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Intermittent vision and goal-directed movement: A review

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Intermittent vision and goal-directed movement: A review

It is well known that vision makes an important contribution to the control of goal-directed movements. However, task performance can be maintained when vision is interrupted, such as when a goalkeeper faces a free kick in soccer and the ball moves behind teammates and opposing players. To maintain behavior, it is necessary to process the visual information available from intermittent samples. In this review, we consider the performance and learning effects of intermittent vision in tasks such as aiming, reaching and grasping, goal-directed locomotion and ball-catching. We review research that finds both interocular and intraocular integration contribute to continuous upper limb control with intermittent visual pickup/sampling. Recent work using intermittent visual presentation (i.e., stroboscopic vision) to facilitate learning of general and task-specific visual-motor skills indicates that training/learning protocols that challenge, but don't alter, the visual-motor processing associated with a specific visual-motor task can be effective. In this theoretical context, we discuss methodological and design factors that could impact the effectiveness of future training studies.

Keywords: word; intermittent vision; upper limb control, stroboscopic vision

Preamble

Over the last several decades, a major focus of our research group has been on the role of vision in the control of rapid goal-directed reaching and aiming movements. In this work, we have been concerned with the contribution of vision to both movement planning and online control. Consistent with the classic work on speed-accuracy trade-offs in goal-directed aiming (e.g., Fitts, 1954; Woodworth, 1899), we have generally limited ourselves to experiments involving upper limb movement to stationary targets. This constraint has allowed us to conduct detailed kinematic analyses of the limb trajectories under a variety of conditions in which we have manipulated the availability of vision, as well as other variables such as feedback uncertainty and target characteristics (see Elliott et al., 2001 for an early review). This research set the foundation for the development of a “multiple process model” of speed-accuracy and limb control (Elliott et al., 2010) which we have recently updated (Elliott et al., 2017).

Our reaching/aiming experiments have often relied on comparisons of performance and limb kinematics between normal vision and no-vision conditions (e.g., Chua & Elliott, 1993; Elliott et al., 1995, 2014; Hansen et al., 2006; Khan et al., 2002). Although the importance of making this comparison for understanding the overall role of vision in limb control should not be underestimated (see also Keele & Posner, 1968 and Woodworth, 1899), it provides only a limited understanding of the specific visual processes that contribute to limb control. Thus in parallel to our work on speed-accuracy in aiming/reaching, we have conducted another line of empirical work designed to better understand how the visual system samples the tremendous amount of information that is available to the performer. To this end, we typically employed an intermittent vision paradigm to study tasks such as reaching and aiming, goal-directed locomotion and ball-catching.

In this review, we take a historical approach beginning with the theoretical issues and experiments that first got us interested in intermittent vision. As will become evident, our early visual manipulations were rather simple. However, as we describe when reviewing our process-oriented research, intermittent vision protocols became more flexible and precise once we were able to take advantage of the occluding properties of the PLATO goggles developed by Paul Milgram (1987). We refer to work that enabled us to better understand the temporal integration of visual information when visual input is discontinuous. We then consider the time-course of interocular and intraocular integration for limb control. As an adjunct to this process-oriented work, we describe how our findings contribute to an understanding of the generality/specificity of motor learning, as well as the implication to our multiple process model of limb control.

Next, we take a sideways step and review recent training studies that have used intermittent vision in an effort to facilitate performance of motor skills in a variety of practical sport settings (Appelbaum et al., 2011, 2012; Mitroff et al., 2013). As we moved towards the end of this review, we integrate what we have learned from our ongoing research program with the current training research, thereby providing a potential framework to guide future work.

Intermittent Vision and Goal-Directed Movement: A Brief Historical Context

Our initial interest in intermittent vision stems from a set of studies published by James Thomson in the early 1980's. Thomson's (1980, 1983) work involved the visual control of goal-directed locomotion. His protocol had participants walking various distances (3 to 21 meters) with either full vision or while blindfolded. Their task was to stop walking at the previewed target distance. In an initial experiment, he found that stopping accuracy was almost as good in the no vision condition as the full vision condition if the distance was less than 12 meters (i.e., equivalent errors at 3, 6 and 9 meters). In subsequent experiments, he introduced various premovement intervals in which vision was eliminated after participants had previewed the target but before they began walking. When vision was eliminated 2 seconds prior to walking, performance deteriorated at 9 meters, whereas a 4 second delay was required to impair performance at 6 meters. What seemed to be most important was the time without vision rather than the distanced walked. Specifically, participants were successful without vision as long as they were able to reach the target area within 8 seconds following the removal of vision. This critical 8-second interval was confirmed in an additional study in which participants were asked to run to the target area (i.e., participants were able to increase the distance at which full vision and no vision performance was equivalent). Based on these findings Thomson (1983) hypothesized that a rather literal representation of the movement environment exists for up to 8 seconds after visual occlusion. This representation is useful for motor control when direct visual contact with the movement environment is eliminated.

Our research group was not able to replicate Thomson's (1980, 1983) 8-second effect. Rather Elliott (1986, 1987) found that distance walked was the only reliable determinant of end-point error/variability (see also Steenhuis & Goodale, 1988). Although a complete explanation of the differences between the two sets of studies is beyond the scope of this paper, the primary problem with Thomson's work was an analysis technique that failed to separate within-participant variability in walking error from between-participant variability (i.e., individual differences in undershooting and overshooting bias).

One of the difficulties in studying intermittent vision within the context of locomotion is that goal-directed walking occurs over periods of at least several seconds. We decided to use the protocol with goal-directed manual aiming movements that were possible to complete in less than a second. In an initial study (Elliott & Madalena, 1987), participants completed rapid aiming movements (i.e., 200-300 ms and 400-500 ms) to targets positioned 25 and 35 cm in front of them. Having been shown the target location, these aiming movements were made either with full vision or under conditions in which the room lights were extinguished upon movement initiation or 2, 5 or 10 seconds prior to movement initiation. Although participants performed with less error in the full vision condition than in the no vision 0-second delay condition, the introduction of a 2-second no vision delay had an additional impact on target aiming accuracy. In a subsequent experiment, we used a small dot of phosphorescent paint to make the target visible over the 2-second no vision delay period and the difference between this condition and the 0-second no vision delay condition was eliminated.

Thus target information appears to be important for target aiming accuracy, and at least some of this information can be maintained for a short period of time when vision is eliminated by turning the lights out. However from this aiming work, it would appear that the critical interval is somewhere between 500 ms (i.e., the longest movement time) and 2-seconds (i.e., the shortest delay interval in the Elliott and Madalena work; see also Elliott et al., 1990, Experiment 1).

Over the next several years, we were able to confirm the importance of visual target information in manual aiming (Elliott, 1988; cf. Carlton, 1981), as well as establish that the persistence of information about target position was visual as opposed to motor (i.e., a motor representation/specific motor program remembered over a short no vision interval). This was accomplished by comparing performance in conditions in which the specific target for a trial was cued either before or after vision was eliminated (Elliott & Calvert, 1990). In another experiment, we compared target aiming performance in conditions in which a visual mask was introduced after target presentation to performance under no mask conditions. The mask disrupted performance for intervals up to and including 900 ms suggesting that visual persistence of target position lasted for almost a full second (Elliott et al., 1990).

Process-Based Research on Intermittent Vision and Motor Performance

Temporal integration under intermittent binocular vision conditions

Although variations of Thomson's no vision delay paradigm did provide us with evidence of visual continuity in the absence of direct visual contact with the environment (see also Elliott et al., 1991), even with manual aiming there were major limitations associated with our temporal control of visual events and the overall movement environment. In order to precisely manipulate the duration of vision and no vision intervals, we began to work with liquid crystal goggles that allowed us to have precise control over visual events (Milgram, 1987). This methodology also enabled us to examine more complex motor skills such as ball catching and balance beam walking.

Some of the motivation for this series of studies came from work by Assaiante et al. (1989) who examined balance beam walking and horizontal ladder walking under stroboscopic vision (i.e., brief flashes) and intermittent vision (i.e., longer flashes) conditions. Participants were able to move almost as quickly across the beam and ladder when visual samples were provided every 83.3 ms (i.e., 12 Hz) as they were under full vision conditions. Longer intervals between samples slowed their walking speed. However, the interval between consecutive samples was more important to performance than the duration of the sample, indicating that static visual samples of only a few ms are sufficient for reasonable performance as long as the interval between them is not too long.

In the studies involving goal-directed walking, the target object on any given movement trial remains stationary during the period of visual occlusion. Any visual representation of the targets position in space must be used in conjunction with proprioceptive information and feedforward information associated with the performer's own locomotion. In contrast for many everyday activities, the goal-object associated with our motor behaviors moves in either a predictable or non-predictable fashion. When vision is occluded under these conditions, we must not only maintain information about where the object was at the point of visual occlusion but we must also use of this information along with data about the objects speed and trajectory to make predictions about where the object might be at future moments. We reasoned that this added complexity would make the frequency and duration of visual samples even more important.

In our first series of studies, we used liquid crystal goggles to examine one-hand ball catching (Elliott et al., 1994b). The PLATO goggles, developed by Paul Milgram (1987), have lenses that can change rapidly (i.e., less than 5 ms) from a transparent state to a translucent state and vice versa. In their translucent setting, the liquid crystals randomly refract the light creating a milky white cloudy state without greatly affecting the amount of light hitting the retina. In all four experiments, we used a ball machine to project tennis balls at participants over distances of 8 to 10 meters. The balls arrived at approximately chest level and participants were asked to make a one-handed catch (preferred hand) before dropping the ball to the floor and preparing for the next ball.

In an initial experiment, we provided participants with 20 ms visual samples and manipulated the time between samples. We used no vision intervals of 40, 60, 80, 100 and 180 ms (i.e., 16.7, 12.5, 10, 8.3 and 5 Hz). Participants performed reasonably well at the 3 highest frequencies, catching over 65% of the balls. However, there was an abrupt deterioration in catching performance at 8.3 Hz, and another sharp decline at 5 Hz where participants caught only 20% of the balls. Thus, like the intermittent locomotion work, this experiment suggests that useful visual information about ball flight persists for up to approximately 80 ms. In catching, like walking, this information would need to be integrated with subsequent visual samples to maintain performance under intermittent conditions.[1] In addition, with catching, the performer must be able to predict the future location of the ball to maintain visual continuity.

In subsequent experiments, we replicated this finding and also demonstrated that longer visual samples only partly mediated the impact of the no vision interval (see Figure 1). As well, by video-taping participants' catching performance, we were able to distinguish between positional and temporal/grasping catching errors. Interestingly while the number grasping errors increased gradually with the interval between visual samples, positional errors increased dramatically between the 8.3 Hz and 5 Hz condition. This finding indicates that spatial judgments about the position of the hand relative to the future spatial position of the ball may require less frequent visual updates than are necessary to maintain accurate temporal control (i.e., grasp). That is, while there was always a better catching performance under full vision conditions (i.e., approximately 95%), it was impressive that participants performed reasonably well when 10 to 20 ms visual samples were provided every 80 ms. The implication is that visual information used to time the grasp (e.g., expansion of the ball on the retina), persists for a period of time as long as 80 ms. Because participants made very few spatial errors at frequencies of 8.3 Hz or greater, it seems that information about where the ball is (and will soon be) in space persists for slightly longer (i.e., 100-120 ms). Because people are able to integrate brief visual samples from the movement environment over time, they are able to exhibit continuous visual-motor control based on discrete visual pickup.

INSERT FIGURE 1 ABOUT HERE

Although our initial work on ball catching provided some information about the time course of between-sample visual integration, it still left open the question of what specific sources of information were useful for judging the position of the ball in space and its arrival time. In terms of the latter, at the time there were at least two competing views as to how arrival time of an approaching object is judged. The view held by most ecological scientists was that information about arrival time is specified directly from the expansion pattern of the approaching ball on the retina (e.g., Savelsbergh et al., 1991). A more computational view held that arrival time of the ball was determined from approach velocity based on judgments of time and distance (e.g., how far the ball travels in a set period of time). Our hypothesis was that, under intermittent vision conditions, the latter type of judgment might depend on the predictability of the time interval between visual samples, whereas for retinal expansion, this time interval should be irrelevant (Lyons et al., 1997).

Based on the thinking outlined above, we created 3 ball-catching scenarios (Lyons et al., 1997). In what we termed the predictable condition, our participants attempted to make one-hand catches under 20 open/80 closed conditions. In an unpredictable-same condition, the 20 ms open-interval was maintained but the closed-interval was randomly varied within a trial between 60, 80 and 100 ms. Importantly, the same amount of overall vision was given within a trial. We also included an unpredictable-more vision condition in which the randomly ordered closed-intervals were 40, 60 and 80 ms. For catches, as well as both grasp/timing and positional errors, only the mean time with vision and not predictability had an impact. Thus, we interpreted our results to be consistent with the idea that information about retinal size and not time-distance was integrated from sample to sample. This interpretation was based on the assumption that a reliable estimate of the time between samples would be required for the actual computation of ball velocity and thus interception time.

During the same time that we were examining intermittent vision and catching, we conducted other work using Milgram's goggles to examine intermittent vision and manual aiming (Elliott et al., 1994a). In an initial study, we had participants perform a variation of a Fitts' sequential aiming task (Fitts, 1954) in which a trial involved 28 consecutive target aiming movements. Between-trials, we also manipulated target size to vary the accuracy demands of the aiming task or index of difficulty (Fitts, 1954; Fitts & Peterson, 1964). In addition, participants sometimes performed with their right hand (preferred) and other times with their left hand (nonpreferred). The visual manipulation included a full visual condition as well as 3 intermittent conditions. Based on our catching work, we chose to keep the sample time constant at 20 ms and vary the time between samples. We used no vision intervals of 80, 140 and 200 ms. The task required participants to move through the target sequence as quickly as possible while maintaining accuracy.

Compared to full vision, we expected reasonable movement time performance in the 20 open/80 closed condition, and a deterioration in aiming outcomes when the no vision interval was 140 and 200 ms. These differences were expected to be most pronounced under small target (i.e., high index of difficulty) conditions. Although participants performed quite well under 20 open/80 closed conditions, they were still slower than under full vision conditions (see panel A Figure 2). Moreover, additional increases in movement time for the 20/140 and 20/200 conditions were gradual and not discrete. This latter finding is consistent with a continuous deterioration in the viability of any visual representation over time. That said, index of difficulty did have its most robust effect in the most visually degraded condition (i.e., 20 open/200 closed). The fact that index of difficulty, but not vision condition, affected the degree of right-hand superiority suggests that manual asymmetries in aiming are not due to a right hand/left hemisphere advantage for processing visual feedback (see Flowers, 1975).

INSERT FIGURE 2 ABOUT HERE

In a second experiment (Elliott et al., 1994a), we attempted to determine if the duration of the visual sample tempers the impact of a reasonably long no vision interval. Thus, different participants performed the same aiming task under full vision conditions and with open/closed intervals of 50/150, 30/150 and 10/150 ms. Although once again participants completed the aiming task more rapidly under full vision condition, the differences between the 3 intermittent situations were small (see panel B Figure 2). In fact, although performance was worse in the 10/150 ms condition, people performed just as well in the 30/150 condition as they did in the 50/150 condition. Thus taken together the two experiments (Elliott et al., 1994a) indicate that while there may be some minimum sample time required for reasonable performance, it is the time between samples that is particularly important.

In a follow-up to Elliott et al. (1994a, Experiment 1), we conducted a discrete aiming study in which we also included a no vision condition (Elliott et al., 1995b). Participants held a stylus on a home position and prepared a single aiming movement to a target 32 cm away on the midline. From trial to trial, we varied the target size as well as vision condition. Participants wore goggles during the experiment that remained transparent in the full vision condition. In no vision condition, the goggles became opaque at movement initiation and remained in that state until the target aiming movement was completed. In the 3 intermittent conditions (20/80, 20/140, 20/200), the goggles cycled between opaque and transparent with the opaque state always first (i.e., at movement initiation). Thus, with a 610 ms movement time, the participant would receive 6 visual samples (20 ms) of the hand and target environment while aiming in the 20/80 condition, but only 2 samples under 20/200 conditions.

Although participants missed the targets more often in the no vision condition than all other visual situations, there was no difference between full vision and the intermittent vision conditions. With respect to movement time, intermittent vision was as good as full vision for low index of difficulty target, but not for high index of difficulty targets. Interestingly, participants completed their aiming in comparable movement times under all 3 intermittent vision conditions. Kinematic data collected in this study indicate that the spatial-temporal characteristics of the movement trajectories under intermittent vision conditions were more similar to the full vision than the no vision condition, even though participants were without vision for the majority of the movement trajectory. This indicates that even when very little visual information is available, people attempt to make use of it.

While our research group has focused on dynamic movement tasks and liquid crystal technology to study intermittent visual and motor control, other researchers have tackled similar theoretical issues using isometric force production with feedback provided on a visual display. For example, Slifkin et al. (2000) required adult participants to maintain a submaximal isometric target force with their index finger while they varied the frequency at which visual feedback about the mean force and force production variability was provided. They examined force production variability over a 15 s force maintenance period and manipulated visual feedback frequency in a range from .2 to 25.6 Hz. Thus the number of pixels, representing the force being produced at that moment in time, relative to the target force (a straight line at 40% MVC/maximum voluntary contraction) varied from 1 pixel every 5 s (.2 Hz) to 25.6 pixels/s (25.6 Hz). Participants performed this task with limited force variability between 6.4 Hz and 25.6 Hz with an abrupt decline in performance between 6.4 Hz and 3.2 Hz. Thus force production performance was unaffected as long as there was a minimum of 156 ms between visual samples.

In a subsequent experiment, Sosnell and Newell (2005a) also manipulated the absolute magnitude of the target force from 5% MVC (maximum voluntary contraction) to 50% MVC and found similar results but with less abrupt changes in force variability at 50% MVC than at lower target forces (e.g., 25% MVC). Differences in the frequency structure of the force output that occurred with the absolute force requirements and visual intermittency lead Sosnell and Newell (2005a) to suggest that there are multiple time scales of visual control. These include both visual feedforward and feedback control processes. This latter notion is consistent with the distinction we have made between impulse control and limb-target control in our work on goal-directed aiming (e.g., Elliott et al., 2010, 2017). In terms of visual intermittency, research involving isometric force maintenance indicates that, like our catching and aiming work, stable performance is possible with fairly long intervals between visual samples (i.e.,, 150 ms; see also Sosnell & Newell, 2006 and Vaillancourt et al., 2001).

Sosnell and Newell (2005b) increased the complexity of their isometric force production task by having participants track a .5, 2 or 4 Hz sinusoidal target-force over 15 s trials. The time between visual samples was varied between 40 ms (25 Hz) and 5000 ms (.2 Hz). Overall, participants were able to track the absolute force magnitudes at all 3 sinusoidal frequencies. As one might expect however, they were only able to maintain low variability tracking for no vision intervals of 40 to 320 ms during low frequency target modulation (i.e., .5 Hz). Extremely frequent samples (i.e., 40 and 80 ms) were needed for even modest variability performance in the 2 Hz target modulation conditions. There was no impact of intermittency for the 4 Hz target. Once again, the frequency structure of participants' force modulation suggests that there is more than one visual-motor process associated with force control in target-force tracking.

In more recent work, Lafe et al. (2016a, 2016b) have used an isometric force production paradigm to examine visual intermittency and bimanual coordination. They also found an interaction between target-force and visual feedback frequency. For the higher target-forces (30, 50 and 70% MVC), there was a significant reduction in error (i.e., RMSE) for no vision intervals around 625 ms, whereas for the low target-force (10 % MVC) participants exhibited low RMSE when vision was presented every 2500 ms. In addition, although the absolute force requirements associated with the coordination task had an impact on phase transitions (Lafe et al., 2016b), anti-phase coordination generally dominated when the time between visual samples was short while in-phase coordination was more prominent when the intervals were long. Across participants however, this shift in coordination with visual feedback frequency was not abrupt but occurred gradually from 25.6 Hz to .2 Hz with the greatest proportion of the change occurring between 6.4 Hz (156 ms between samples) and .8 Hz (1250 ms between samples; Lafe et al., 2016b). In line with the force tracking research (e.g., Sosnell & Newell, 2005b), this work suggests that there is more than one level of visual-motor control and that these are recruited based on the interaction between perceptual and motor constraints.

Intraocular and Interocular Integration

The experiments described in the last section were all designed to examine the limits for temporal integration under intermittent binocular vision conditions. However, we realized during this work that in most situations, participants have access to a combination of binocular and monocular visual cues about the position of the limbs and body in space relative to objects of interest. In our next series of experiments, we used the PLATO goggles with one-hand ball catching in order to examine interocular integration in a skill specific context.

Following on from Lyons et al., (1997), we conducted two ball catching studies in which there was an independent manipulation of visual information provided to the right and left eye (Olivier et al. 1998). Our goal was to examine the relative importance of binocular and monocular visual cues for ball catching, as well as to establish the time course of binocular and monocular integration. In our initial experiment, we compared a full vision binocular and full vision monocular condition to intermittent binocular and intermittent monocular conditions. In the full vision binocular condition, both goggle lenses remained open over the course of the trial, while under full vision monocular conditions only one eye received continuous vision while one lens remained closed.

Under intermittent binocular conditions, one lens always remained open while the other lens cycled at 20 open/20 closed, 20 open/50 closed, or 20 open/80 closed. For intermittent monocular conditions, one lens remained off while the other lens cycled at the same frequencies. As in earlier work, we measured not only the proportion of balls caught but also distinguished grasp/timing errors from spatial/positional errors.

Under full vision conditions, binocular viewing resulted in better catching performance than monocular viewing, thus confirming the contribution of additional binocular information to one-hand catching. Moreover, although binocular performance was maintained over the 20, 50 and 80 ms intermittent occlusion intervals for the other eye, monocular performance deteriorated sharply with occlusion time. This deterioration was due to an increase in both spatial and timing errors. Consistent with our previous work was the finding that under binocular conditions, reasonable performance was maintained as long as a binocular sample was provided every 80 ms.

In a second study, we examined the time course of binocular integration more closely using a protocol in which we alternated visual samples between the two eyes. Thus along with control conditions that involved continuous binocular vision and continuous monocular vision (right eye only, left eye only), we exposed participants to conditions in which vision alternated between the two eyes (i.e., 20 ms right/20 ms left, 40/40, 60/60, 80/80, 100/100 and 120/120). In these latter conditions, vision was always available but only from one eye. The idea was to determine if, depending of the between-sample interval, binocular visual cues were available from the interocular integration of alternate monocular samples. Although continuous binocular vision resulted in the best catching performance, alternating vision at 20/20 and 80/80 was better than continuous monocular vision. The difference between continuous monocular vision and the 40/40 and 60/60 conditions approached conventional levels of significance. Positional errors were particularly pronounced under 120/120 conditions, indicating that if the interval is too long between alternating monocular samples, performance is actually worse than continuous monocular vision.

Bennett et al. (2003a) extended this work on interocular integration by anipulating the time between visual samples in both a monocular and binocular context. In one binocular condition, vision information to the two eyes was manipulated in tandem such that the lenses associated with both eyes remained open for 20 ms and then closed for 20, 40 or 80 ms (e.g., similar to the early work by Elliott et al., 1994). In a second binocular situation, the left lens always remained open while the right lens was open for 20 ms and then closed for 20, 40 or 80 ms. Under monocular conditions, the left lens was always closed and the right lens was open for 20 ms with closed times of 20, 40 and 80 ms.

Compared to continuous vision, when the goggle lenses were closed together in the first binocular situation, participants maintained their catching performance under 20/20, 20/40 and 20/60 conditions, but showed a deterioration in catching when the between sample interval was extended to 80 ms. This deterioration in catching performance was due to an increase in both positional and grasping errors. For monocular vision, the impact of the no vision interval was apparent even earlier. Specifically, catching performance was affected by a no vision interval as short as 20 ms and deteriorated gradually with each additional 20 ms no vision interval. Interestingly, when the left lens remained open in the second binocular situation, no vision intervals associated with the right lens did not matter. That is, participants maintained almost perfect catching performance even when the right lens was closed for as long as 80 ms. Although it might be tempting to over interpret this finding with respect to binocular integration, it is notable that in this study continuous monocular vision was just a good as continuous binocular vision for overall catching performance. [2] Taken together with Olivier et al. (1998), it seems that people are reasonably flexible in their ability to extract binocular and monocular cues necessary for temporal and spatial control in one hand catching. That said, monocular cues alone appear to be much less viable when monocular samples are separated by even short no vision intervals.

Our next examination of temporal and interocular integration involved a 4-experiment study in which we again introduced independent manipulation of vision to the two eyes (Bennett et al., 2006). In the first experiment, the control conditions included continuous binocular vision, continuous monocular vision and an alternating 20 ms left/20 ms right situation. The other conditions included a no vision interval of either 40 or 80 ms. Thus, in the binocular situation both lenses were open for 20 ms and then closed for either 40 or 80 ms. In the monocular situation, one lens was open for 20 ms and then both lenses closed for 40 or 80 ms, while the alternating situation was similar except the eye with the 20 ms sample was alternated from cycle to cycle. This resulted in a 3 viewing condition (binocular, monocular, alternating) by 3 no vision interval (0, 40, 80 ms) experimental design. As one might expect, the analysis revealed two main effects as well as the interaction. Overall, binocular vision was superior to both monocular and alternating vision, and catching performance deteriorated with the length of the no vision interval. The deterioration was more pronounced under monocular and alternating conditions than under binocular conditions, and the differences at no vision intervals of 40 and 80 ms was due to both increased positional errors and timing error associated with monocular and alternating situations. Still, this experiment failed to detect any advantage for alternating monocular vision over continuous monocular vision (cf. Olivier et al., 1998), which motivated us to conduct a second experiment using shorter no vision intervals.

In experiment 2, we included the same viewing conditions (i.e., binocular, monocular and alternating) with no vision intervals of 0, 10, 20, 30 and 40 ms. For catching, we found only 2 main effects. That is, binocular catching was better than monocular and alternating catching, and performance in all situations deteriorated with the no vision interval. Because of the short no vision intervals used in this experiment however, participants were still catching approximately 70% of the balls even under monocular and alternating conditions with the 40 ms no vision interval. The difference between binocular performance and monocular/alternating performances in the 40 ms no vision situations were primarily due to more positional errors in the latter. This finding would suggest that while monocular cues may be sufficient for judging arrival time, binocular cues may be important for getting the limb to the correct position in 3-dimensional space.

Because we again failed to replicate the advantage for the alternating vision over continuous monocular vision found by Olivier et al. (1998), we repeated the experimental design used in experiment 2 but used less skilled catchers. These were people who were only able to catch 50% of the ball even under continuous binocular conditions. The results of this study were similar to experiment 2 but with much lower overall performance. This led us to conduct a final experiment in which we not only manipulated viewing condition (binocular, monocular, alternating) and no vision interval (0, 20, 40, 60 and 80 ms), but also the spatial variability of ball flight (i.e., low variability trajectory, high variability trajectory). Once again, the difference between binocular vision and the two monocular situations became more pronounced when the no vision interval was 40 ms or more (see Figure 3). As well, the impact of variability had a greater effect on catching performance for the 3 longest no vision intervals (40, 60 and 80 ms), although this was independent of viewing condition. Spatial variability did interact with viewing condition, but this was in the positional error analysis only. Specifically, very few positional errors were made under binocular conditions regardless of spatial variability, whereas positional errors were greater under alternating and continuous monocular conditions in the high spatial variability condition. Spatial variability did not impact grasp errors. Overall, then, the consistent finding in this series of studies was a failure to replicate the small advantage of alternating vision over continuous monocular vision reported by Olivier et al. (1998).

INSERT FIGURE 3 ABOUT HERE

To further investigate how the monocular sources of information were perceived in the two monocular conditions, we performed a series of comparisons on data obtained when the no-vision interval between consecutive samples to the same eye in the alternating condition was matched to the no-vision interval between consecutive samples to the same eye in the monocular condition (i.e., alternating continuous vs. monocular 20/20; alternating 20/10 vs. monocular 20/40). This showed that for skilled catchers only, there was a significant difference between the two monocular conditions for the proportion of catches, position errors, and grasp errors. The implication is that skilled catchers did not resort to using information provided by a single eye in the alternating monocular conditions, but instead combined the monocular retinal inputs from both eyes. Importantly, however, performance in the alternating monocular condition was still inferior to the binocular condition, potentially indicating the processing of alternate monocular samples did not result in binocular fusion.

At the same time these catching studies were being conducted, we also ran a series of interocular studies involving reaching and aiming. In an initial experiment

(Coull et al., 2000), we had participants make rapid aiming movement to small targets directly in front of them on the midline. In different blocks of trials, the participant had full binocular vision, full mononcular vision (right eye) or alternating monocular vision (20 ms right/20 ms left, 70/70 or 120/120). Although these visual manipulations were shown to have an impact on catching (Olivier et al., 1998), they failed to influence movement time, movement error or any of the limb kinematics in our aiming task.

Based on the notion that the absence of a difference between monocular and binocular conditions was due to movement planning with full binocular vision, in Experiment 2 we created a situation in which the visual manipulation was introduced at the beginning of the planning period rather than at the time of movement initiation (Coull et al., 2000). On separate blocks of trials, we examined both aiming and grasping (i.e., reaching and picking up a small target object with a pincer grasp). To our surprise, there were once again no performance or kinematic differences between full binocular vision, full monocular vision and alternating monocular vision (20/20, 70/70, 120/120). This finding indicates that monocular cues alone were sufficient for performing this type of aiming and reach-grasping task.

In a third experiment (Coull et al., 2000), we sought to increase the spatial difficulty by using a 3-dimensional aiming task (i.e., z-positioning of the target was not constrained by the table top) and also limiting vision, and thus our visual manipulation, to the movement preparation period (i.e., the goggles closed completely on movement initiation). In this experiment, we also moved the target coincident with movement initiation so that participants would not contact it and thus receive tactile feedback that might influence performance on a subsequent trial. Under this specific combination of conditions, we found a difference between binocular and monocular performance.

Specifically, participants initiated their movements more quickly, achieved higher velocities and exhibited less spatial error when aiming under binocular conditions.

In a follow-up experiment (Bennett et al., 2003b), we again returned to a prehesion task (i.e., reaching and grasping) in which we also introduced a between-participant manipulation of accuracy vs speed instructions. Our visual manipulations were similar to the Bennett et al. (2003a) catching study such that on separate trial blocks participants received continuous binocular vision, continuous monocular vision or intermittent binocular and monocular vision. For intermittent binocular vision, one lens always stayed open while the other lens cycled at either 20 open/60 closed or 20 open/120 closed. For intermittent monocular vision, the same intervals were used with one lens always closed. In terms of outcome, participants made more grasping errors in the 20/120 monocular than in the 20/120 binocular conditions. As well, movement initiation times were shorter under binocular conditions than under monocular conditions. This finding indicates that when participants were aware that binocular cues would be available, they took less time to plan their movements. They also took more time to prepare their movements under 20/60 and 20/120 intermittent conditions than with continuous visual information. Although there was an overall group effect consistent with the accuracy vs. speed instructions for movement time, peak velocity and time to achieve peak velocity, both groups exhibited lower peak velocities under intermittent than continuous vision conditions. Both groups also opened their hand wider in the monocular compared to binocular condition, as well as under intermittent vs continuous conditions. Differences in temporal kinematic measures between vision conditions were most pronounced under accuracy instructions. That is, monocular viewing and intermittent vision had additive effects with respect to prolonging movement time.

In more recent work on interocular integration (Hansen et al., 2011), we had adult participants perform a prehension task under alternating monocular conditions, as well as under intermittent monocular and binocular conditions. In all 3 vision conditions, we manipulated the duration of a no vision interval between visual samples, although a specific set of comparisons was made to examine interocular and intraocular integration. In Experiment 1, participants were uncertain about the impending vision condition on each trial, as well as target size and location. In Experiment 2, a precue provided information on target location. Although uncertainty had very little impact on movement time, participants did take more time to complete their movements as the duration of the no vision interval increased. These increases in movement time were due to both the time before and after peak velocity, and were thus consistent with the use of a more cautious reaching strategy. Interestingly, while differences between monocular and binocular vision conditions were modest irrespective of the no-vision interval, there was a more general intolerance for alternating monocular samples. That is, participants' movement kinematics were different in the alternating monocular condition even when the sample were provided consecutively without a no vison delay.

In a follow-up study (Hansen et al., 2013), we continued to examine the effect of a delay between alternating monocular samples but now in a manual aiming protocol that was intended to reduce the demand on fine binocular disparity for the control of grip aperture. Contrary to our earlier prehension study, we found no differences between the alternating condition with a zero second delay and continuous binocular and monocular conditions. However, participants modified their movements considerably (i.e., increased movement time, reduced peak velocity, longer time-to-peak and time-after-peak velocity) when 25 ms and 50 ms delays were introduced between alternating monocular samples. Together, the two sets of studies indicate that the impact of an interocular delay on performance depends on the contribution of specific visual information (for a discussion see Melmoth & Grant, 2006; Melmoth et al., 2007). Presenting alternating monocular samples without an interocular delay during reach-to-grasp tasks would seem to disrupt the perception of coarse and/or fine binocular disparity, which impacts on-line control and grasp formation. However, for aiming tasks, it would seem that participants are able to gain sufficient information from alternating monocular samples to maintain performance based on vergence, as well as form in depth from alternating monocular samples.

In summary, we have shown across a number of studies that adult performers are quite flexible with respect to their use of monocular vs binocular cues. Findings from experiments where we have manipulated intraocular and interocular integration indicate that there are a multitude of redundant cues that can be used, if required, to determine the position of a ball or stationary target relative the hand. Moreover, the requirement for binocular information, and thus the potential for a binocular advantage, is dependent on the environmental and task demands.

Intermittent Vision and Specificity of Learning

A tremendously important theoretical issue in the area of perceptual-motor learning is that of specificity to a particular environmental or task context. In the 1960's, this issue fostered a huge debate associated with validity of a number of general abilities thought to underlie various complex motor skills (see the Henry vs Fleisman argument; Fleisman & Bartlett, 1969; Henry, 1968). In the 1970's, Adams' (1971) closed-loop learning theory and Schmidt's (1975) schema theory provided a theoretical framework for a strong specificity and generality position, respectively. Although much of the empirical work generated by these two theories involved the manipulation of various task parameters (e.g., research associated with generalized motor program theory; see

Schmidt, 1976 for a review), here we are interested in the work of Luc Proteau and colleagues (Proteau et al., 1987, 1992; see also Elliott & Jaeger, 1998), who examined specificity of learning in a manner relevant to the theme of this paper. That is, they studied learning and transfer effects associated with the sensory context in which a specific perceptual-motor skill is practiced.

Proteau et al.'s (1987) most influential paper involved participants practicing a rapid aiming movement under one of 4 different conditions. Participants practiced either under full vision conditions or under conditions in which vision was eliminated upon movement initiation and not restored until the execution of the aiming movement was complete (i.e., terminal visual feedback but not concurrent visual feedback). Half the participants in each of these two feedback groups practiced for 200 trials and half for 2000 trials. At the end of practice, all participants were transferred to the no vision situation in which they completed some additional trials, this time without terminal feedback.

With respect to closed motor skills, the traditional wisdom was that as practice progresses the learner gradually becomes less dependent on visual and other types of concurrent feedback (Pew, 1966; Schmidt & McCabe, 1976). The idea is that, with practice, an internal representation, model or motor program of the movement is developed that is able to control the movement without the need for feedback processing. Although this sort of notion makes some intuitive sense, it was completely at odds with the outcome of the Proteau et al. (1987) study and the work of Elliott and Jaeger (1988). Specifically, contrary to the hypothesis that more practice results in greater feedforward control, Proteau and colleagues found that the participants who practiced with vision for 2000 trials were more disrupted by the removal of vision than the participants who had practiced for 200 trials. This result suggests that as people practice with a particular type of feedback they become more dependent on that source of feedback for subsequent performance (see also Proteau et al., 1992). If one adopts a strong specificity of learning position based on these sorts of data, the implication would be that the best way to practice any skill is under exactly the same sensory conditions in which the skill will ultimately be performed. Therefore, for the most part, the best form of practice would be under the full vision conditions typically associated with the normal performance context.

Although it is beyond the scope of this paper to review the many specificity of learning studies conducted in the late 1980's, 1990's and early 2000's by Proteau and others (e.g., Elliott et al., 1995, 1997; Khan et al., 1998; Khan & Franks, 2003; Mackrous & Proteau, 2007; Robin et al., 2005), a strong specificity position did not withstand the test of time. Thus, while "all or none" manipulations of visual and other types of feedback were consistent with the specificity position, it was also the case that subtle manipulations of feedback can often lead to robust between-task transfer effects. With respect to optimal training, we have suggested that the goal should be to develop a sensory context that challenges and fosters development of information processing procedures that will ultimately be useful for task performance (see Elliott et al., 1995). However, the sensory context should not change to the extent that a completely different strategic approach is taken to task performance. In the context of the intermittent vision work, it is important to note that even when vision is very degraded due to long intervals between visual samples, participants still performed their goal directed movements more like they did under full vision conditions than no vision conditions (see Elliott et al., 1995 for manual aiming and Robertson et al., 1994 for balance beam walking).

Within the theoretical context of specificity of learning theory, we decided to examine transfer of learning effects in one-hand ball catching (Bennett et al., 2004). In an initial study, we had skilled and less skilled catchers perform under continuous binocular vision conditions and in intermittent binocular conditions of 20 open/40 closed, 20 open/80 closed and 20 open/120 closed. Although the skilled catchers caught more balls than the unskilled catchers, their pattern of performance across vision conditions was similar. That is, both groups exhibited a systematic decrease in catching performance with increases in the no vision interval. This catching trend was associated with a steady increase in grasp/timing errors and a more abrupt increase in positional/spatial errors between the 20/40 and 20/80 intermittent conditions.

In a subsequent learning study, participants were randomly assigned to one of 5 practice groups. All participants performed a pre-test and post-test in which they attempted to catch balls in a 20 open/80 closed intermittent condition. In practice, they performed 80 trials either with full vision or 20/40, 20/80 or 20/120 intermittent vision. A control group received no practice. This protocol revealed that 20/40 and 20/120 intermittent vision practice was just as effective as 20/80 intermittent vision practice for post-test performance (see Figure 4). However, all three forms of intermittent vision practice resulted in better post-test performance than practice under full vision and no practice, which were not different from each other. Thus, the results provide evidence for the generality of learning, as long as the practice conditions involved similar processing requirements as the post-test.

INSERT FIGURE 4 ABOUT HERE

In another ball catching study (Lyons et al., 1997; see also Elliott & Lyons, 1998), we attempted to directly contrast a weak process-based specificity of learning position with Proteau et al.’ s stronger representational view. Participants were assigned to one of two intermittent training conditions. In what we termed the predictable condition, participants practiced ball catching with a 20 ms on (goggles open) and 80 ms off (goggles closed) cycling schedule. Participants in the unpredictable group had their goggles programmed to provide 20 ms of vision separated by no vision intervals of 50, 80 or 110 ms. The scheduling of these no vision intervals was random with the constraint that they occurred equally often so that the absolute amount of vision over individual ball flights was equal to the vision received by individuals in the predictable group. All participants received 200 practice trials and then returned to the lab 24 hours later for a retention and transfer test. Retention involved 20 catching attempts under the condition in which they were trained (i.e., retention test) followed by 20 trials of transfer under the other visual conditions (i.e., transfer test).

Contrary to a strong specificity position, participants did not simply excel when retention mimicked their own training conditions. Rather, participants in both the predictable and unpredictable training groups caught more balls under predictable conditions. This outcome was in spite of the fact that there were no differences between the two groups during the acquisition phase of the experiment. Thus predictable training benefited the unpredictable transfer situation more than actually training in the unpredictable situation. Presumably predictable training better fostered visual-motor processes important for ball catching than unpredictable training. Once again, more work is required to isolate what these specific processes might be.

Summary of Performance and Specificity of Learning Findings

A general summary of our findings indicate that in tasks such as aiming/reaching, ball catching and goal-directed locomotion, adults performers depend heavily on vision. Even when vision is only available 10% of the time, performers adopt a strategy to use vision rather than to ignore it. This reliance on vision results in kinematic outcomes that more closely resemble full vision than no vision conditions, and also superior performance outcomes compared to a no vision situation.

Although for most motor tasks having some vision available is useful, for catching, there is a pronounced deterioration in performance when the interval between visual samples is greater than 80 ms. Initial deterioration is primarily due to a breakdown in timing "time to contact" with the ball (e.g., grasping errors). Information about the position of the limb in space relative to the target object appears to persist slightly longer, but also deteriorates rapidly after no vision intervals approaching 150 ms (e.g., spatial errors). Longer visual sample times have only a limited impact on reducing between-sample time effects. This is true for both catching and reaching. Moreover, the impact of both the sample time and the between-sample intervals is more pronounced under monocular, as opposed to binocular, viewing condition. This difference between binocular and monocular vision conditions indicates that monocular cues such as retinal expansion/contraction are not the sole contributors to timing-based performance in one-handed catching.

With respect to training, our limited findings support a weak specificity of learning position. That is, visual training manipulations that challenge the information processing systems generally important for catching, aiming/reaching and goal-directed locomotion, but do not lead to a complete change in strategy, can be expected to result in positive transfer. What might be an optimal training protocol for a given task remains an empirical question.

Implications for Vision and Goal-Directed Aiming/Reaching

As we mention at the beginning of this paper, our work on intermittent vision was conducted in parallel to a larger body of research concerned with the optimization of speed, accuracy and energy expenditure in goal-directed aiming/reaching (e.g., Elliott et al., 2001, 2010, 2017). This research program led to the development of the multiple process model of aiming/reaching. One of the main features of this model is the distinction between two types of visual feedback utilization that we have termed "impulse control" and "limb-target control".

Impulse control is a rapid (e.g., 80-100 ms) and early form of feedback utilization that involves a comparison of the visual and proprioceptive perceived consequences of a movement to the expected sensory consequences. Expected sensory consequences are part of an internal model generated during movement planning. These expectations depend on the task demands including the position of the target object in three-dimensional space and any speed, accuracy and energy constraints associated with moving the limb to the target location. The specific model and associated expectations also depend on the performer's past experiences with similar reaching and aiming tasks and an understanding as to what specific sources of feedback will be available to the perceptual-motor system during the execution of the movement. Of primary importance to this early control process are the expected and perceived velocity and direction of the limb movement.

In contrast, limb-target involves a late corrective process that depends on visual information about the position of the target and visual and proprioceptive information about the position of the limb as it moves into the target area. This corrective process is discrete in nature. Because in goal-directed aiming/reaching the primary submovement often undershoots the target position (Elliott et al., 2004; Lyons et al., 2006), limb-target control often entails a second acceleration designed to move the limb onto the target object. Although the actual corrective process typically occurs late in the movement trajectory, limb-target control can be based on the pickup of information available earlier in the movement. That said, this corrective process takes more time to operate than impulse control (e.g., 180-200 ms; see Elliott et al., 2010 for a review).

Both impulse control and limb-target control depend on reliable information about the position of the target in space. For impulse control, information on target position plays an important role determining the characteristics of the internal model/representation for a specific movement at the time of movement planning. For effective limb-target control, visual information available during the actual execution of the movement is used to reduce any discrepancy between the limb and target location. Our early work on intermittent vision and manual aiming indicate that when visual information is eliminated before movement onset, a reliable representation of target position may persist for as long as 900 ms (e.g., Elliott et al., 1990). This information should be available to both the feedforward processing system associated with impulse control and the feedback processing system associated with limb-target control.

For both impulse control and limb-target control, there are other important sources of information that come from the moving limb. For impulse control, this includes early information about the direction and the velocity of the limb trajectory. Our aiming work using intermittent aiming and grasping protocols indicate that the pickup of this information does not need to be continuous. Specifically, 20 ms visual samples of the limb every 60-80 ms seems to be sufficient for near optimal performance. Our work on interocular integration indicates that adult performers are able to use both monocular and binocular visual cues to evaluate the characteristics of the movement trajectory. That said, monocular visual cues seem to be sufficient for optimal performance when an environment surface constrains the accuracy requirements to only 2 dimensions (e.g., Coull et al., 2000). For limb-target control, it is the spatial position of the limb relative to target that informs the discrete corrective process. Once again, brief visual samples of the moving limb seem to be sufficient for reasonably precise performance. Although our model holds that this information will be most useful late in the movement (i.e., when the limb reaches the target area), recent work by Tremblay and colleagues (2017) suggests that visual samples of the limb just prior to peak velocity are particularly important for limb-target control, with even earlier visual pickup being necessary for impulse control. In this context, it is interesting that even when only widely spaced visual samples are available, participants make use of the available visual information and perform more effectively than under no vision conditions (see Hansen et al., 2006 for a comparison of limb trajectories under vision and no vision conditions).

Recent Training Studies to Enhance Performance in Normal Vision

Although a large part of our work was designed to better understand how the visual system extracts the necessary information for motor control from the visual information that is available to the performer, to a lesser extent we also used the intermittent vision protocol to examine processes of perceptual-motor learning. As described in the previous section, we mainly considered whether there was transfer between intermittent practice conditions performed with the same task. In recent years, there has been interest in whether so-called stroboscopic vision training in both semi-skilled (Appelbaum et al., 2011) and elite athletes (Mitroff et al., 2013) can actually facilitate perceptual and perceptual-motor learning. Note the distinction here between intermittent vision and stroboscopic vision tends to reflects the eyewear used in these studies, which as we discuss later is not simply a matter of semantics. This recent research was partly motivated by the introduction of Nike SPARQ Vapor Strobe eyewear as a training tool for athletes engaged in skilled individual and team sports in which the rapid pick-up and use of visual information is important for both limb and whole body control. The eyewear takes advantage of battery-powered liquid-crystal lenses that can be programmed to change rapidly from a clear state to a semi-transparent state at various frequencies. Specifically, the eyewear is said to have a clear state of 100 ms and semi-transparent states that vary can vary from 900 to 67 ms for frequencies of 1 to 6 Hz. Although no longer available (for a comment on other eyewear see Appelbaum & Ericksen, 2018), the Nike eyewear was a less flexible, but also less expensive version of the type of liquid crystal goggles developed by Paul Milgram, as a research tool in the late 1980's (Milgram, 1987).

The idea behind the use of stroboscopic vision for training is based on the notion that reducing the availability of visual information for perceptual-motor control will force athletes to learn to process skill-related information more rapidly (for a review see Wilkins & Appelbaum, 2019). This learned processing advantage would then result in more rapid and effective performance in the context in which the training occurred. More importantly, the athlete should also exhibit improved perceptual-motor control when transferring back to the actual performance or game context. Among the claims associated with the marketing of the eyewear are increased focus and attention, and improved anticipation, imagery, visualization, balance and peripheral vision.

In an initial study, Appelbaum et al. (2011) took a rather broad approach in which they examined the generality of stroboscopic training effects following both lab-based and field-based training with the Nike eyewear. The goal of both protocols was to determine if stroboscopic training had any general impact on specific perceptual-motor processes associated with a number of individual and team sport related skills. Specifically, the authors developed computer-based tests designed to measure visual sensitivity to central and peripheral motion, transient spatial attention and sustained attention. These tests were administered both pre and post-training. In both the lab and field protocol, there was an experimental group that received stroboscopic training and a control group who performed the same training activities with full vision. For the experimental group, the general procedure was to reduce the frequency of the stroboscopic visual samples (i.e., lower the goggle cycling frequency) as training progressed.

The lab-based protocol associated with this study involved university students who during training performed a series of prescribed ball catching activities in a controlled in-door environment. The training took place over several days. The field-based protocol involved two groups of varsity athletes from both the football team (men) and the ultimate Frisbee team (men and women). Training for these two groups involved performing the normal activities associated with practice for that particular sport (e.g., throwing and catching Frisbees). Thus, while the control of the specific training events was not as precise as in the lab-based study, participants assigned to the control (i.e., full vision) and experimental/stroboscopic groups performed identical activities.

Data from the in-lab protocol and Frisbee protocol were pooled to examine the impact of training on visual sensitivity to motion. For this variable, a training advantage for the stroboscopic group over the control group was found for sensitivity to motion in central but not peripheral vision. The assessment of transient spatial attention involved a dual-task procedure that again had a central and peripheral component. This assessment was given to both the football players and in-lab participants. Once again there was a small but significant training advantage for participants in the experimental group, but only with the central component of the task. The third visual task was performed by football players and Frisbee players, as well as the in-lab participants, and involved the visual tracking of multiple objects. Here, Appelbaum et al. (2011) found no impact of either training or training group on performance on this sustained attention task.

Interestingly, Appelbaum et al. (2011) did not examine any improvements that might have taken place in the tasks being practiced. Thus, while the study leaves open the question of whether or not stroboscopic training might be useful for the development or fine-tuning of specific sport skills, it did provide some useful insight about the generality of perceptual-motor learning on two underlying processes. This idea was extended in a follow-up study by Appelbaum et al. (2012), where it was hypothesized that stroboscopic training may impact the interface between visual sensory memory and visual short-term memory (see Elliott et al., 1990). Similar to the previous study, Appelbaum et al. (2012) examined typical undergraduate students, who trained with an in-lab activity (i.e., catching), and student athletes (i.e., soccer and basketball) wore either control or stroboscopic goggles while engaged in normal practice activities. In Experiment 1, all participants completed a computer-based pre-test and post-test that involved a variation of Sperling's (1960) classic full and partial report paradigm (see Lu et al., 2005). The protocol measured participants' ability to maintain and retrieve information (i.e., printed letters in various spatial positions) from sensory visual memory (iconic memory) and transfer that information to more permanent short-term memory over increasingly longer report intervals. Half the participants associated with both the in-lab group and the student athlete groups trained with the Nike eyewear and half with clear lens goggles. For the stroboscopic groups, training began under high frequency conditions (i.e., easier) and progressed to low frequency conditions (i.e., more difficult). Appelbaum et al. (2012) found improvement from pre-test to post-test with greater improvement in the participants who trained with stroboscopic vision. In a second experiment maintenance of this stroboscopic training advantage was found over a 24-hour retention interval.

Although Appelbaum et al. (2012) found further evidence that some aspect of stroboscopic vision training is generalizable to basic perceptual/cognitive processes, the authors did not examine whether the training activities per se were (e.g., catching, soccer drills etc.) affected. This issue however was tackled by Smith and Mitroff (2012), who examined the impact of stroboscopic training on anticipation timing. Based on the premise that the estimation of time-to-contact with objects (e.g., balls, pucks) and other players is important for many sports skills, Smith and Mitroff (2012) were interested to know if participants exhibited improved performance on the Bassin Anticipation Timer having practiced either with (stroboscopic group) or without (control group) Nike eyewear. The timer consists of a runway of equally spaced red light emitting diodes (LEDs) that sequentially illuminate and then turn off. The sequential illumination of this string of lights gives the impression of a single light moving down the runway toward the participant (i.e., apparent motion) at a rate that depends on the interval between successive LED illuminations. The participant stands at the end of the runway and his/her task is to push a button coincident with the arrival of the light at the end of the runway. The system then provides the experimenter with a signed error (in ms) associated with performance on that trial.[3]

Participants were given a pre-test without goggles on the Bassin Anticipation Timer, and then completed 5 blocks of 10 trials in their respective practice condition. For the stroboscopic group, the goggles were set at 4 Hz (100 ms open/150 ms closed). Following practice, the goggles were removed and post-test performance was examined immediately, at 10-minutes and at 10 days following training. The analysis of timing error and consistency did reveal some short-lived advantages associated with stroboscopic training. Compared to the control group, the stroboscopic group was more accurate immediately following training, as well as being more consistent in their temporal response both immediately and at 10 minutes following training. This advantage occurred in spite of the fact that they exhibited greater anticipation timing error during the training phase than control participants. However, the stroboscopic training advantage was no longer present at the 10 day post-test. Thus, this study provides evidence for a short-lived skill specific training advantage associated with stroboscopic training.

Some of the first evidence for positive transfer of stroboscopic vision training to on-field sports performance (i.e., professional ice hockey) was reported by Mitroff et al. (2013). Like the earlier work, this study involved a pre-test, training and a post-test phase. The pre and post-tests involved a skills assessment that, depending on whether the player was defence or forward, could involve more or less emphasis on hockey skills such a stick-handling, shooting and passing. The training involved the players performing their normal position specific activities. Half the participants wore the Nike eyewear (i.e., experimental group) for some portion of their on-ice and off-ice training while the other half did not (i.e., control group). For the experimental group, no attempt was made to control either the frequency of the stroboscopic manipulation or the precise activities in which the players were engaged (e.g., shooting, passing, skating, conditioning etc.). In spite of this absence of overall control, Mitroff et al. (2013) reported an 18% improvement in post-test skill assessment scores in the stroboscopic group and no improvement in the control group. This study represents a potentially exciting result given that these players were already playing in the top hockey league in the world and thus highly skilled.

In another field-based study that might be better described as pilot work, Hulsdunker et al. (2019) compared 5 elite badminton players who completed stroboscopic training to 5 players who underwent normal full vision training. The training occurred over four weeks and involved the use of MJ Impulse Strobe glasses, which are also are similar to the original Nike eyewear but with better control over the cycling frequency and duty cycle. Once again, the control group trained with normal vision while the experimental group received a mix of frequencies and duty cycles as well as some full vision training. These authors did find greater training benefits in the stroboscopic training group than the normal vision group for some badminton-specific measures of visuomotor performance. However, with only 5 participants per group, such results should be treated with caution until replicated with larger sample sizes.

In a mixed methods study with 3 elite youth soccer goalkeepers, Wilkins, Nelson and Twiddle (2017) found little quantitative evidence for the efficacy of 7-week stroboscopic training (Senaptec Strobe glasses) program on 10 measures of visual and perceptual skills compared to normal vision training. On the other hand, the authors did report qualitative evidence that participants enjoyed the training experience and believed it to be useful to both the visual and perceptual skills, as well as on-field performance.

In another study from this group, Wilkins and Gray (2015) employed two different stroboscopic training protocols to examine improvements in tennis ball catching as well as several other visual-perceptual variables hypothesized to be of importance for catching. Although they used PLATO spectacles (i.e., complete occlusion), they limited their frequency manipulations to those associated with the Nike eyewear to facilitate comparison to previous studies. A pseudo control group of participants practiced catching under the easiest setting associated with the Nike eyewear (i.e., 100 ms on/25 ms off), while the experimental group received training at a variety of frequency settings in a protocol that involved increases in the off-time duration following successful ball catching performance at a higher frequency (i.e., frequency decreased only with off-time because on-time for the Nike eyewear is always 100 ms). It was found that after six weeks of practice, there was no training benefits for either group. Catching success remained relatively low at around 55%, with the vast majority of catching errors in both groups occurring in temporal control (e.g., grasp errors). Motion sensitivity did improve pre to post in both groups, but this could simply reflect the impact of repeated testing.

In summary, the research on the benefits of stroboscopic training is probably best described as mixed. Perhaps this is not surprising given the variation in sports activities and types of interventions that have been investigated (for a review see Wilkins & Appelbaum, 2019). Without doubt, additional research across a range of lab and field tasks is required on the frequencies and duty cycles used to facilitate training. Recent developments in the control offered by commercially available strobe vision eyewear are therefore welcome. In addition, it will be important to include groups with more participants, as well as appropriate control groups in order to better control for threats to validity such as motivation and expectation regarding the treatment or lack thereof (see Ballester et al., 2017). The importance of these potential confounding effects is confirmed by the discrepant quantitative and qualitative findings reported in Wilkins et al. (2017). Moreover, as was initially highlighted in Wilkins and Gray (2015), and will become more apparent in the next section of this review, it is important to consider the type of visual manipulation created by the goggles (e.g., opaque vs semitransparent closed states).

Synthesizing Process-Oriented Performance Research and Recent Training Studies

While stroboscopic vision training may have some positive impact on learning of some perceptual and perceptual-motor skills, it remains to be understood what processes underpin these short-term effects. Initially, it was intuitively appealing to suggest that stroboscopic vision training was analogous to altitude training for the endurance athlete (Appelbaum & Erickson, 2016). The basic premise is that practicing in stroboscopic vision encourages participants to adapt to the altered information available during intermittent periods of occlusion. Having adapted, the logic is that participants are then able to improve performance when they return to the normal vision environment, thus leading strobe vison training to be referred to as altitude training for the brain.

In a recent review, Wilkins and Appelbaum (2019) provided some much needed clarification on this adaptation process by suggesting that strobe vision training results in: 1) more efficient use of the limited information available; and/or 2) more effective use of other sensory modalities. Referring to some of our work, they also recognized that attention is likely to play a key role in these positive transfer effects. For example, strobe vision training can promote attentional vigilance such that participants remain engaged with the task (Ballester et al., 2017) and/or change the allocation (i.e., focus, amount) of attention (Bennett et al., 2018). In this respect, it could be said that these recent strobe vision training studies lend support to our suggestion of a weak specificity of learning position. That is, visual training manipulations that challenge key information processing systems (e.g., increase attention and processing efficiency), but do not lead to a complete change in strategy, can facilitate positive transfer.

In our earlier process-oriented work on intermittent vision, we noted that participants always attempted to use the limited visual information available and did not adopt a movement control strategy consistent with performing in a no vision condition. With hindsight, this turns out to be an important finding as it may help explain some of the equivocality in the results of strobe vision training studies. This is exemplified in a two-experiment study we conducted to examine the performance and acquisition effects of stroboscopic vision methods that afford a different visual experience (Bennett et al., 2018). In Experiment 1, we used a within-subject design to study performance of a multiple object tracking (MOT) task in different stroboscopic vision conditions at three levels of strobe frequency (i.e., 5.6, 3.2 or 1.8Hz). The lenses of Nike eyewear switch between more ("open") or less ("closed") transparent states, with the latter acting as a neutral density filter that reduces transmission of ambient light (81% in our laboratory setting).[4] This contrasts with the lenses of the PLATO visual occlusion eyewear that reduced light transmission by only 44% but importantly scattered the light and thus prevented image formation on the retina (Milgram, 1987). For experimental control, we also included conditions in which there was no manipulation of the available visual information (i.e., normal vision) or manipulation was achieved by intermittent presentation of the stimuli on the computer display.

We found that MOT performance when wearing the Nike eyewear was not influenced by strobe frequency. However, MOT performance did deteriorate in the other two stroboscopic vision conditions as a function of strobe frequency. Interestingly, at the lowest strobe frequency there was an increase in probe reaction time in all vision condition, thus indicating an increased attentional demand irrespective of the way in which stroboscopic vision was experienced. In Experiment 2, we conducted a learning study in which participants practiced a novel precision-aiming task (i.e., multiple object avoidance - MOA) in different vision conditions (Normal Vision, Nike Vapor Strobe, PLATO visual occlusion). We found that participants in the PLATO visual occlusion group exhibited worse performance during practice and at post-test than the Vapor Strobe and normal vision groups. In fact, the PLATO group performed at a similar level in the post-test as a control group that didn't receive any treatment during the practice phase. Conversely, the Vapor Strobe group demonstrated greater success, longer movement time and reduced end-point error than the normal vision and PLATO groups (see Figure 5).

INSERT FIGURE 5 ABOUT HERE

We interpreted the above findings as showing that both an intermittent perturbation (Nike Vapor Strobe) and elimination (PLATO visual occlusion, intermittent display presentation) of visual motion and form are more attention demanding (Experiment 1) than a normal vision condition, but only intermittent perturbation appears to facilitate acquisition of perceptual-motor skill (Experiment 2). Consistent with a weak specificity of learning position, it could be that there is sufficient similarity of information processing between the intermittent perturbation and normal vision conditions to facilitate positive transfer. On the other hand, intermittent elimination of vision may have been a step too far and thus restricted any learning effects. Such conditions could even lead to disengagement if participants felt that they were not making any progress.

A similar lack of perceptual learning when training with PLATO visual occlusion goggles has recently been reported by Braly and DeLucia (2020). Using computer-generated time-to-contact stimuli, it was found that both stroboscopic training and repeated practice in normal vision led to a reduction in performance (increase in constant error) for approach motion and lateral motion. In fact, of all the comparisons across this 2-experiment study, there was only a single finding of a stroboscopic advantage (i.e., no decrement in variable error when TTC was 3.0 s in the lateral motion condition). Referring to our earlier study on strobe vision and vigilance (Ballester et al., 2017), the authors suggested that a longer extrapolation interval requires greater involvement of cognitive processes, which could have helped maintain attention and task engagement. Importantly, however, as we noted in Ballester et al. (2017), future work needs to consider for how long participants can maintain effortful processing, and whether there are negative carry-over effects from cognitive overload when transferring to normal vision.

Final Comments and Implications

As described in the preceding pages, much of our research has been focused on the role of vision in the control of rapid goal-directed reaching and aiming movements. Although primarily concerned with how vision contributes to both movement planning and online control, in parallel we also considered whether participants need to continuously sample the available information to maintain performance. Across tasks such as upper limb reaching and aiming, goal-directed locomotion and ball-catching, we found that performance in binocular vision conditions is generally well maintained if visual samples are separated by no more than 80 ms. However, there was less tolerance for intervals as short as 20 ms between intraocular and interocular monocular samples. This was particularly evident in situations that demand a very precise interaction with the object, which is consistent with the role of binocular vision in limb-target control. Another interesting finding from our work is that positive transfer following intermittent vision training seems to be dependent on challenging the information processing systems but not to an extent that there is a complete change in strategy. We suggest that this weak specificity of learning position would also account for the somewhat mixed findings in recent training studies that have used intermittent/stroboscopic vision in an effort to facilitate performance of motor skills in a variety of practical sport settings.

Conditions that significantly reduce the ability to integrate or extrapolate information between visual samples could limit progress and lead to disengagement or use a different strategy that does not facilitate performance in the normal sport setting. The challenge for future training studies will be to ensure that there is sufficient similarity of information processing between the intermittent training condition and normal vision condition to provide an opportunity for positive transfer.

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Footnotes

1. Human participants are able to track moving objects with some degree of smooth eye movements even with intermittent no vision intervals as long as 960 ms (Barnes & Asselman, 1992).
2. The absence of a difference could be due to a ceiling effect given that in both situations participants were catching almost 100% of the ball. Thus, it seems that either the ball catching task was easier or the catchers were more skilled than Olivier et al. (1998).
3. We find it curious that Smith and Mitroff (2012) chose to examine anticipation timing with the Bassin Timer, which like the goggles is an intermittent device (i.e., depending on runway speed there are longer or shorter between-LED intervals).
4. Although not empirically verified with these eyewear, reduced light transmission (i.e., low level light) impacts upon basic function such as visual acuity (von Noorden & Burian, 1959), contrast sensitivity (Owsley et al., 1983), motion perception (Grossman & Blake, 1999), and ocular accommodation (Johnson, 1976)

References

Adams, J.A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111-150.

Appelbaum, L.G., Cain, M.S., Schroeder, J.E., Darling, E.F., & Mitroff, S.R. (2012). Stroboscopic visual training improves information encoding in short-term memory. *Attention, Perception and Psychophysics, 74,* 1681-1691.

Appelbaum, L.G. & Erickson, G. (2016). Sports vision training: A review of the state-of-the-art in digital training techniques. *International Review of Sport and Exercise Psychology, 11*, 160-189.

Appelbaum, L.G., Schroeder, J.E., Cain, M.S. & Mitroff, S.R. (2011). Improved visual cognition through stroboscopic training. *Frontiers in Psychology, 2,* 276.

Assaiante, C., Marchand, A.R. & Ambland, B. (1989). Discrete visual samples may control equilibrium and foot positioning in man. *Journal of Motor Behavior, 21*, 72-91.

Ballester, R., Huertas, F., Uji, M., & Bennett, S.J. (2018). Stroboscopic vision and sustained attention during coincidence anticipation. *Scientific Reports, 7,* 17898.

Barnes, G.R. & Asselman, P.T. (1992). Pursuit of intermittently illuminated moving targets in the human. *Journal of Physiology, 445*, 617-637.

Bennett, S.J., Ashford, D.G., & Elliott, D (2003a). Intermittent vision and one-handed catching: The temporal limits of binocular and monocular integration. *Motor Control, 7,* 378-387.

Bennett, S.J., Ashford, D., Rioja, N., Coull, J. & Elliott, D. (2006). Integration of intermittent visual samples over time and between the eyes. *Journal of Motor Behavior, 38,* 439-450.

Bennett. S., Ashford, D., Rioja, N. & Elliott, D. (2004). Intermittent vision and one-handed catching: The effect of general and specific task experience. *Journal of Motor Behavior*, *36*, 442-449.

Bennett, S.J., Elliott, D., Weeks, D.J., & Keil, D. (2003b). The effects of intermittent vision on prehension under binocular and monocular viewing. *Motor Control, 7,* 46-56.

Bennett, S.J., Hayes, S.J., & Uji, M. (2018). Stroboscopic vision when interacting with multiple objects: Perturbation is not the same as elimination. *Frontiers in Psychology, 9,* 1290.

Braly, A.M. & DeLucia, P.R. (2020). Can stroboscopic training improve judgments of time-to-collision? *Human Factors, 62*, 152-165.

Carlton, L.G. (1981). Visual information: The control of aiming movements. *Quarterly Journal of Experimental Psychology, 33(a)*, 87-93.

Chua, R. & Elliott, D. (1993). Visual regulation of manual aiming. *Human Movement Science, 12*, 365-401.

Coull, J., Weir, P.L., Tremblay, L., Weeks, D.J. & Elliott, D. (2000). Monocular and binocular vision in the control of goal-directed movement: An elusive binocular advantage. *Journal of Motor Behavior, 32,* 347-360.

Elliott, D. (1986). Continuous visual information may be important afterall: A failure to replicate Thomson (1983). *Journal of Experimental Psychology: Human Perception and Performance, 12*, 388-391.

Elliott, D. (1987). The influence of walking speed and prior practice on locomotor distance estimation. *Journal of Motor Behavior, 19,* 476-485.

Elliott, D. (1988). The influence of visual target and limb information on manual aiming. *Canadian Journal of Psychology, 42*, 57-68.

Elliott, D., & Calvert, R. (1990). The influence of uncertainty and premovement visual information on manual aiming. *Canadian Journal of Psychology, 44*, 501-511.

Elliott, D., Calvert, R., Jaeger, M. & Jones, R. (1990). A visual representation and the control of manual aiming movements. *Journal of Motor Behavior, 22*, 327-348.

Elliott, D., Carson, R. G., Goodman, D., & Chua, R. (1991). Discrete vs. continuous visual control of manual aiming. *Human Movement Science, 10*, 393-418.

Elliott, D., Chua, R., & Pollock, B.J. (1994a). The influence of intermittent vision on manual aiming. *Acta Psychologica, 85*, 1-13.

Elliott, D., Chua, R., Pollock, B.J., & Lyons, J. (1995a). Optimizing the use of vision in manual aiming: The role of practice. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 48(A)*, 72-83.

Elliott, D., Dutoy, C., Andrew, M., Burkitt, J.J., Grierson, L.E.M., Lyons, J.L., Hayes, S.J., & Bennett, S.J. (2014). The influence of visual feedback and prior knowledge about feedback on vertical aiming. *Journal of Motor Behavior, 46*, 433-443.

Elliott, D., Hansen, S., Grierson, L.E.M., Lyons, J., Bennett, S.J. & Hayes, S.J. (2010). Goal-directed aiming: Two components, but multiple processes. *Psychological Bulletin, 136*, 1023.

Elliott, D., Hansen, S., Mendoza, J. & Tremblay, L. (2004). Learning to optimize speed, accuracy and energy expenditure: A framework for understanding speed-accuracy relations of goal-directed aiming. *Journal of Motor Behavior, 36*, 339-351.

Elliott, D., Helsen, W.F. & Chua, R. (2001). A century later: Woodworth's two-component model of goal-directed aiming. *Psychological Bulletin, 127*, 342-357.

Elliott, D., & Jaeger, M. (1988). Practice and the visual control of manual aiming movements. *Journal of Human Movement Studies, 14*, 279-291.

Elliott, D., & Lyons, J. (1998). Optimizing the use of vision in skill acquisition. In J. Piek (Ed.), *Motor control and human skill: A multidisciplinary perspective.* Champaign, IL: Human Kinetics, pp. 57-72.

Elliott, D., Lyons, J. & Dyson, K. (1997). Rescaling an acquired discrete aiming movement: Specific or general motor learning? *Human Movement Science, 16*, 81-96.

Elliott, D., Lyons, J.L., Hayes, S.J., Burkitt, J.J., Roberts, J.W., Grierson, L.E.M., Hansen, S., & Bennett, S.J. (2017). The multiple process model of goal-directed reaching revisited. *Neuroscience Biobehavioral Reviews, 72*, 95-110.

Elliott, D. & Madalena, J. (1987). The influence of premovement visual information on manual aiming. *Quarterly Journal of Experimental Psychology, 39(A)*, 541-559.

Elliott, D., Pollock, B.J., Lyons, J., & Chua, R. (1995b). Intermittent vision and discrete manual aiming. *Perceptual and Motor Skills, 80*, 1203-1213.

Elliott, D., Zuberec, S., & Milgram, P. (1994b). The effects of periodic visual occlusion on ball catching. *Journal of Motor Behavior, 26*,113-122.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381-391.

Fitts, P.M. & Peterson, J.R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67*, 103-112.

Fleisman, E.A. & Bartlett, C.J. (1969). Human abilities. *Annual Review of Psychology, 20*, 349-380.

Flowers, K. (1975). Handedness and controlled movement. *British Journal of Psychology, 66*, 39-52.

Grossman, E.D. & Blake, R. (1999). Perception of coherent motion, biological motion and form-from-motion under dim-light conditions. *Vision Research, 39*, 3721-3727.

Hansen, S., Glazebrook, C., Anson, J.G., Weeks, D.J. & Elliott, D. (2006). The influence of advance information about target location and visual feedback on movement planning and execution. *Canadian Journal of Experimental Psychology, 60*, 200-208.

Hansen, S., Hayes, S., & Bennett, S.J. (2011). Inter-ocular and intra-ocular integration during prehension. *Neuroscience Letters, 487*, 17-21.

Hansen, S., Hayes, S.J., & Bennett, S.J. (2013). Integration of alternating monocular samples during goal-directed aiming. *Motor Control 17*, 95-104.

Henry, F.M. (1968). Specificity vs. generality in learning motor skill. In R.C. Brown & G.S. Kenyon (Eds.), *Classical studies on physical activity*. Englewood Cliff, NJ: Prentice Hall.

Hulducker, T., Rentz, C., Ruhnow, D., Kasbauer, H., Strueder, H.K., & Mierau, A. (2019). The effect of 4-week stroboscopic training on visual function and sport-specific visuomotor performance in top level badminton players. *International Journal of Sports Physiology and Performance, 14*, 343-350.

Johnson, C.A. (1976). Effects of luminance and stimulus distance on accommodation and visual resolution. *Journal of the Optimal Society of America, 66*, 138-142.

Keele, S.W. & Posner, M.I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology, 77*, 155-158.

Khan, M.A., Elliott, D., Coull, J., Chua, R. & Lyons, J. (2002). Optimal control strategies under different feedback schedules: Kinematic evidence. *Journal of Motor Behavior, 34*, 45-57.

Khan. M.A., & Franks, I.M. (2003). Online versus offline processing of visual feedback in the production of component submovements. *Journal of Motor Behavior, 35*, 285-295.

Khan, M.A., Franks, I.M. & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependence between programming and feedback processing. *Quarterly Journal of Experimental Psychology, 51(a)*, 425-444.

Lafe, C.L., Pacheco, M.M., & Newell, K.M. (2016a). Adapting relative phases of bimanual isometric force coordination through scaling visual information intermittency. *Human Movement Science, 47*, 186-196.

Lafe, C. L., Pacheco, M. M., & Newell, K. M. (2016b). Bimanual coordination and the intermittency of visual information in isometric force tracking. *Experimental Brain Research, 234*, 2025-2034.

Lu, Z.-L., Neuse, J., Madigan, S. & Dosher, B.A. (2005). Fast decay of iconic memory in observers with mild cognitive impairments. *Proceedings of the National Academy of Sciences, 102*, 1797-1802.

Lyons, J., Fontaine, R., & Elliott, D. (1997). I lost it in the lights: The effects of predictable and variable intermittent vision on unimanual catching. *Journal of Motor Behavior, 29*, 113-118.

Lyons, J., Hansen, S., Hurding, S., & Elliott, D. (2006). Optimizing rapid aiming behaviour: movement kinematics depend on the cost of corrective modifications.*Experimental Brain Research, 174,* 95-100.

Mackrous, I. & Proteau, L. (2007). Specificity of practice results from differences in movement planning strategies. *Experimental Brain Research, 183,* 181-193.

Melmoth, D., & Grant, S. (2006). Advantages of binocular vision for the control of reaching and grasping. *Experimental Brain Research, 171*, 371–388.

Melmoth, D.R., Storoni, M., Todd, G., Finlay, A.L., & Grant, S. (2007). Dissociation between vergence and binocular disparity cues in the control of prehension. *Experimental Brain Research, 183,* 283–298.

Milgram, P. (1987). A spectacle-mounted liquid-crystal tachistoscope. *Behavior Research Methods, Instruments and Computers, 19,* 449-456.

Mitroff, S.R., Friesen, P., Bennett, D., Yoo, H. & Reichow, A.W. (2013). Enhancing ice hockey skills through stroboscopic visual training. *Athletic Training & Sport Health Care, 5,* 1-5.

Olivier, I., Weeks, D.J., Lyons, J., Ricker, K.L., & Elliott, D. (1998). Monocular and binocular vision in one-handed ball catching: Interocular integration. *Journal of Motor Behavior, 30*, 343-351.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23*, 689-699.

Pew, R.W. (1966). Acquisition of hierarchical control over the temporal organization of a skill. *Journal of Experimental Psychology, 71*, 764-771.

Proteau, L., Marteniuk, R.G., Girouard, Y., & Dugas, C. (1987). On the type of information used to control and learn an aiming movement after moderate and extensive practice. *Human Movement Science, 6*, 181-199.

Proteau, L., Marteniuk, R.G. & Lévesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology, 44(A),* 557-575.

Robertson, S., Collins, J., Elliott, D., & Starkes, J. (1994). The influence of skill and intermittent vision on dynamic balance. *Journal of Motor Behavior, 26*, 333-339.

Robin, C., Toussaint, L., Blandin, Y. & Proteau, L. (2005). Specificity of learning in a video-aiming task: Modifying the salience of dynamic visual cues. *Journal of Motor Behavior, 37*, 367-376.

Savelsbergh, G.J.P., Whiting, H.T.A., & Bootsma, R.J. (1991). Grasping Tau. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 315-322.

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*, 225-260.

Schmidt, R.A. (1976). Control processes in motor skills. *Exercise and Sport Sciences Reviews, 4*, 229-261.

Schmidt, R.A. & McCabe, J.F. (1976). Motor program utilization over extended practice. *Journal of Human Movement Studies, 2*, 239-247.

Slifkin, A. B., Vaillancourt, D. E., & Newell, K. M. (2000). Intermittency in continuous isometric force production. *Journal of Neurophysiology, 84*, 1708-1718.

Smith, T.Q. & Mitroff, S.R. (2012). Stroboscopic training enhances anticipation timing. *International Journal of Exercise Science, 5*, 344-353.

Sosnoff, J. J., & Newell, K. M. (2005a). Intermittent visual information and the multiple timescales of visual motor control of continuous isometric force production. *Perception and Psychophysics*, *67*, 335-344.

Sosnoff, J. J., & Newell, K. M. (2005b). Intermittency of force production and the frequency of rhythmical force production. *Journal of Motor Behavior*, *37*, 325-334.

Sosnoff,, J. J., & Newell,, K. M. (2006). Aging, visual intermittency and variability in isometric force output. Journal of Gerontology: B. Psychological Sciences, 61, P117-124.

Sperling, G. (1960). The information available in brief visual presentation. *Psychological Monographs, 74* (11, Whole No. 498), 1-29.

Steenhuis, R.E. & Goodale, M.A. (1988). The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short term memory for spatial location exist? *Journal of Motor Behavior, 20,* 399-415.

Thomson, J.A. (1980). How do we use visual information to control locomotion? *Trends in Neuroscience, 3* 247-249.

Thomson, J.A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance, 9*, 427-443.

Tremblay, L., Crainic, V.A., de Grobois, J., Bhattacharjee, A., Kennedy, A., Hansen, S., & Welsh, T.N. (2017). An optimal velocity for online limb-target regulation processes? *Experimental Brain Research, 235*, 29-40.

Vaillancourt, D., Slifkin, A. B., & Newell, K. M. (2001). Intermittency in the visual control of force in Parkinson's disease. Experimental Brain Research, 138, 118-127.

Von Noorden, G.K. & Burian, H.M. (1959). Visual acuity in normal and amblyopic patients under reduced illumination: I. behavior of visual acuity with and without neutral density filter. *Archives of Ophthalmology, 61*, 533-535.

Wilkins, L. & Appelbaum, L.G. (2019) An early review of stroboscopic visual training: Insights, challenges and accomplishments to guide future studies. *International Review of Sport and Exercise Psychology*. Online first.

Wilkins, L., & Gray, R. (2015). Effects of stroboscopic visual training on visual attention, motion perception, and catching performance. *Perceptual and Motor Skills, 121*, 57-79.

Wilkins, L., Nelson, C., & Tweddle, S. (2017) Stroboscopic visual training: A pilot study with three elite youth football goalkeepers. *Journal of Cognitive Enhancement, 2*, 1-7.

Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Review, 3, (Monograph Supplement)*, 1-119.

Figures

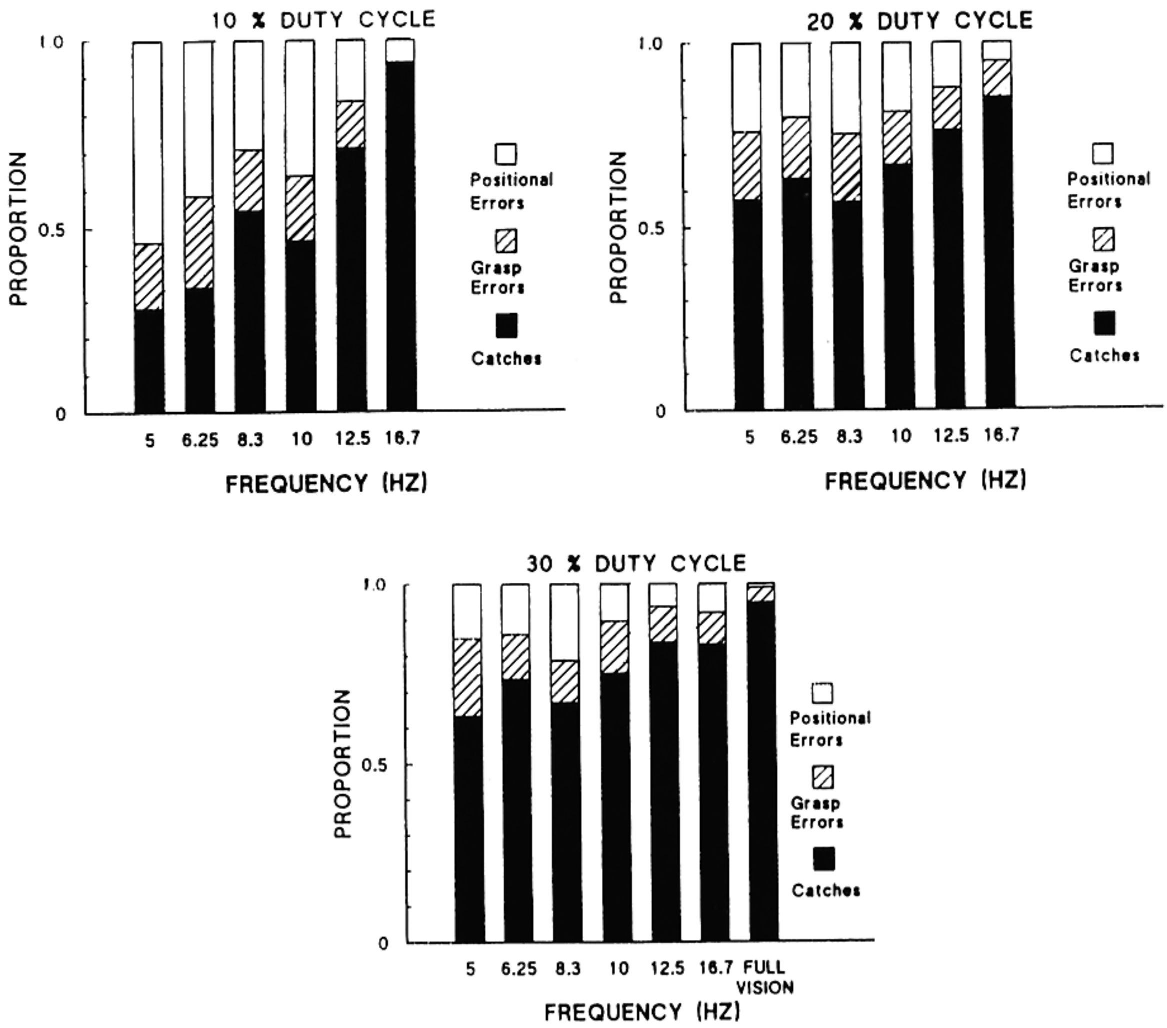


Figure 1: Proportion of catches, grasping errors and positional errors as a function of duty cycle and frequency. The duty cycle represents the percentage of the trial that the lens of PLATO goggles were translucent and participants had clear vision. Figure adapted from Elliott et al. (1994b) and reprinted with permission.

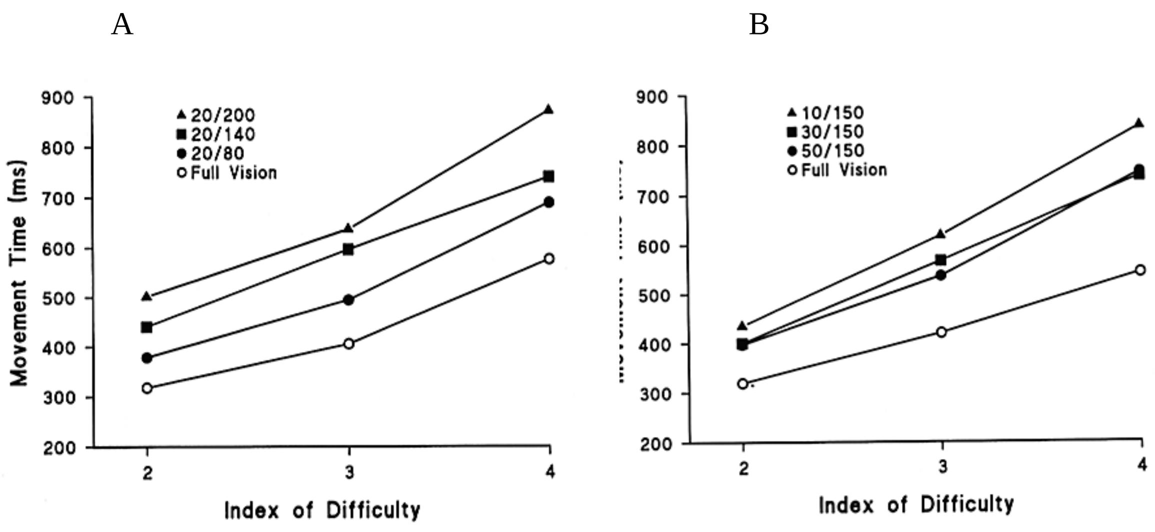


Figure 2: Movement time as a function of index of difficulty, sample time and no vision interval in experiment 1 (panel A) and experiment 2 (panel B). Figure adapted from Elliott et al. (1994a) and reprinted with permission.

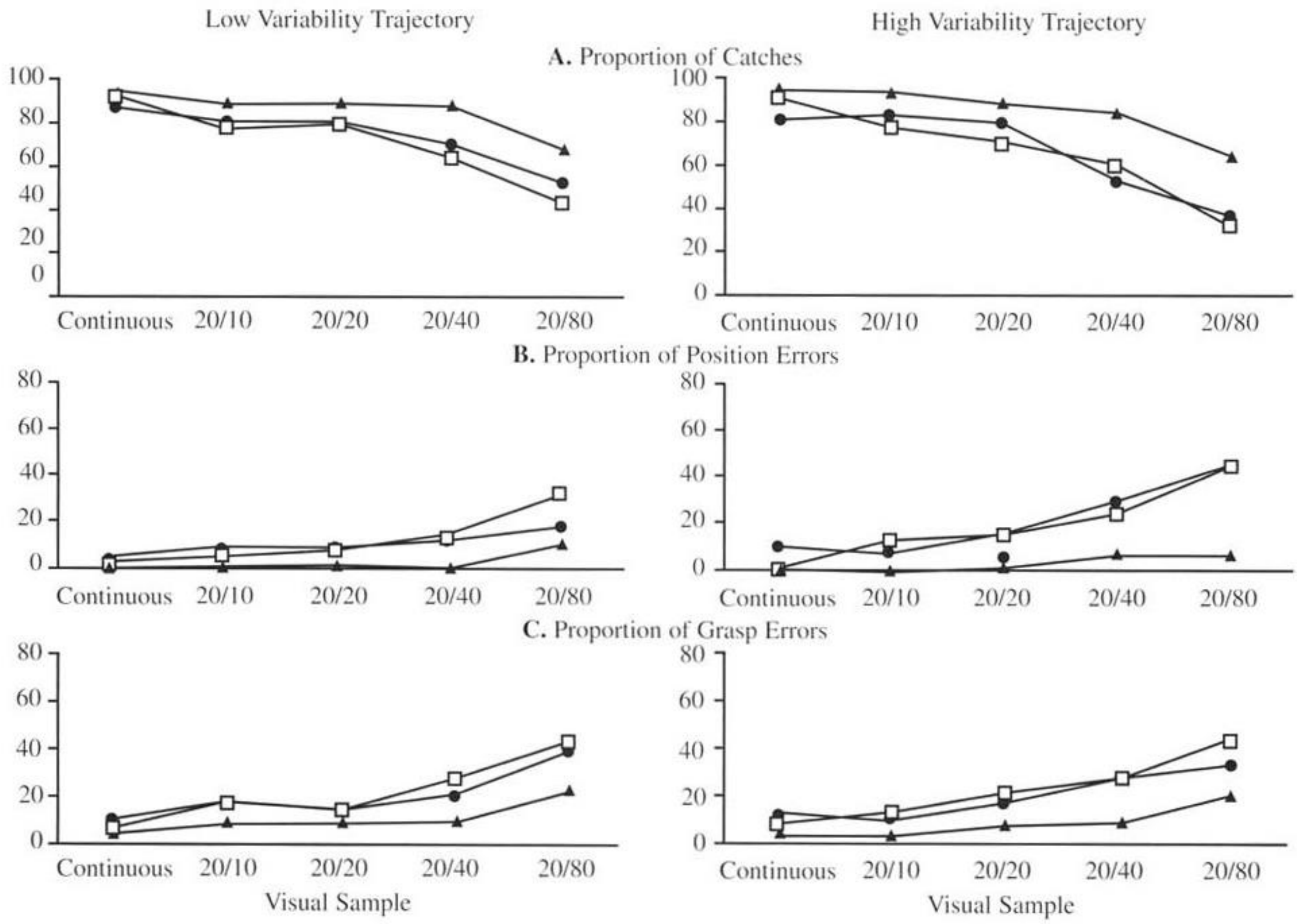


Figure 3: Proportion of catches (A – upper panels), position errors (B – middle panels) and grasp errors (C – lower pannels) as a function of trajectory variability (low and high), viewing condition (filled circles – monocular; open squares – alternating; filled triangles – binocular) and no vision interval (10, 20, 40, 80 ms). Figure from Bennett et al. (2006) and reprinted with permission.

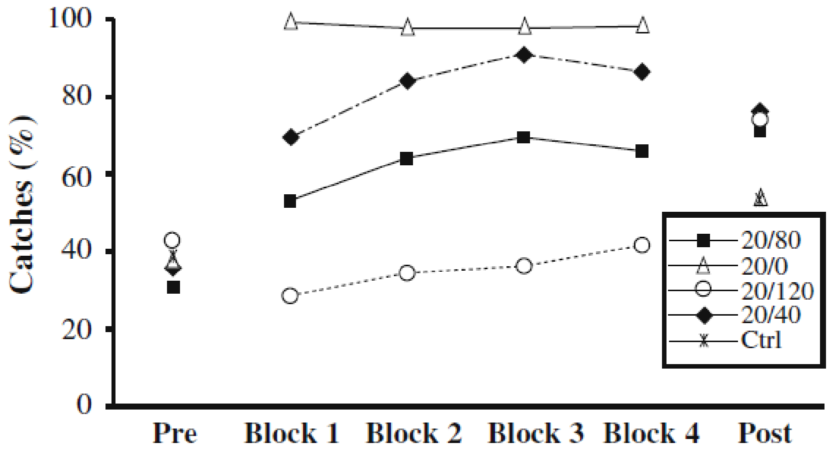
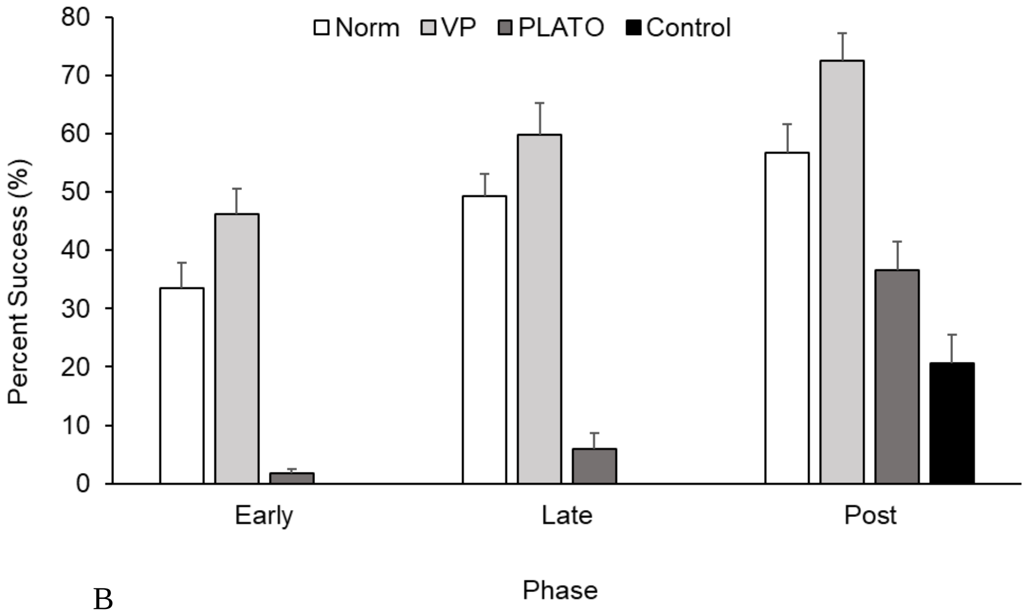


Figure 4: Proportion of catches as a function of test (pre, post), block (1-4) and group.

Figure from Bennett et al. (2004) and reprinted with permission.

A



B

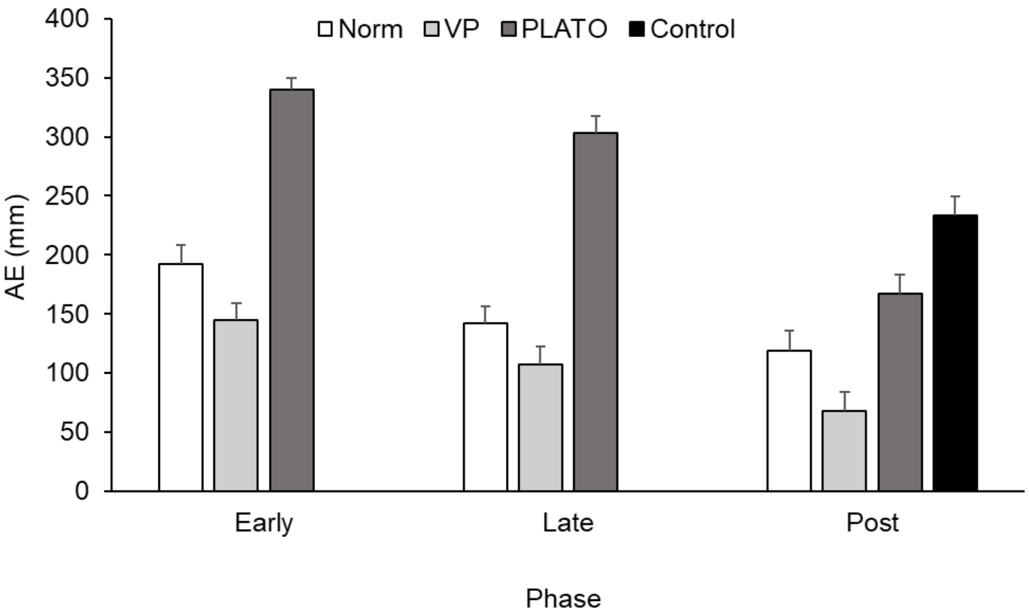


Figure 5: Percent successful responses (panel A) and AE (panel B) as a function of group (VP-Nike Vapor Strobe; PLATO; Norm - Normal Vision; Control) and phase (Early, Late, Post). Error bars represent the standard error of the mean. Figure adapted from Bennett et al. (2018).