framework (Hadlow, Panchuk, Mann, Portus, & Abernethy, 2018). It also makes SVT a more appealing prospect from the logistical perspective of coaches and athletes. Anecdotal reports indicate that SVT has been used by elite athletes in a wide range of sports, including American football (Athletic Republic, 2011b), baseball (Berardino, 2016), basketball (Haberstroh, 2016), ice hockey (Jackson, 2013), rugby (Carayannis, 2016), and soccer (Kent, 2014). Given the positive reception towards the training, it is likely that such practices will continue and increase in use.
From a coaching perspective, SVT has the logistical benefit of being easy to administer, and can allow athletes a degree of autonomy over their training. Studies such as the one by Mitroff et al. (2013) have demonstrated that significant improvements can be found even when the SVT is not regulated or recorded. Alongside the data showing that SVT is both highly enjoyable and highly motivating (Wilkins & Gray, 2015), it is reasonable to suggest that coaches could implement the practice with minimal guidance or monitoring.

Coaches do, however, need to be aware of the safety limitations with SVT. First of all, athletes with epilepsy or a history of seizures should not use the eyewear. Though the strobe eyewear operates at a frequency below the photo-epileptic seizure sensitivity threshold, and the prevalence of this disorder is less than 1% (World Health Organisation, 2017), it is recommended that athletes are carefully monitored to mitigate possible risks. Secondly, disrupting an athlete’s vision whilst they are undertaking physical activity – particularly if that involves intercepting moving objects – brings with it potential physical hazards. Having athletes perform tasks slightly below full speed, or with softer equipment (e.g. tennis balls instead of cricket balls, or slightly deflated footballs), may reduce contextual matching, but would provide less risk of injury.

Another potential application of stroboscopic training is that of rehabilitation and health care. In a recent review, Grooms, Appelbaum, and Onate (2015) discuss the possibility of incorporating SVT into the athletic rehabilitation process for neuromuscular injuries, in particular, ruptures of the anterior cruciate ligament. They argue that such injuries cause athletes to experience a reduction in somatosensory input that is compensated for by an over-reliance on visual feedback. This adaptation may become detrimental when returning to the sport as the complex and challenging athletic environment has the potential to overload the now more-utilised visual system. Consequently, resources for neuromuscular control are reduced and the risk of re-injury (or new injury) increases. Training with stroboscopic glasses during the rehabilitation process reduces the visual input an individual receives and therefore, in theory, reduces over-reliance from occurring. Instead, the central nervous system is forced to use more proprioceptive inputs, which should lead to a smoother and safer transition when returning to the challenging athletic environment. Such a theory has begun to receive empirical support from recent clinical studies testing this approach during lower-extremity injury rehabilitation (Kim, Kim, & Grooms, 2017; Rhodes et al., 2017).

Finally, it should be noted that SVT has the potential to be a useful tool in any domain which benefits from improved visual and perceptual skills. Notably, recent research by Zavlin and colleagues (2019) has demonstrated improvements in surgical training task performance of medical students following SVT, demonstrating efficacy in domains outside of sports. Though there is not currently empirical evidence to support their claims, it is worth noting that manufacturers, such as Vima, advertise their Rev Tactical strobe glasses as being ‘built for athletes, professional shooters, military, law enforcement, and first responders’ (www.vima.com). Driving safety may be a particularly fruitful avenue given that the visual skills shown to be enhanced by SVT, such as motion-in-depth-sensitivity, have also been associated with improved driving performance (Wilkins, Gray, Gaska, & Winterbottom, 2013). Indeed, early work has already investigated whether SVT can improve time-to-collision judgements (Braly & DeLucia, 2017). Thus, research exploring the effects of SVT on performance in these various areas may be is desirable.
Future of SVT

SVT has rapidly emerged as a viable visual training approach that is easy to use and has gained traction in sport and other domains. Based on this growth and the larger growth of digital sports vision training tools (reviewed in Appelbaum & Erickson, 2016) it is important to consider how future use, and future research, with this tool can be optimized. As the growth of SVT continues, it is essential that research guides the parameters and protocols employed. As identified previously, the current literature varies in a multitude of factors including intervention duration, training drills performed, and strobe frequency used. Future research can build on the currently reviewed studies to provide a more systematic exploration of the optimal SVT strategy. Moreover, as this field continues to grow, and more empirical studies emerge, it will be possible to conduct meta-analyses that aggregate empirical findings that speak to the magnitude of effect sizes, moderators that influence effects and publication biases that may present or absent within the literature at-large.

A number of open questions remain. For example, while numerous studies have found immediate improvements following SVT, it is unclear how long these effects last. Systematic studies of retention may inform this gap. As noted earlier, SVT presents a unique challenge for blinding and for creating placebo-controlled reference groups. Future studies may wish to explore dose–response relationships (both over time and over level) as a way to infer more information, given these challenges. Comparisons of SVT with other digital visual and perceptual training programmes – like Dynavision, Neurotracker, Neuro-Trainer, or EyeGym – would be particularly useful from an applied perspective, as they would provide coaches with direct evidence for the most effective types of visual/perceptual training for their athletes. In addition, future studies may wish to explicitly test how skill level (e.g. expert versus novice) interacts with strobe training effects.

In light of the challenges highlighted in this review, it is important that future SVT studies make efforts to ensure the following:

1. Inclusion of assessments that measure of both visual/perceptual performance and sport-specific motor performance.
2. Training and testing protocols that are (1) systematic, repeatable, and based on best evidence, and (2) specific to the nature of the sport in question.
3. Inclusion of appropriate reference conditions such as adequate control group with equal motivation, or dose–response designs.
4. Blinding of investigators during the statistical analysis of data.
5. Hypotheses are pre-registered prior to data collection (e.g. Appelbaum et al 2018).

Conclusions

The purpose of this paper has been to review the emerging scientific literature that has tested stroboscopic visual training in athletic contexts. The goals of this review have been to frame out the methodological considerations that have been used, their pros and cons, and to make recommendations where the nascent field can be strengthened. The goal of SVT as an athletic training tool is to transfer to performance under normal visual conditions. This is an important point to consider given findings demonstrating
that fundamental visual abilities correlate with on-field performance in domains such as baseball (Burris et al., 2018; Klemish et al. 2018). Moreover, the growth of studies which explore the direct effect of stroboscopic vision on performance present a plausible approach to enhance these fundamental abilities and improve sporting outcomes. In light of this, the promising findings of early SVT research, and the abundance of positive anecdotal reports, it would appear that SVT will remain a training tool for athletes and sports teams for the foreseeable future.

Despite the limited amount of studies, there are a number of key themes which have emerged. First, it does appear that SVT can enhance visual and perceptual skills. Specifically, skills relating to fast, foveal vision – as opposed to more sustained and peripheral vision – have been shown to improve following SVT. Impressively, two studies have demonstrated that training effects translate to sporting performance in both professional hockey (Mitroff et al., 2013) and elite handball (Hülsdünker et al., 2018).

Secondly, there is considerable variation in how SVT research is carried out, and this limits our ability to draw firm conclusions on the topic. There is as yet no consensus as to the optimal training protocol, which will determine the effectiveness of SVT interventions. With additional research that is more systematic in its design, evidence for SVT may be able to back up the theoretically-driven approach and the considerable anecdotal support that exists. The implications of this could extend far beyond sport and into important areas such as motor vehicle safety, rehabilitation, military combat, and many more.

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