VISION TESTING AND VISUAL TRAINING IN SPORT

by

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ABSTRACT

This thesis examines vision testing and visual training in sport. Through four related studies, the predictive ability of visual and perceptual tests was examined in a range of activities including driving and one-handed ball catching. The potential benefits of visual training methods were investigated (with particular emphasis on stroboscopic training), as well as the mechanisms that may underpin any changes. A key theme throughout the thesis was that of task representativeness; a concept by which it is believed the more a study design reflects the environment it is meant to predict, the more valid and reliable the results obtained are. Chapter one is a review of the literature highlighting the key areas which the thesis as a whole addresses. Chapter's two to five include the studies undertaken in this thesis and follow the same format each time; an introduction to the relevant research, a methods section detailing the experimental procedure, a results section which statistically analysed the measures employed, and a discussion of the findings with reference to the existing literature. Finally, in chapter six the strengths and limitations of the thesis are considered, before suggestions are made for future studies, and concluding remarks made.

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CHAPTER ONE

"It is in the use of the master eye, they say, that enables you to shoot straight, to hit a golf ball, to smash a tennis ball, to pot the red, and such other things in the same category that call for the use of 'eye'."

- Robert W. Doyne (1910)

GENERAL INTRODUCTION

If you were to observe a tennis coach giving a lesson to a beginner, it would not surprise you to hear the phrase "keep your eye on the ball". Likewise, football commentators are keen to point out what great vision Xavi or Iniesta have following a defence-splitting pass. Whilst in cricket, once a batsman reaches 20 or 30 runs, he is often said to have "gotten his eye in". Anecdotally then, the importance of our visual abilities to our sporting performance seems evident. However, whilst it may seem obvious that the ability to catch a ball, aim at a target, or make a pass would be compromised under poor visual conditions, the existing literature on the subject remains ambiguous. And if it is not yet clear whether degraded vision negatively affects our performance, then the question of whether superior vision enhances it is open to even greater debate.

To emphasise the point, one of the earliest studies to investigate the role of vision in sports looked at visual skills in both varsity football and basketball and produced two contrasting findings. Measuring a number of visual functions including acuity, fusion, stereopsis, and a form of visual attention, Tussing (1940) reported that there was a tendency for left eye acuity to decrease after fatigue (i.e. a training session) for football players but to increase after fatigue for basketball players. Though it was suggested that the latter may be due to a "greater opportunity to use (exercise) the eyes" (p. 17), no explanation was given for why the reverse was true for football players. Thus, ambiguity has surrounded the literature since the beginning, and though there is growing evidence in recent years that athletes do indeed have *some* visual abilities that are superior to non-athletes, it is far from conclusive (Williams, Davids, & Williams, 1999). Indeed, it accordingly leads to numerous subsequent questions. Do athletes from one sport have particular visual skills that are stronger or weaker than athletes from another sport? Do athletes from the same sport differ on the visual abilities according to the position they play? Can visual training programmes improve visual abilities? And, do these improvements transfer to enhanced athletic performance?

This thesis centres on two aspects that are currently seeing a resurgence in sports science research: visual testing and vision training. In this Introduction I review research on vision and sports, focusing on potential factors that could explain discrepancies in vision testing studies and provide an analysis of the advantages and disadvantages of visual training programmes. Within this introduction I hope to emphasise key gaps in the current literature whilst highlighting how the studies I have conducted aim to address these issues. Whilst some visual terms are defined in the text, an appendix has been provided at the end of this thesis containing full definitions of all the visual functions mentioned.

This thesis had four primary aims related to vision testing and training: i) address the lack of 3-dimensional motion tasks in testing and training, ii) investigate the transfer of potential stroboscopic training effects to sports performance, iii) examine how stroboscopic training effects motor control, and iv) further explore the issue of task representativeness in the design of visual-perceptual testing.

A Review of Sports-Related Vision Research

To best understand the current state of the sports vision literature, it is necessary to recognise the research that has preceded it. As previously mentioned, the ambiguities in sports vision literature were evident over seventy years ago, yet Tussing wasn't the first to study visual skills in the sporting domain. In 1921, Fullerton conducted a series of experiments which seemed to show that the legendary baseball player Babe Ruth had significantly superior visual skills and quicker reaction time compared to the average person (Fullerton, 1921), whilst ten years later, Banister and Blackburn were reporting that many athletes in ball sports had below average visual acuity (Banister & Blackburn, 1931). Discussions on the merits of unilateral and bilateral vision in sports such as cricket, tennis, and shooting occur in the British Medical Journal even further back than these; with Doyne (1910) arguing for an emphasis on bilateral vision, alongside an acknowledgement for the role that the brain plays in our visual skills. Mills (1928) later went on to state that "in all sports the crossed dextral and sinistrals are at an anatomical and physiological disadvantage" (p. 191). Finally, Kretchmar, Sherman, and Mooney's (1949) interesting examination of visual skills in the area of teaching physical education refers to work that appears to show the importance of different visual functions in balance (Bass, 1939), golf putting (Griffith, 1931), American football intelligence (Meser, 1938), and certain athletic activities (Griffith, 1928).

These studies were, however, infrequent and often plagued by opinion and conjecture, rather than controlled scientific experimentation. It wasn't until the 1970s and 1980s that empirical research into visual skills (and subsequently, visual training) in sports began to become more common. Indeed, in one of the foremost publications on the topic – Williams et al.'s, (1999) *Visual Perception and Action in Sport* – 331 pieces of work are referenced from 1980-1989, compared to 135 for the period 1970-1979, and 84 for the whole time before that. This rise in publications from the 1970s onwards is in stark contrast to many other scientific fields (Larsen & von Ins, 2010), and there are particular reasons as to why studies into visual skills in sport were not widespread before this time, many of which centre around the introduction of the corneal contact lens.

Prior to contact lenses, athletes with visual impairments struggled for a number of reasons. Whilst the safety issues regarding playing sport whilst wearing glasses seems apparent (broken lenses falling into the eye, lenses clouding during changes in weather, etc), it has also been suggested than the frames of glasses could reduce the peripheral vision of athletes by up to 25%; a significant factor in many sports (Burke, 1992). However, the most impactful hurdle, both to the athletes and to the progression of sports vision literature, was the stigma that was associated with visual aids. Wearing glasses during sport, especially in the first half of the 20th century, was seen as a sign of weakness; a visible flaw on show to both an opponent, and the individual's coach. Such was the negativity towards visual aids that many athletes avoided using them in all but the most severe of cases, often denying any need for glasses. Because of this, the issue of how visual skills (particularly below-average skills) impacted sports performance did not attract much notice amongst researchers in the sports science fields. It wasn't until a combination of the introduction of soft contact lens and the emergence of role models sporting visual aids (such as Billie Jean King and M.J.K. Smith) that the stigma associated with visual aids in sport began to dissipate.

Since the 1970s the sports vision literature has moved forward considerably. Studies have looked at a wide range of visual skills, however, as we will see, the findings have often been ambiguous. It is interesting to note then, that one of the primary explanations recently proposed for this ambiguity was initially suggested as far back as 1910 in Doyne's assessment of sports vision. He declared that "such things are so much more the result of experience and brain judgement than of actual visual acuity" (para. 4). This quote was a foreshadowing of the inconsistency in classifying visual functions that has been common in this literature.

Visual Hardware and Visual Software

Numerous visual skills and abilities have been investigated in relation to sports performance, with some of the most common being acuity, size of the visual field, depth perception, visual attention and memory, saccadic eye movements, and visual reaction time (Williams et al., 1999). A common distinction that has frequently been made between these different skills is that of visual hardware or visual software (Starkes, 1987). Visual hardware refers to more general abilities that are underpinned by the mechanical and biological aspects of the visual system (and are not specifically or uniquely related to sport), and would include acuity, visual field size, and depth perception, as well as others such as contrast sensitivity and accommodation. Visual software, on the other hand, is associated with more cognitive aspects of the visual system, is often specific to the activity at hand, and thus, would correspond to skills such as visual attention and memory, visual search strategies, anticipation, and visual reaction time.

The majority of research suggests that it is visual software skills that differ as a function of sporting expertise. Epstein (2013) surmises as much when he states that “the result of expertise study…can be summarised in a single phrase that played like a broken record in my interviews with psychologists who research expertise: It’s software, not hardware” (p. 37). This idea relates back to a general finding in sports-science literature made famous by Chase and Simon (1973), in which experts are only shown to excel at tasks which are specific to their domain. Our visual and perceptual skills seem to follow the same path. However, it cannot be ignored that there are plenty of studies which do find differences between athletes and non-athletes (and between elite athletes and non-elite athletes) in hardware visual skills, and several of these will be included in the section below where I review some of the key studies that have compared visual functions for athletes of different skill levels.

Abernethy and Neal (1999) investigated the visual abilities of 11 skilled and 12 novice clay target shooters. Tests of static and dynamic acuity, ocular muscle balance, eye dominance, depth perception, colour vision, simple and choice reaction time, speed of target detection, peripheral response time, saccadic eye movements, and coincidence-timing were used. The results failed to show an expert advantage in any of the visual skills measured (experts did have significantly quicker simple reaction time than the novices, though this was due to the below-average scores of the novices, rather than an above-average score for the experts). Consequently, they state that “an advantage for the skilled performer is only seen if vision is tested in a functional way, using sport-specific stimuli which closely replicate the visual processing requirements of the sport task” (p. 15). These findings replicate a previous paper showing no differences in visual hardware abilities amongst expert, intermediate, and novice snooker players (Abernethy, Neal, & Koning, 1994).

A possible confound related to this study is in the age of the participants. Whilst the expert shooters had a mean age of 38 years, the novice group averaged only 22 years. Considering that substantial research has shown visual abilities deteriorate once we reach our twenties (Burg, 1966, Ishigaki & Miyao, 1994, Kosnik, Winslow, Kline, Rasinski, & Sekuler, 1988), this 16-year difference could be significant in diminishing any potential advantages for the experts. The same criticism can be made of their earlier study on snooker players, where the novice group was again, over a decade younger.

The latest thinking regarding the different roles that visual hardware and visual software play in sporting performance is probably best epitomised by the hypotheses made in a recent study by Poltavski and Biberdorf (2014). This study investigated the extent to which eleven different visual measures could predict the statistical performance of highly skilled ice hockey players, hypothesising that the dynamic measures used would be greater predictors than the static ones. The findings partially supported this, with 69% of the variance in goals made being explained by near-far quickness (a task requiring a combination of accommodation and vergence), perception span (the extent of the visual field in which responses to visual stimuli can be correctly made), go/no-go score (the ability to recognise quickly, and respond correctly, to visual stimuli), and hand reaction time (the ability to initiate movement to a visual stimulus as quickly as possible). These are all dynamic measures. In contrast, static acuity, depth perception threshold, contrast sensitivity – all static measures – were not able to predict ice hockey performance. However, it must be noted that the same was true of dynamic acuity and eye-hand coordination, though the authors suggest that this may be due to the former possibly measuring something other than dynamic acuity, and the latter not incorporating a two-handed approach that would be more representative of hockey performance. I next review studies that have focused on one (or a small set) of visual functions.

Visual acuity has long been the predominant marker of visual ability in sports science research, and the findings with regards to sporting expertise are again highly variable. This difference, though, is often related to how acuity is measured. Static visual acuity (SVA) was the original standard measure of acuity; assessing one's ability to "visually discern detail in an object" (Knudson & Kluka, 1997, p.3). Dynamic visual acuity (DVA), on the other hand, refers to "the ability to discriminate an object when there is relative movement between the observer and the object" (Burg, 1966, p. 460), and it is here – rather than in SVA – that performance differences in sport can be found. Indeed, in a series of seminal studies by Ludvigh and Miller (1958), they reported that the relationship between the two is often negligible, with individuals of equal SVA frequently differing distinctly in DVA.

Given the dynamic nature of sport, it is not surprising that the literature tends to find performance differences only for DVA and not SVA. Studies have shown the expert advantage in the former for water polo (Quevedo-Junyent, Aznar-Casanova, Merindano-Encina, Cardona, & Sole-Forto, 2011), table-tennis (Hughes, Bhundell, & Waken, 1993), softball (Millslagle, 2000) baseball (Uchida, Kudoh, Higuchi, Honda, & Kanosue, 2013), motorsports (Schneiders et al., 2010), and tennis and badminton (Ishigaki & Miyao, 1993). Whilst both DVA and SVA are usually classified as visual hardware, clearly DVA better reflects the environment of many sports (which contain multiple moving objects) than SVA. This line of reasoning is supported by the work of Uchida, Kudoh, Murakami, Honda, & Kitazawa (2012) who found that the superior DVA of a sample of baseball players was due to better visual tracking of a moving object (a software skill) and not better processing of a moving image on the retina (a hardware skill). However, as with much of the research on visual testing in sport, there are studies which have produced contradictory findings, whether it is a lack of expert differences in DVA and SVA scores (Ward & Williams, 2000, Hoshina et al., 2013), or superior SVA found in highly skilled athletes (Ikarugi, Hattori, Awata, Tanifuji, & Ikarugi, 2005). If nothing else, this difficulty in classifying visual attributes, and the varied findings reported depending on how and what is measured, simply add to the uncertainty often found in vision testing.

The idea that some athletes may possess greater than average visual functioning has, though, received both anecdotal and empirical support. Baseball players are often said to have superior vision compared to the ‘normal’ person; for example, it has been reported that the average player has a static visual acuity of 20-12 (the ability to see at twenty feet what the average person sees at twelve feet) (Harvey, 2013). Likewise, in a re-analysis of Keele’s (1973) investigation into Muhammad Ali’s visual reaction and movement times, Kamin and Grant-Henry (1987) showed that the boxer had a visual reaction time of 140 milliseconds – considerably quicker than the 190 milliseconds that Keele suggested was average for the general population. This superiority is potentially even greater if Ali’s motor programming time is taken into consideration as well; given that the usual methodology employed is a simple finger response on a button, and not the full-scale, 16.5 inch jab that Ali was measured upon.

Research investigating visual reaction time often reports conflicting conclusions akin to that of acuity. Again, this may be due to exactly which type of reaction time is measured, be it simple reaction time – where the required response to a stimulus is known prior to the event – or choice reaction time – where individuals must determine the required response to a stimulus on initiation of the event (Klapp, 2010). For example, whilst Berry reported that visual reaction time could not predict a baseball batter's hitting performance (Berry, 1995); Ghuntla, Mehta, Gokhale, and Shah (2012) reported that a sample of basketball players had significantly faster reaction time than a control group. It is possible that some visual functions, such as reaction time, are able to differentiate between athletes and non-athletes, but are not quite sensitive enough to differentiate between athletes of varying abilities.

The difference between visual hardware and visual software may be best demonstrated by Zwierko (2007) in her study comparing the peripheral perception of hand-ball players and non-athletes. Peripheral perception in this case was defined as composing two main visual functions: visual field measures (components of visual hardware) and visual reaction time measures (components of visual software). Of specific interest was the finding that athletes showed significantly quicker visual reaction time than non-athletes, yet showed no difference in field of vision. These results are in accordance with the work of Abernethy and colleagues (1994, 1999) described earlier.

Depth perception refers to the ability of an individual to judge distances and spatial relationships between objects and places (Williams et al., 1999). This attribute would appear to be important in many sports; most obviously in target-based sports such as golf, but also in judging the distance to ensure the correct 'weight' of a pass or shot in sports such as football and basketball. Isaacs (1981) investigated the relationship between depth perception and basketball shooting performance and found that this aspect of vision significantly correlated with free-throw shooting but not with field-goal shooting. One potential reason for this difference could lie in the fact that the latter is a much more varied and open skill, often performed whilst in motion, and thus less likely to be linked with a static visual measure such as depth perception. This point is similarly emphasised by Zinn and Solomon (1985) who found no correlation between static and dynamic scores of stereopsis (a measure of the use of a particular depth cue which relies on combining information from the two eyes). Again, the extent to which the test reflects the task of interest is likely to be fundamental in identifying performance differences.

It seems that for every study which finds an association between athletic performance and visual abilities (Laby et al., 1996), another finds the opposite (Sherman, 1980). In the former of these examples, 387 professional baseball players were found to have significantly better visual acuity than the general population, whilst in the latter, 15% of NFL players and 20% of NBA players were found to have worse visual acuity than the general population. The same is true for depth perception; Blundell's (1984) study on tennis players indicated expert-novice differences, contradicting the findings of Isaac's (1981) study on basketball shooting ability. Finally, the literature on peripheral vision follows the same pattern; research has shown athletes to be superior to non-athletes (Williams & Thirer, 1975), whilst it has also been stated that some studies show no expertise effect (Williams et al., 1999).

Whilst the selection of a sport is often due to the geographical location of the study (i.e. South Africa and rugby, Australia and cricket, Japan and baseball), basketball has proven a popular choice amongst visual skills research. For example, Quintana, Roman, Calvo, and Molinuevo (2007) found that skilled youth basketball players had better than average visual acuity, visual reaction time, stereoscopic vision, and horizontal visual fields. To emphasise the importance of this, the authors noted that visual testing has been employed in summer camps by the Spanish National Basketball Federation since 2002. The sport assessed in a study, though, is an important factor that perhaps is not considered enough. Cockerill and MacGillivary (1981, p. 124) stress this point when discussing studies of depth perception in sport. They suggest that, although differences in depth perception may exist between athletes and non-athletes, there is likely just as much difference within the games playing (athlete) group as well. It is logical that to accurately assess the 3-dimensional, dynamic world of sport we must employ 3-dimensional, dynamic tests. In an extension of this, it seems reasonable that the specific nature of a sport may also influence which visual skills may be predictive of performance in them. Measuring the peripheral vision of professional golfers, or the visual acuity of elite-sprinters, for example, is highly unlikely to produce expertise-related differences, as these visual skills are not a requirement for the skills in each sport. By contrast, the visual skills found by Quintana et al. (2007) to be significantly different in basketball players (larger visual fields, greater depth perception, and superior stereoscopic vision) are all likely to play a role in the performance of basketball skills such as successfully tracking opponents/teammates and judging the weight on passes and shots.

This idea is demonstrated in a study by Kioumourtzoglou, Kourtessis, Michalopoulou, and Derri (1998) who assessed the visual skills (specifically identified by the coaches as being important in their sport) of basketball, volleyball, and water-polo players. They found that the significant differences obtained were dependent upon which sport the participant played. Specifically, basketball players had better selective attention, volleyball players had superior processing speed and detection of the speed and direction of motion, and water-polo players had greater visual reaction time. These findings *may* reflect the distinctive requirements of each of the sports. Furthermore, accounts of Olympic archers with superior visual acuity but not depth perception, and softball players with the reverse are pointed to by Epstein (2013) as evidence that “clearly, visual hardware interacts with the particular sports task at hand” (p. 43).

Wimshurst, Sowden, and Cardinale (2012) extended this argument even further by investigating whether the visual performance of athletes within a single sport differed depending on the position played. In this study, 21 field hockey players performed six computer-based visual tests, which included measures of dynamic acuity, peripheral awareness, depth perception, visual memory, and saccadic eye movements. No significant position-related differences were found for any of the visual measures. A similar finding was reported by Alves, Spaniol, and Erichsen (2014), who found that depth perception, convergence, divergence, visual recognition, and visual tracking did not differ amongst elite footballers depending on position. However, limited evidence for positional specificity has been found for cognitive skills, such as a decision making task in netball scenarios; here it was found that the skilled goalkeepers and attackers outperformed novices in response accuracy, but skilled defenders did not (Bruce, Farrow, & Raynor, 2012).

There are additional important factors that must be considered when evaluating the positional specificity of visual skills. Most notably is that in the majority of sports, individuals tend to practice and compete in a variety of different positions over the course of their sporting career, often alternating between attack and defence. This may increase further still when athletes change teams and/or coaches. Furthermore, it is often not until the highest level of sport are reached (whose athletes are rarely if ever used as participants in this type of research) when athletes can consistently play at the same position. Another consideration is the idea that, given the often increased speeds and movements associated with top-level sport, *all* visual skills are improved as one makes progress to the elite level. Finally, there is also the possibility that elite-level athletes innately have greater visual skills, and as such do not differ between positions, though this argument opposes many studies showing no differences between athletes and non-athletes on measures of visual hardware.

Turning to research that has focused on visual software skills; studies in this area have incorporated designs that attempt to better replicate the performer's 'expert' environment than research on visual hardware. For example, the use of video clips depicting sporting situations is integral in temporal and spatial occlusion paradigms which are designed to assess the visual informational pick-up characteristics of groups of individuals, including skills such as anticipation (Farrow, Abernethy, & Jackson, 2005). Whilst it may seem more difficult to incorporate aspects of the sporting environment in measures of visual hardware, it is not impossible, and is an important step in clarifying whether the current ambiguity in the literature is a result of the naturally more task-representative design in visual software studies, or of an underlying difference in which visual skills predict expert performance. This question will be addressed specifically in the study described in Chapter Five of this thesis.

An example of the ease in which the measurement of software skills can be adapted to sport-specific situations is in a study by Allard, Graham, and Paarsalų (1980). Here the seminal study by Chase and Simon (1973) was tailored to a basketball scenario in order to assess visual memory. That is, participants were asked to remember the locations of players from two types of photographed scenes: structured (picture taken during match-play) and unstructured (picture taken during a time-out). As expected, in structured scenes, basketball players recalled far more than non-players (80% vs. 50%), but in unstructured scenes there was no differences. It is clear that with regards visual memory, the expert advantage is not general, but rather specific to their domain.

The temporal and spatial occlusion paradigms have been used to demonstrate the expert's advantage in anticipation and/or advanced cue utilisation in a wide range of sports including badminton (Abernethy & Russell, 1987), cricket (Weissensteiner, Abernethy, Farrow, & Muller, 2008), football (Savelsbergh, Williams, Van Der Kamp, & Ward, 2002), ice hockey (Salmela & Fiorito, 1979), rugby league (Gabbett & Abernethy, 2013), squash (Abernethy, 1990), tennis (Buckolz, Prapavesis, & Fairs, 1988; Jones & Miles, 1978), and volleyball (Starkes, Edwards, Dissanayake, & Dunn, 1995). The procedure for such studies usually involves two or more groups of differing expertise viewing footage of a critical moment in their sport (for example, the bowler's delivery in cricket, or the opponent's serve in tennis). Explicit information pertaining to a situational judgement is removed at either a specific time (temporal occlusion) or from a specific place (spatial occlusion). Differences in measures such as anticipation and visual search between these occluded trials and non-occluded trials therefore infer that the occluded time frame/area is important for information pick-up. The importance of anticipation in sport (particularly high-speed ones such as tennis and squash) was emphasised by Abernethy, who stated that "an ability to accurately anticipate the opposing player's actions is essential for successful competitive performance" (Abernethy, 1990, p. 17).

Not surprisingly then, visual search is another software skill that has received much attention in the existing literature. Indeed, Savelsbergh, Haans, Kooijman, and van Kampen (2010) stated that the differences in visual search behaviours found between high and low-ability participants (in their study, for an interception task in football) may lead to the differences in anticipation between such groups. Visual search generally refers to three aspects when viewing a scenario: number of fixations, duration of fixations, and location of fixations, with 'efficient' visual search strategy seen as one in which there are fewer fixations of longer duration (Williams et al., 1999). A study by Savelsbergh et al. (2002) found that expert football goalkeepers, for a penalty saving task, had a more efficient visual search strategy compared to novices. Likewise, similar results have been obtained in basketball shooting (Vickers, 1996), golf putting (Vickers, 1992), and rifle shooting (Janelle et al., 2000).

Whilst fewer fixations of longer duration are believed to allow for greater information pick-up (Mann, Williams, Ward, & Janelle, 2007), the literature is not clear-cut. For example, the "efficient" search strategy results were not replicated by Vaeyens, Lenoir, Williams, Mazyn, and Philippaerts (2007), who found no significant differences in fixation number and duration between football players of different abilities, though fixation location did differ (elite fixated less on defensive players and unmarked attackers). Likewise, Williams and Davids (1998) found that experienced football players (when responding to 1-on-1 offensive match situations) had the opposite: more fixations of shorter duration compared to less experienced payers, illustrating the ambiguity in visual search findings. It has been suggested that these differences may be a result of varying nature of skills between different sports, or indeed, within the same sport (Martell & Vickers, 2004).

As with acuity, research on visual reaction time could be argued to contain both software and hardware elements; this time based on how they are measured. Specifically, Mori, Ohtani, and Imanaka (2002) noted that reaction time to generic stimuli (such as flashes of light) often produce null findings, or only small differences between experts and novices. In contrast, studies which have incorporated sport-specific methods have generally found experts to have significantly faster reaction times (Allard & Starkes, 1980). A recent study comparing both anticipation and reaction time in volleyball players and sprinters may also lend support to this idea. Nuri, Shadmehr, Ghotbi, and Moghadam (2013) found that sprinters had significantly better auditory reaction time whilst volleyball players had significantly better anticipatory skills. Given the nature and requirements of sprinting and volleyball, it is clear that the skills in which each set of athletes were superior are specific to their sport.

As can be seen from the studies reviewed so far, the majority of research tends to focus on either visual hardware or visual software, though there are exceptions. Starkes (1987), for example, assessed expert, moderate, and novice hockey players on three measures of visual hardware (dynamic visual acuity, simple reaction time, and coincidence anticipation) and four measures of visual software (visual memory recall, advance cue usage, simple sport-specific decision accuracy and speed, and complex sport-specific decision accuracy and speed). Consistent with much of the literature, the expert advantage was revealed only in visual software skills (with the exception of simple sport-specific decision accuracy and speed and complex sport-specific decision speed). Indeed, for simple reaction time, experts actually were significantly slower than the moderate and novice groups.

Another study with a similar aim was that of Helsen and Starkes (1999). In this instance, the same expert and intermediate football players were used for all three experiments. In the first, the participants were compared on their visual hardware performance, with measures including central and peripheral reaction time, static and dynamic acuity, and visual correction time. In the second and third experiments, participants were compared on their visual software, with the stimuli (offensive football scenarios) being presented statically (i.e. slides) in the former and dynamically (i.e. video) in the latter. The software skills measured included visual fixation frequency, duration, and location, response accuracy, and response speed. No significant differences were found between the expert and intermediate football players on the visual hardware measures. In contrast, experiment two found experts to have significantly faster and more accurate responses than intermediates, as well as fewer fixations located on different areas of the scenario. Experiment three confirmed these findings in response to dynamic, videoed stimuli.

A meta-analysis examining the expert-novice difference in response accuracy, response time, number of visual fixations, and duration of visual fixations was conducted by Mann et al. (2007). The study also incorporated moderator variables to investigate whether any of the expert-novice differences found in these visual software skills were influenced by other factors. This included sport type (interceptive, strategic, and other), research paradigm (occlusion, anticipation, recall, recognition, decision making, task performance, and eye movement), and presentation method (video, static, and field).

The results agreed with the ‘efficient’ visual search of experts (fewer but longer fixations), and also that experts have quicker and more accurate responses; skills that are all likely to benefit the athlete during sport performance. Interestingly, for response accuracy and response time, the smallest effect sizes were found when recall and recognition paradigms were employed. Whilst these tasks are still specific to the domain in question, they are often less skill dependent as compared to anticipation and decision making paradigms. Sport type moderated the effect on response time and number and duration of fixations, whilst presentational method moderated the effect on response accuracy and number and duration of fixations. In the former case was, the moderating effect was inconsistent (e.g. other sports produced a significantly smaller effect than strategic sports for response time, but a significantly larger effect than interceptive sports for fixation duration). With regards the moderating effect of presentational method, studies taking a real-world/field approach generated the largest effect sizes. Such differences may be due, in part, to the degrees of task representativeness involved in each sport type, paradigm, and presentation method – an idea that will be looked at in detail later in this chapter.

Memmert, Simons, and Grimme (2009) provide further evidence supporting the role of task representativeness in their study on the differences in basic visual attention abilities of expert handball players, individual-sport athletes, and novice athletes. In their study, the attentional tasks consisted of a functional field of view test, multiple object tracking test, and an inattentional blindness test; all of which involved the detection or tracking of generic, computerised stimuli. No significant differences between the groups were apparent in any of the three tests. These findings generally conflict with previous research that experts have superior attentional abilities compared to novices (Memmert, 2006; Pesce-Anzeneder & Bosel, 1998). As a result, the authors suggested that future studies should involve tests which assess attentional abilities that are more specific to the domain of expertise, in an attempt to find performance differences.

Garland and Barry's (1990) review on the contribution of visual, perceptual, and cognitive skills to sporting expertise still provides an accurate summary of the existing literature on the topic today. In examining literature on largely visual hardware-based skills such as stereopsis, acuity, eye-movements, and perceptual organisation ("the ability to integrate efficiently complex perceptual stimuli in the visual field", Garland & Barry, 1990, p. 1302), the authors conclude that there is little evidence to suggest that expert and novice athletes differ on these abilities. In contrast, they state that the research on cognitive skills – including aspects of visual software such as visual memory and anticipation – is unequivocal in its support for expert-novice differences. Indeed, they write that "although visual-perceptual abilities are inherent in all levels of sport performance, cognitive factors are essential for sport expertise" (p. 1299).

Recent evidence, then, seems to be harmonizing the existing literature to the view that visual skills which are based more on cognitive and perceptual processes ("software") may indeed be linked to sporting and motor performance. In contrast, those which are based on more basic visual processes ("hardware"), such as static visual acuity and depth perception, are less likely to make a difference. However, the ambiguity within visual hardware literature needs to be examined, and it is possible that one of the reasons for this ambiguity lies in the type of tests being used in experiments. Whilst measuring the search strategies and visual memory of athletes using sport-specific videos is commonplace amongst research, ensuring that measures of acuity and depth perception include both dynamic/motion and 3-dimensional aspects is less so. This is crucial given the nature of most sporting environments.

Degraded Vision

As discussed above, the question of whether elite sports performance relies on superior visual functioning is unclear. But can athletes with inferior vision succeed in sport? In January 2013 the transfer of footballer George Boyd from Peterborough United to Nottingham Forest was cancelled after the player failed an eye exam ("Boyd deal a sight for sore eyes", 2013). In June 2014, rugby player Sean Gleeson was forced to retire from the sport because of an injury suffered to his eye a few months earlier ("Hull KR centre Sean Gleeson retires with eye injury", 2014). A month later cricketer Craig Kieswetter sustained damage to his eye socket from a delivery that has been described as potentially career-ending ("Craig Kieswetter: Injury could end Somerset batsman's career", 2015). Such instances may indicate the importance of normal vision, or at least, the negative impact of degraded vision, though for every story like this, there is another in which poor visual functioning has not impaired performance. For example, darts player Gary Anderson reached the semi-finals of the World Matchplay tournament, despite claiming that, when playing, he cannot see, and is "just aiming for the blurs" (Lewis, 2013).

The effect of inferior vision on sports performance has been studied by using degraded vision paradigms. For example, by having participants wear lenses of varying refractive conditions whilst performing a sporting skill, researchers can systematically induce differing levels of reduced visual acuity (i.e., blur). Here a common theme does tend to emerge: visual acuity has to be decreased to levels approaching legal blindness before changes in performance are noticed. That is, small amounts of induced blur have been found to have no effect on an individual's ability to perform a set shot in basketball (Applegate & Applegate, 1992), bat in cricket (Muller & Abernethy, 2006, Mann, Ho, De Souza, Watson, & Taylor, 2007), or putt in golf (Bulson, Ciuffreda, & Hung, 2008). Equally, the degraded vision associated with monocularity (such as a reduced peripheral visual field) did not stop Westlake (2001) arguing the case that one-eyed individuals possess competent enough visual skills to be allowed to participate in motor racing.

In the previously mentioned study by Applegate and Applegate (1992), the basketball set-shot performance of 19 adolescents was examined under varying levels of induced blur. Specifically, participants performed 25 shots under each of the following visual acuity conditions: normal (6/6 or better), 6/12, 6/24, 6/48, and 6/75 (these denote the ability to see from six metres what a 'normal' individual can see from 6, 12, 24, 48, and 75 metres, respectively). Though performance decreased from the normal condition to the 6/12 condition, further degradation in acuity had no impact on shooting performance. In Bulson et al.'s (2008) study, golf putting performance of novices was measured under similar levels of blur-induced visual acuity and again, performance generally stayed the same. There was one exception to this; putting performance did get significantly worse under the extreme induced blur condition, which corresponded to a visual acuity of approximately 6/610.

In Mann et al.'s (2007) study, 11 youth cricketers were required to 'play a shot to' (intercept) a cricket ball delivered by a bowling machine in each of four visual conditions: normal, 6/18, 6/40, and 6/60. Performance measures included the percentage of deliveries in which bat-ball contact was made, percentage of deliveries in which "good" bat-ball contact was made, and the average shot quality. The latter two were subjective measures graded by a qualified cricket coach. The results show no significant difference for any of the performance measures between the normal vision condition and the 6/18 and 6/40 conditions. Percentage of bat-ball contact did significantly decrease in the 6/60 condition compared to the 6/18 and 6/40, whilst shot quality was also significantly lower in the 6/60 condition compared to all other conditions. Another study analysing cricket batting showed that completely occluding vision prior to the point of ball bounce produced no significant difference in foot movement or bat-ball contact percentage compared to when vision was not occluded at all (Muller & Abernethy, 2006).

Whilst these studies provide evidence that degraded vision (at least up until severe levels) does not inhibit sporting performance, there are caveats in their findings; the first of which lies in the tasks selected. Both the basketball set shot and golf putting are closed skills, and the visual requirements for each lack any fine details with which it would be expected the individual could struggle with (note, the golf putting task in Bulson et al.'s (2008) study was a straight putt; putting across a slope that involves 'breaks' may well require good discrimination of fine details). Indeed, Applegate and Applegate state that "subjects could always see the backboard and rim easily" (p. 767), whilst muscle memory may also have played a role in performance. Whether or not such findings would have occurred had the task required more precise or dynamic movements is unclear.

Though Mann's study avoids this pitfall, the authors note that the auditory cues associated with the bowling machine may have provided some aid during batting. It would also be interesting to see whether such minimal performance differences in the low refractive conditions remain if the deliveries were not performed in 15-trial blocks (potentially allowing for pre-emptive actions given that the direction varied in only 1 of 4 locations) and not delivered by a bowling machine (where speed and trajectory is more predictable). However, it should be stated that in a later study following an analogous protocol, similar findings were reported when a live bowler was used that matched the velocity of the bowling machine (though performance did significantly decrease in the 6/40 condition when the live bowler was at a higher velocity) (Mann, Abernethy, & Farrow, 2010).

Finally, an extreme case of whether or not degraded vision is detrimental to sports performance is discussed by Westlake (2001), who analyses the literature with a view to answering whether an individual with retinoblastoma should be eligible to compete in motor racing. Retinoblastoma is a cancer of the retina, and in this individual's case, resulted in the loss of the right eye at age 2. There are inherent limitations with monocularity; in particular, the peripheral visual field is reduced by between 20 and 40 degrees whilst the resolution in the remainder of this area is also reduced (though this reduction is less for dynamic, rather than static, targets). In addition, it has been shown that the depth perception/stereopsis and contrast sensitivity of monocular drivers is worse than that of binocular drivers (McKnight, Shinar, & Hilburn, 1991). The key, though, is whether these reductions in visual skills limit the sporting (in this case, motor racing) performance of the individual. Westlake highlights a number of studies which indicate no relationship between size of the peripheral field and driver crash records (Council & Allen, 1974; Hills & Burg, 1978), though it is suggested that one of the reasons for this is a modification of driving behaviour by those with reduced visual fields – a factor that is not conducive for the motor racing driver. Similar findings are reported with regards degraded stereopsis and crash records (Owsley et al., 1998).

As with much of the research on degraded vision, Westlake (2001) concludes by stating that, though the visual deficiencies associated with monocularity cannot be argued, the impact they have on driving performance is likely to be minimal. Vision does not appear to be a limiting factor in many aspects of driving performance, and this appears to be the case in sporting performance also, with many studies showing severe levels of degradation needed to bring about decrements in cricket batting, golf putting, and basketball shooting. However, this literature is based on measuring aspects of visual hardware (predominantly static acuity), and we have already seen that the links between these types of visual skills and sporting performance is ambiguous at best. These traditional visual measures – static, 2-dimensional tests – may not be reflective of the environment that an athlete excels in. In the same way that the relationship between visual skills and sporting performance is unlikely to be understood without sufficient studies utilising dynamic, 3-dimensional measures, nor will we understand the complete effect of degraded vision (and enhanced vision) on sports performance.

Visual Training

Once research began to link visual ability with sporting performance, the idea of training such skills to provide athletes with an advantage was a logical next step. Much of the early work attempted to market these programmes commercially, with a lesser focus on scientific research; 'Sports Vision', 'Eyerobics', and 'Dynavision' are such examples (Knudson & Kluka, 1997). As a result, the existing literature on the topic tends to examine the claims of these specific programmes (such as that visual training "may well make the difference between winning and losing" for athletes, Revien & Gabor, 1981, p. 21), although some have looked at different forms of visual training, particularly in the past decade or so.

The methods used to assess the effectiveness of visual training programmes have been vast and varied; some have focused on just one aspect of vision, others a number of different areas, some have measured both visual and sporting performance, others just one or the other. The list of sports investigated is also great and includes American football, badminton, baseball, basketball, cricket, field hockey, football, ice hockey, synchronised swimming, table tennis, tennis, and ultimate Frisbee, whilst other motor skills, often synonymous with sports, such as catching and anticipatory timing, have been examined as well. Within this, the abilities, age, sex, and number of participants used are yet more factors that differ across studies. This all contributes towards the ambiguity often found in the literature regarding the effectiveness of visual training programmes.

Abernethy and Wood (2001) identified three factors necessary for visual training programmes to be effective in the sporting domain. First, athletes should possess greater visual skills than non-athletes, and, depending on the population targeted by the training programme, elite-athletes should possess greater visual skills than less-skilled athletes. As we have already seen, and as Abernethy and Wood also mention, the validity of this assumption is dependent upon the visual skills measured; visual software, i.e. domain specific visual skills related to perception and cognition, have been shown to potentially differentiate these sets of population. The second factor is that visual skills can be improved through training. The general consensus amongst the literature is that this is true, with studies showing training to improve a variety of visual skills, including both static (Otto & Michelson, 2014) and dynamic acuity (Holliday, 2013), contrast sensitivity (Deveau, Ozer, & Seitz, 2014), saccadic eye movements (Rezaee, Ghasemi, & Momeni, 2012), depth perception (Paul, Biswas, & Sandhu, 2011), accommodation (Calder & Kluka, 2009), anticipation (Hagemann, Strauss, & Canal-Bruland, 2006, Smith & Mitroff, 2012), reaction time (Schwab & Memmert, 2012), visual search speed (Kumar, 2011), divided attention (Appelbaum, Schroeder, Cain, & Mitroff, 2011), and hand-eye coordination (McLeod, 1991). However, as previously stated, it is important that research recognizes the difference between improving poor vision to normal vision, and improving normal vision to above-average vision. Finally, the third factor necessary for visual training programmes to be effective for athletes is the idea that improvements in visual performance will transfer to improvements in sporting performance. Training programmes – visual or not – should target the limiting factors in an athlete's performance. If visual ability is not the limiting factor, it is unlikely that any improvements made should transfer to their motor performance. Because of this it has been proposed that visual training may be most beneficial to elite athletes, where the technical, physical, and tactical abilities of individuals are likely to be more similar than between novice athletes. However, Abernethy and Wood (2001) acknowledge that there may be secondary factors that arise from training programmes, unrelated to visual performance, that may be ultimately responsible for improvements in sporting ability, such as increased confidence and technique modification.

Aside from identifying these three key components needed for an effective training programme, Abernethy and Wood's (2001) study provided a thorough examination of two highly popular and highly commercialised visual training programmes: *Sports Vision* (Revien & Gabor, 1981), and *Eyrobics* (Revien, 1987).

The *Sports Vision* training programme uses a manual consisting of 9 optometry-based (rather than sports-specific) exercises aimed at improving a variety of different visual skills. Visual acuity was targeted through light stimulation – a method used to increase the sensitivity of the retinal receptors by shining a torch on the eyes and alternating between states of light and dark. Accommodation and convergence ability were developed with chord ball training – a modified Brock string task (see Figure 1a.) in which individuals alternate their fixation rapidly between beads of different distance along a line. Two exercises specifically aimed to improve peripheral awareness; a coloured rotor exercise, whereby individuals must track a black dot amongst various shapes and colours on a rotating disk, and a marbles in a carton exercise, in which individuals attempt to focus on a central dot in a moving carton filled with marbles. Finally, a modified Howard-Dolman method (see Figure 1b.) aimed to enhance depth perception, whilst other training drills targeted speed and span of visual recognition, hand-eye coordination, visual tracking, and concentration.

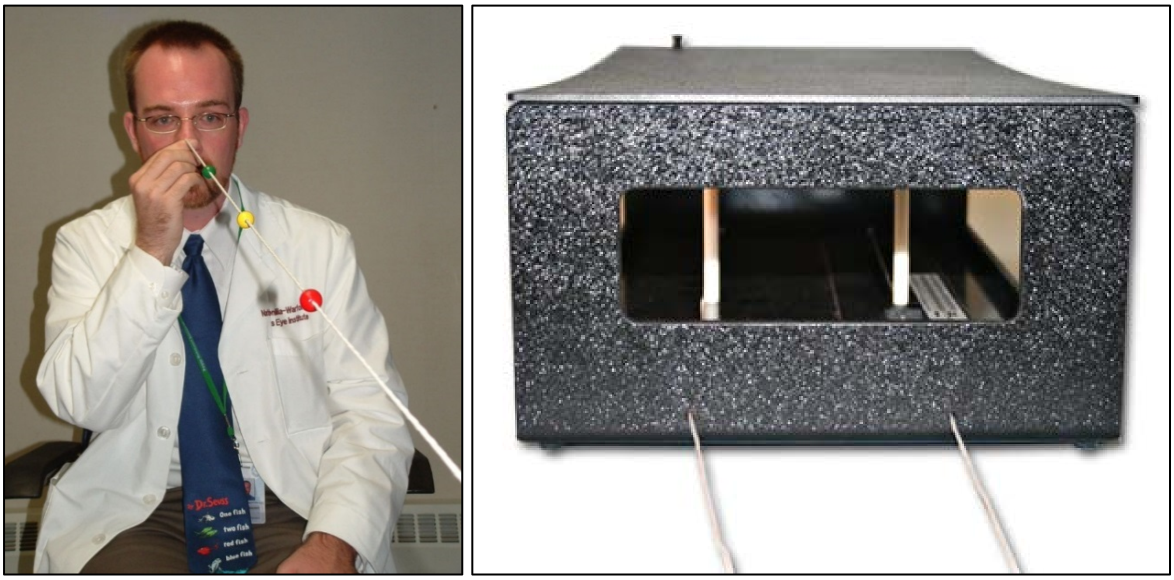

Figure 1. a) An image of the Brock String task being performed. Participants are required to shift their focus from one bead to another, b) an image of a Howard-Dolman apparatus; participants stand facing the apparatus and use the strings to attempt to align the white bars inside.

Eyerobics is a video based training programme which walks users through six exercises aimed to strengthen the muscles around the eyes. As a consequence of this the quality and magnitude of the visual information that the individual receives is enhanced (Revien, 1987). The exercises include: ‘rotating spiral’, ‘rotating target’, ‘grid tracing’, ‘speed and span of recognition’, ‘barber pole’, and ‘rotation 3D’. Amongst the visual skills targeted through these are visual acuity, visualisation, eye coordination, concentration, visual tracking, recognition speed, recognition breadth, visual reaction time, spatial orientation, and depth perception.

In Abernethy and Wood's study, 40 novice racquet sport players were assigned to one of four training groups: 1) *Sports Vision*, 2) *Eyerobics*, 3) reading, and 4) a control. In total, 12 visual-perceptual skills were measured (static and dynamic acuity, ocular muscle balance, accommodation, vergence, stereopsis, depth perception, reaction time, field of view, peripheral response time, eye-movement skills, and coincidence-timing) alongside a sport-specific motor task that tested the accuracy of participants' tennis forehand drive. The training programmes lasted four weeks. Each group underwent one, 20-minute motor session per week practicing the tennis forehand drive. In addition, groups one and two performed four, 20-minute sessions per week of *Sports Vision* and *Eyerobics*, respectively, whilst group three performed four, 20-minute sessions per week of other tennis-related activities (e.g. reading and watching matches). The results revealed no significant differences between *any* of the groups for *any* of the 12 visual-perceptual measures, or for the sport-specific motor task (tennis forehand drive). The study provides perhaps the most comprehensive examination of visual training programmes to date and concludes that there is "no evidence that the visual training programmes led to improvements in either vision or motor performance" (p. 203).

It is possible that the null findings of Abernethy and Wood's study were due to the methodology employed. We've already seen that it is in visual *software* that any potential differences between experts and novices may emerge, and therefore a stronger focus on these measures (only peripheral response time, eye-movement skills, and coincidence-anticipation would probably fall under this category) may yield more positive results. In addition, Rezaee et al. (2012) have suggested that a four week training programme may not be long enough to obtain the benefits of visual training, proposing instead, that an eight week programme (as used in their study described below) is more appropriate. Finally, the findings can only be generalised to tennis performance, and specifically, the forehand drive. There may be aspects of this skill that make it less susceptible to improvements in visual ability; a task in which there are multiple-targets to focus on (rather than one tennis ball), or where distinction of the important information is smaller (such as the seams of a spinning cricket ball) may again, have produced different results.

The idea that different sports, or possibly, different tasks within a sport, may be more predisposed to the benefits of visual training was also suggested by Rezaee et al. (2012) following the results of their study looking at basketball and table tennis performance. 90 participants (again, novices) were assigned to one of six groups: 1) *Sports Vision* and basketball training, 2) *Sports Vision* and table tennis training, 3) only basketball training, 4) only table tennis training, 5) only *Sports Vision* training, and 6) a control. Interestingly, after eight weeks of training, all groups except for the basketball-only training and the control showed significant improvements in accommodation, saccadic eye movements, eye-hand coordination, and recognition speed, though no improvements were found for visual memory or peripheral vision. The key difference appears to be in the importance of vision to each sport. The basketball skill used was the lay-up shot – a task in which enhanced accommodation, saccadic eye movements, and recognition speed are unlikely to be limiting factors (though, conceivably, eye-hand coordination would be). Conversely, the table tennis skill used was the forehand drive – a task in which it is plausible for these four visual skills to be the limiting factors (visual memory and peripheral vision are also less likely to play a role here). This study emphasises the importance of specificity in both visual training programmes and visual testing measures.

Linked to this is the improvements following a visual training programme often found in software skills, but less so in hardware skills. Hardware skills, by nature, are more generalised aspects of the visual system, and are likely to be used continuously in everyday life. As such, it is possible that there is a ceiling effect wherein these skills improve to a certain point and no further. This is supported by research showing visual acuity gradually declines after around 30 years of age (Elliott, Yang, & Whitaker, 1995). There may be a limit to which our visual hardware can reach. Visual software, on the other hand, is by definition, very specific to the task at hand. For example, visual memory has been shown to be specific to the domain in which it is practiced (Chase & Simon, 1973). Therefore in an individual's lifetime – particularly growing up – less time is spent in these specific situations than is in more general, everyday situations, and consequently, the opportunity to develop these visual skills is smaller. All of this result in a greater scope for improvement following a visual training programme for visual software skills but not visual hardware skills.

One such software skill that has received much interest with regards training is that of anticipation. As previously identified, superior anticipation is often characterised as a hallmark of expert performance (Williams et al., 1999), and therefore it is not surprising that researchers have attempted to find ways to improve it. One such study is that of Williams, Ward, Smeeton, and Allen (2004), who examined the effectiveness of perceptual training on an in-situ, tennis serve anticipation task. The perceptual training involved instructions on cue usage and tennis swing biomechanics with ('perception-action') or without ('perception-only') physical practice returning the serves. Following one, 45-minute training session, both perceptual training groups significantly improved their response time (though response accuracy did not change) compared to a control group who received no training. This replicated previous work showing an improvement in tennis serve anticipation using an implicit perceptual training intervention (Farrow & Abernethy, 2002).

Abernethy, Schorer, Jackson, and Hagemann (2012) examined the effect of four different perceptual training methods on the anticipation of videotaped handball penalties. The training groups included explicit instruction on a handball thrower's biomechanics, implicit incidental learning, and two types of guided discovery towards shoulder-located cues (verbal and colour), as well as a placebo group and control group. Immediately following training, anticipatory performance significantly improved for the explicit and verbal guided discovery groups, compared to the control group. However, when later performed under stressful conditions, the implicit group's improvement from the post-test was significantly greater than the explicit group's, whilst the improvement for the verbal guided discovery group was significantly less compared to the control group. Finally, in a retention test five months later, only the implicit group showed significant improvements from the post-test compared to the control group. These results are in line with re-investment theory (Masters, 1992); in that explicit learning enables an individual to (erroneously) break down an otherwise automatic process under stressful conditions, which negatively impacts on performance. On the whole, though, they indicate that there are numerous methods that are effective in improving anticipation.

Both of these studies demonstrate that the visual software skill of anticipation can be improved, though both do so with novice participants and using monitored training methods. The findings of a recent study by Murgia et al. (2014) provide evidence that anticipation can also be enhanced when the training is on expert athletes and is self-controlled. In this study, skilled goalkeepers in the experimental group received a home-based DVD training session once a week, in which videos of penalties were occluded before foot-ball contact, and various feedback provided following a prediction of the penalty's direction. The experimental group significantly improved their anticipation performance on a verbal penalty-saving test compared to a control group and a placebo group (who received weekly DVDs of penalty shootouts) of equal goalkeeping ability.

Turning away from anticipation training, the idea of enhancing an individual's visual attention has also been a focus of considerable research. One method has been found to be particularly effective recently: playing action video games (Hubert-Wallander, Green, & Bavelier, 2011). Action video games, such as *Halo* and *Call of Duty*, often involve rapid responses to scenes containing multiple elements and distractions and therefore it is logical that practice with them may beneficially affect attention. For example, Green and Bavelier (2003) found that one hour per day of action video game playing for 10 days produced significant improvements on a modified useful-field-of-view (UFOV) and attentional blink tests (measures of visual attention over space and time, respectively) compared to a control group. Similar findings have been reported by Green and Bavelier (2006), whilst action video game experience has also been associated with faster visual reaction times (Bialystok, 2006), superior visual short-term memory (Boot, Kramer, Simons, Fabiani, & Gratton, 2008) and enhanced visual search strategies (Castel, Pratt, & Drummond, 2005). Thus, there is sufficient support for training programmes that improve a variety of visual software skills, even when considering only video game playing interventions.

Finally, quiet eye (QE) training has become one of the largest topics in visual training research in recent years, with a Google Scholar search finding over 500 published articles since 2010. Indeed, a thesis could be written on this area alone, and therefore the literature will only be summarised here. The QE refers to "the final fixation towards a relevant target prior to the execution of the critical phase of movement" (Vine & Wilson, 2011, p. 340), and has been identified as a measure of visual attentional control (Vickers, 2007). It has consistently been shown to differentiate between expert and novice performers (Wilson, Causer, & Vickers, 2015), with longer QE durations associated with both experts and successful performance (Vickers, 1996). QE training involves "guiding decisions about where and when to fixate areas of interest within the visuomotor work-space whilst performing a skill" (Vine, Moore, & Wilson, 2014, p. S236), and therefore the links with other software skills such as visual search are clear.

QE training has been shown to increase the duration of the QE period and/or improve performance in a wide range of sports, including basketball (Harle & Vickers, 2001), football (Wood & Wilson, 2011), golf (Vine, Moore, & Wilson, 2011), and shooting (Causer, Holmes, & Williams, 2011). Along with anticipation and attentional training, this provides a fruitful avenue for future research, and appears to demonstrate the effectiveness of training programmes aimed at visual software skills.

Stroboscopic Visual Training

Of late a new form of visual training has become increasingly popular with athletes and has been the topic of several recent studies: stroboscopic training. This is in large part due to the release of a sports training tool by the company Nike in late 2011 called the SPARQ Vapor Strobes – a specialised set of eyewear used to produce a stroboscopic effect.

Studies on the effects of stroboscopic (or 'intermittent', as it was often termed then) vision dates back over a century, though it was especially prominent in the 1980s and 1990s with Elliott and colleagues investigating its direct impact on motor control. However, it is the recent research of Appelbaum and colleagues, who applied it as a training tool and placed great emphasis on its sporting implications, which has resulted in a resurgence in the literature. Stroboscopic visual training entails individuals performing motor tasks whilst being exposed to conditions of intermittent vision, usually through the form of specialised eyewear which contain lenses programmed to switch between clear and opaque states. As a consequence of this reduced reliance on visual information, it is proposed that visual and perceptual skills such as dynamic acuity (Holliday, 2013) and anticipatory timing (Smith & Mitroff, 2012) can be improved, which in turn, leads to enhanced sporting performance.

Appelbaum and colleagues (2011) conducted the first study using the Nike Vapor Strobe eyewear. Participants were recruited from both the Duke University Ultimate Frisbee and University Football teams, as well as from the Duke University community, and were assigned to either a training group or a control group. They then performed a series of visual and perceptual tests before and after completion of a stroboscopic training programme. For the training group, the programme involved a number of simple tasks such as Frisbee practice (Ultimate Frisbee team), speed and agility drills (Football team), or ball-catching (University community) whilst wearing the stroboscopic eyewear. When participants performed the tasks successfully, the strobe rate would decrease (i.e. the time in which the lenses remain occluded increased, making the task more difficult); starting at 6Hz and ending eight 'levels' later at 1Hz. The programme involved between two and 10 sessions (dependent on the cohort), with each session lasting between 15 and 30 minutes. The control group performed exactly the same procedures; however, the glasses they wore were customised to remain transparent throughout.

In the first of the three experiments, a motion coherence task was used, whereby participants were required to determine which of two presentations contained dots moving in a coherent horizontal direction. With each response, the percentage of coherent dots in the presentation was either reduced by 2% (correct response) or increased by 4% (incorrect response) enabling a threshold point for motion coherence to be obtained. This was done for both the central and peripheral visual field. The results showed a significantly greater improvement in central field motion sensitivity for the training group compared to the control group, whilst there was no difference in effect for the peripheral field.

In the second experiment, an individual's ability to divide attention was assessed using a modified dual-task sub-test of the UFOV test. Here, participants have to report some form of detail in a centrally presented stimulus (in this instance, the case of a letter), as well as the location of a peripherally presented stimulus (a black filled-in circle). A significant effect of group was found on central stimulus accuracy but not for peripheral stimulus accuracy. That is, given correct identification of the peripheral stimulus, participants from the training group were significantly more likely to correctly assess the central stimulus than participants from the control group (though not vice versa).

Finally, the third experiment employed a multiple-object tracking task in which the participants were required to track a subset of 'target' dots moving randomly amongst other dots for eight seconds. Once all the dots stopped moving, one would turn yellow and participants had to report whether this was one of the 'target' dots. The findings revealed no significant difference between the training group and the control group in the accuracy of target dot identification.

This study – the first using the Nike stroboscopic eyewear – is much like the ones that followed it. It demonstrates evidence that training under stroboscopic conditions may improve certain visual and perceptual skills, though it does not address the issue of transfer to sporting performance. Though it is understandable that enhanced divided attention may help, say, a quarterback focus on a receiver whilst simultaneously recognising blitzing defenders, whether or not these skills are limiting factors to the athlete's ability remain unresolved. And if they are not limiting factors, then as mentioned previously, the training programme is likely to be unnecessary, if not altogether redundant.

One study which has investigated the impact of stroboscopic training on sporting performance is that of Mitroff, Friesen, Bennett, Yoo, and Reichow's (2013) pilot study with professional ice hockey players. As in Appelbaum et al.'s study, the athletes were assigned to either a strobe training group, or a control group. They were also divided according to position, such that the strobe group consisted of four forwards and two defensemen, and the control group consisted of three forwards and two defensemen. Those in the strobe group performed normal ice-hockey training drills whilst wearing the stroboscopic eyewear for at least 10 minutes per day, for 16 days. The control group did the same training drills without the eyewear. Two measures of ice-hockey performance were employed; for the forwards, athletes were required to skate a figure-8 pattern with the puck, before shooting at the goal, whilst for the defensemen, athletes were required to skate around the back of the goal with the puck, before making a long pass to the midline on the opposite boards of the rink. The results showed that those in the strobe group significantly improved their ice-hockey performance whilst the control group did not. Though the study has its limitations (small sample size, no visual/perceptual measures taken, and an uncontrolled training programme), it provides promising preliminary evidence that stroboscopic training may enhance sporting performance.

The work of Holliday (2013) is, at present, the only research using the Nike stroboscopic eyewear to employ measures of both visual and sporting ability. In this study, 16 college American football athletes performed three tests of vision and perception: static acuity, dynamic acuity, and perception time. The measure of sporting ability was taken from performance during training and included both average catch percentage and average strobe level reached (in each session). Similar to Appelbaum et al. (2011), the training programme entailed simple ball-catching drills in which the strobe group progressed through increasing levels of difficulty (lenses remained occluded for longer), whilst the control group wore customised eyewear that remained transparent throughout. No significant differences were found between the two groups for either static visual acuity or perception time. Dynamic visual acuity, however, did differ. It was found that the strobe group significantly improved their left, upwards, and total dynamic acuity compared to both pre-training and compared to the changes experienced by the control group. However, for sporting performance, both groups significantly improved their catch percentage and level reached from session one to session eight. The study, then, provides more support for the idea that stroboscopic training can induce benefits in certain visual skills, yet its effects on sporting performance remain unclear.

Other studies corroborate these conclusions. Appelbaum, Cain, Schroeder, Darling, and Mitroff (2012), for example, reported significant improvements in short-term visual memory retention for participants who underwent a stroboscopic training programme, compared to a group of control participants. Furthermore, this improvement was retained 24 hours later. Similarly, Smith and Mitroff found that a much shorter period of stroboscopic training (5-7 minutes) led to numerous improvements in anticipatory timing compared to a control group who underwent the training without the stroboscopic eyewear. Of note was a significant decrease in absolute errors immediately after training, and a significantly more consistent response both immediately and 10 minutes after training.

Finally, Clark, Ellis, Bench, Khoury, and Graman (2012) investigated the impact of a visual training programme that included stroboscopic training on the statistical performance of the University of Cincinnati baseball team. Numerous performance data from the 2010 and 2011 seasons were analysed, in between which the team had undergone a visual training programme. This consisted of eight activities (dynavision, tachistoscope, brock string, eyeport, rotary pursuit, saccade charts, near-far cards, and stroboscopic eyewear) performed three times per week for six weeks. The statistical analyses showed that the University of Cincinnati team had significantly improved their batting average, slugging percentage, and on base percentage in the 2011 season compared to other teams in their conference (none of which were known to have undergone any visual training programme). Whilst stroboscopic training was just one of a number of visual training drills employed, the study provides additional evidence that sporting performance benefits may be accrued through stroboscopic and/or generalised visual training programmes.

As with much of visual training literature as a whole, research on stroboscopic training tends to have the same limitations. Studies often measure either visual skills or motor skills, though very rarely both, resulting in the inability to infer either causation (in the case of the former) or sporting benefits (in the case of the latter). However, stroboscopic training frequently suffers from another methodological weakness; that of an adequate control group. Given the novel and fashionable image of the eyewear, it remains a difficult task to equalize motivation across an experimental group and a control group whilst also investigating the stroboscopic training effect. Despite this, there seems to be a general consensus amongst the stroboscopic (and generalised) visual training literature: visual and perceptual performance can be improved, though whether this transfers to enhanced sporting performance is questionable.

The same reasons put forward by Rezaee et al. (2012) to explain the ambiguities in generalised visual training research may also be applicable to stroboscopic training. That is, the training programmes employed may either be too short, or may not have been used by a sample that is expert enough to have their visual and perceptual skills as limiting factors in their sporting performance. Another possible explanation has been proposed by Clark et al. (2012). In discussing their results, they suggested that the specificity of the training drills employed is likely to have contributed to the visual training benefits found. Drills were chosen based on their relevance to baseball batting performance; for example, the tachistoscope exercise "may help with the 'snapshot' of information from the pitcher holding the ball", whilst the rotary pursuit exercise "may help the batter follow the ball" (p. 5). In a similar fashion, it should come as no surprise that the visual and perceptual improvements found by Appelbaum et al. (2011) related only to the central field and not the peripheral field, given that the training drills used were often heavily focussed on forward-facing catches requiring predominantly central vision. These suggestions may be essential in determining the effectiveness of both stroboscopic training and visual training as a whole.

The next step, therefore, requires visual (and in particular, stroboscopic) training research to design more studies which incorporate both visual/perceptual *and* sporting measures. From this we may be able to answer whether the visual-perceptual benefits often found are transferable/related to athletic performance, the extent to which the benefits are specific to the particular training protocol employed (e.g. central field improvements from training drills requiring predominantly central vision), and – given appropriate population samples – whether visual ability provides the limiting factor essential for a training program to be effective. Specific to stroboscopic training, research is required that explores the underpinning mechanisms of possible training benefits. Understanding why something is working should enable both researchers and applied practitioners to optimise their use of stroboscopic training methods.

Task Representativeness

It appears then, that a growing body of literature is indicating that visual testing, and consequently, visual training may be beneficial provided that the methodology employed focuses specifically on the particular skills associated with the sport in question. Using static measures for dynamic activities, or acuity tests for tasks where fine detail is irrelevant, are unlikely to produce the performance differences that may come from comparing the visual reaction times of athletes from fast-paced sports, or the stereopsis of skills requiring depth perception. This concept of specificity leads us to an approach that has been gaining popularity in the field of sports psychology over the past decade or so: task representativeness.

The work of Brunswik from the 1950s and onwards has underpinned several different concepts and theories in both sports psychology, and across scientific research of human behaviour in general. Ideas such as the expert-performance approach, especial skills, the specificity of learning hypothesis, perception-action coupling, and stimulus-response compatibility, all can be related back to Brunswik pre-eminent research regarding task representativeness (Brunswik, 1955). These are all critical concepts in this thesis and will be explored in detail.

Task representativeness (or 'representative experimental design') refers to "the arrangement of conditions of an experiment so that they represent the behavioural setting to which the results are intended to apply (Araujo, Davids, & Passo, 2007, p. 6). This methodological approach states that the greater the correspondence between the experimental design and the environment, the more accurate the results obtained will be in reflecting behaviour. As such, ensuring experiments are designed with the primary goal of achieving a high level of representativeness is essential for scientific research.

Unfortunately, the field of sports psychology has traditionally adopted the methods employed by other, perhaps more established, areas of sports science, such as biomechanics and physiology. Opting for such techniques brings with it certain advantages, like in controllability and replicability. It does however, have a major drawback that is more superfluous for these other fields: it reduces ecological validity. Whilst the biomechanical differences induced by the treadmill may be negligible compared to outdoor running (Riley et al., 2008), it is not hard to imagine that many of the motivational and attentional attributes gauged in studies would differ considerably if measured in a laboratory setting compared to during a match situation on the pitch, court, or field. This idea of task-representativeness has become increasingly popular since the early 1990s, when it became a fundamental element in Ericsson and Smith's (1991) "expert-performance approach".

The expert-performance approach (EPA) is a "theoretical framework for understanding how elite performers function in a given domain" (Lorains, Ball, & MacMahon, 2013, p. 293). Within this are three key aspects: first, expert-novice differences in a skill need to be elicited through laboratory or field testing, second, the study design should include methods to ascertain the mechanisms behind these differences (such as occlusion paradigms) and be representative of the situation that the task is performed in, and third, how this expert advantage is developed should be examined. It is in the second aspect of the EPA that this thesis will now focus.

Though the EPA seems a clear and reasonable method to take, much of the early literature regarding expertise – and to a broader degree, skill acquisition in general – failed to implement it. To a large extent, the research in field of sports science has focussed primarily on securing strict and controllable conditions and variables – aspects important in ensuring experimental reliability but with the downside of detracting from its external validity. This factor is arguably even more relevant in sports psychology-related disciplines, where variations in measured variables (such as motivation and decision making) are likely to be greater across the various experimental settings than physiological measures like heart rate and VO_2 max.

Indeed, we are constantly surrounded by tests that bear little or no obvious relation to the measures that they supposedly predict. In sport, the annual NFL Combine is a huge media event designed to indicate which of the top college athletes will perform best in the NFL, yet research has shown that the tests employed in it fail to significantly predict almost all aspects of possible performance-assessment criteria (Kuzmits & Adams, 2008). Similarly in driving, the only visual requisite to obtain a license in many countries is the ability to read a standard car registration plate from a distance of 20.5 metres though the use of static measures of visual acuity for dynamic behaviours such as driving has been criticised on numerous occasions (Young et al., 2013). And perhaps the most controversial area affected by this is in the use of IQ tests. These tests – aimed to assess intelligence – are often used to discern "gifted children"; with the social and academic consequences of such a label multiplying over time (Steenbergen-Hu & Moon, 2011). Such an advantage has a huge impact on an individual's social development (Gallagher, Smith, & Merrotsy, 2011), career, and many other aspects of life (Reis & Renzulli, 2010). Given that numerous studies have shown IQ testing to bear little resemblance to all-round intelligence, it seems illogical to place such a prestigious benefit on its results (Connor, 2012).

Thus, ensuring testing methods follow a task representative design would seem an important step in developing our knowledge of skill acquisition in numerous fields and avoiding the pitfalls of potentially meaningless testing. In the sports domain in particular, the importance of employing this approach in research has critical implications for coaches and athletes alike. Mann et al. (2007) have stated that the novice-expert differences found in many studies of perceptual-cognitive expertise would be enhanced even further if the tests used replicated more closely the sports domain. As a consequence, the ability to identify talented individuals from laboratory tests relies on the specificity of the methods employed.

A prime example is demonstrated by the research of Pinder, Davids, Renshaw, and Araujo (2011). They found significant differences in the mechanics of a cricket batsman's movements, as well as the quality of bat-ball contact, depending on whether they faced a live bowler, a ball-projector machine, or a video simulation. Under the ball-projector condition, batsmen showed significantly later initiation of front foot movement, later placement of front foot, a shorter front foot step, slower backswing initiation, and shorter backswing height. They also had significantly worse quality of bat-ball contact than when facing a live bowler. Similar results have been found in other sports, such as tennis, where response times were shown to be significantly quicker when reacting to a live opponent compared to a ball-projector machine (Shim, Carlton, Chow, & Chae, 2005). It is suggested that these differences emerge because of the "removal of key sources of perceptual information" (Pinder et al., 2011, p. 1249) in the ball-projector condition. Thus, altering the visual and perceptual information – from a very task representative design (live bowler) to a not-so task representative design (video simulation) – effects how individuals respond, with great implications for the learning process of motor skills.

As alluded to earlier in the introduction, an analysis of the moderating variables on the expert-novice difference in perceptual and cognitive skills also offers insight into the importance of task representativeness in study designs (Mann et al., 2007). Studies which used presentational stimuli in-situ (or near to) generated significantly greater effects than those which used video or static slides. Thus, ensuring that the study design resembles "the behavioural setting to which the results are intended to apply" (Araujo et al., 2007, p. 6), as the in-situ/field presentations clearly would, is important in determining the extent of expert-novice differences in perception and cognition. Furthermore, the analysis of sport type as a moderating variable highlights the need to carefully select the choice of participants depending upon what visual, perceptual, or cognitive skill is being measured. For example, the expert-novice effect is likely to be much greater if the sample consists of tennis players (labelled 'interceptive' sport athletes) than if they consist of golfers (labelled 'other' sport athletes).

The specificity of learning hypothesis states that the skills an individual acquires are very specific to the conditions in which they were taught (Henry, 1968). This is because the performance of the skill becomes increasingly dependent upon certain cues identified in the learning process. The hypothesis states that limited transfer is possible between different environmental situations, and therefore tests aimed at measuring ability must recognize and reflect these learning conditions.

Two experiments examining the inattentional blindness paradigm were conducted by Memmert (2006) and provide support for the specificity of learning in an individual's visual attention and perception. Inattentional blindness refers to the phenomenon whereby an individual fails to perceive an object – often appearing in central fixation – when their attention is diverted elsewhere (Mack & Rock, 1998). In this particular paradigm the participant is required to watch a video of two opposing groups of people throwing a basketball to one another, and count how many successful passes one of the groups make. During the video, another person dressed in a gorilla costume walks into the scene, stands momentarily in the middle, and then exits. In the first experiment 60% of young children with no experience in sports games failed to notice the gorilla – replicating previous findings (Mack & Rock, 1998). However, in the second experiment, different participants were used, amongst them basketball experts and basketball novices. As expected, the inattentional blindness phenomenon occurred to a significantly higher degree in the novice group (63.5%) compared to the expert group (39%). Thus, the extent to which the participants' domain of expertise is reflected in the task constraints (basketball passing) has a significant bearing on the findings of a study.

The concept of especial skills is underpinned by the specificity of learning hypothesis. An especial skill is a unique, highly-practiced skill that is specific to one particular situation and produces significantly better performance than would be otherwise expected from other, similar situations (Keetch, Lee, & Schmidt, 2008). For example, shooting accuracy in basketball worsens with increasing distance from the basket. However, at a distance of 15feet, expert players perform significantly better than would be predicted based on distances closer and further away (Breslin, Schmidt, & Lee, 2012). This phenomenon occurs because of the massive amount of practice put into the free throw shot – a skill regularly used in basketball and one that always take place from 15feet. An especial skill has also been identified for the pitching distance in expert baseball pitchers (Simons, Wilson, Wilson, & Theall, 2009). The visual-context hypothesis has been proposed to explain this effect. This states that during the learning phase of the skill, the visual cues dictating the correct shooting distance and angle remain constant throughout and are embedded into memory. Altering these cues creates a new environment separate to which the skill was learned, and therefore brings about decreased performance. Thus, the importance of perceptual cues in motor performance is great, and has been emphasised in the ideas of task representativeness and the expert-performance approach. It is also key in Gibson's (1979) theory of perception.

Gibson's (1979) theory of perception emphasises that the way we view (and act in) the world is initiated by environmental stimuli. Altering these stimuli impacts the behavioural response to it, and therefore it is proposed that perception and action are inherently connected (Bruce, Green, & Georgeson, 1996). As a result, when studying human behaviour, it is essential that this perception-action coupling remains intact in order to ensure that what is being observed and measured reflects the real-life target behaviour (Farrow & Abernethy, 2003). This is particularly important in research on motor expertise, where it is the specificity of the task to the expert's domain that often dictates whether differences with novices are found.

Such an approach has been taken with regards measuring the anticipatory performance of tennis players of differing skill levels (Farrow & Abernethy, 2003). In this study participants were required to respond to a tennis serve in two different manners: one in which perception-action was coupled (moving as one would in a real game situation) and one where perception and action were uncoupled (verbally stating whether the serve was directed to the forehand or backhand side). Additionally a temporal occlusion paradigm was employed to investigate whether any performance differences between the degrees of perception-action coupling was dependent upon the amount of information afforded to the participant. The results indicated that the expert superiority in response accuracy was only apparent when the response involved high degrees of perception-action coupling. Furthermore, responses involving high-degrees of perception-action coupling were significantly more accurate than uncoupled responses only when ball-flight information was made available. Thus, when designing studies, it is not only the extent to which tests reflect the natural environment but also the method of response measures used that affects the results that are obtained.

Akin to this is another feature of task representative designs; that of stimulus-response (SR) compatibility. The degree to which a stimulus is related to the response it provokes is important in maintaining the fidelity of a study’s design, and research has shown that tasks in which the stimulus and the response share physical or conceptual characteristics are performed faster and/or more accurately than those which do not (Fitts & Deininger, 1954). From a sporting perspective this has substantial implications. For example, research by Nakamoto and Mori (2008) found that college baseball players had a significantly faster reaction time than non-baseball players only when the SR compatibility involved a baseball batting specific response (i.e. to swing or not to swing). When the compatibility was low (unrelated to baseball), no differences emerged between the groups. This SR effect was also found by Kato and Asami (1998) in their investigation of pre-motor response times. The incompatible condition involved responding to a stimulus presented on one side of the visual field with the opposing arm (i.e. stimulus presented on the left; right arm responds, and vice versa). In the compatible condition, the side of stimulus presentation and arm used to respond to it were matched. As expected, pre-motor response times were significantly slower in the incompatible condition compared to the compatible condition. Again, this emphasises the importance of the task design in determining a study’s outcome.

This concept was also investigated by Roca, Williams, and Ford (2014), who measured (via verbal communication) the anticipation, decision making accuracy, and verbal reports of 20 semi-professional footballers assigned to either a ‘stationary’ group or a ‘movement’ group. Those in the movement group were able to ‘interact’ with the video as they would if they were playing the match themselves, providing a condition in which responses were made in a context more representative of the footballers' natural environment. In contrast, those in the stationary group remained seated throughout the experiment. Though the groups did not differ in anticipation, there was a tendency for the movement group to perform better on the decision making task. Furthermore, the movement group verbally reported more cognitive processes than the stationary group. As such, the authors suggest that the greater stimulus-response compatibility afforded by the movement group enabled participants to process more information, more effectively. Indeed, they state that the "findings highlight the importance of designing representative tasks that offer participants a more realistic context for continuous decision making, perception, and action as per the environmental characteristics of the actual performance domain" (Roca et al., 2014, p. 176).

Much of the findings on task representatives, the expert-performance approach, perception-action coupling, and stimulus-response compatibility can be related back to the visual testing and training literature. Tests measuring visual software – where experts routinely perform better than novices – tend to be specific to a domain or environmental situation. By incorporating similar stimuli in the laboratory to that which the expert uses to base their actions on in-situ, the experimental design maintains perception-action coupling and can be said to have high task representativeness. The less the stimuli match the performance environment (as is the case in tests measuring visual hardware), the weaker the task representativeness is. The importance of this in uncovering performance differences between skill levels has been detailed previously.

However, tests of visual software do vary in the degree to which they incorporate a task representative design and this issue has received increasing interest in the literature. For example, Lee et al. (2013) reported that there was no difference in reaction time when responding to a more task-representative 3-dimensional (3D) video as compared to the less-task representative 2-dimensional (2D) video. However, the 2D condition did evoke significantly more visual fixations than the 3D condition; suggesting that the participants were able to gauge sufficient information from fewer fixations in the 3D condition. This is a potentially important finding in a sport context as it may indicate that fewer attentional resources are being used in this instance, and therefore a greater amount of resources are leftover to attend to other, advantageous areas. Another study investigated whether the level of graphical detail of a stimulus (opposing player) influenced the motor response of elite handball goalkeepers (Vignais et al., 2009). This varied from very low (point-light display) to moderate (wire-frame representation), and then to high (textured animation). Though the results indicated that time-to-response and percentage of successful (virtual) saves did not change regardless of the level of detail of the stimulus, movement kinematics did significantly differ. Specifically, it appears that different sources of the visual stimuli are being used by the goalkeepers to initiate movement when presented with a point-light display compared to when presented with a textured animation.

Taken together, studies such as these emphasise the importance of utilising 3D stimuli with high levels of graphical detail in research on expert performance. Failure to do so may overlook key findings and result in important contributions to the literature being neglected. Perhaps more problematic is the idea that findings from studies using low task-representative designs may be erroneously generalised to real-life settings, despite not reflecting the same stimuli and perception-action coupling response. This point is highlighted by Kingstone, Smilek, Ristic, Friesen, and Eastwood (2003) who identified that simply altering the Posner paradigm (a cueing task used to measure attention) to represent a schematic face, rather than a simple arrow, produced results contradictory to 20 years of research. Thus, “laboratory studies devoid of real-life context may generate fundamental misconceptions" (p. 179), whilst incorporating a more task-representative design is likely to obtain a more accurate reflection of human behaviour in the real world.

There are potentially important practical applications that could stem from validating a task-representative approach in study designs. For example, talent identification programmes usually involve measures of motor performance, such as dribbling around a cone in football, to infer technical ability (Reilly, Williams, Nevill, & Franks, 2000). Yet it has been argued that this may be misleading; Vilar, Araujo, Davids, and Renshaw (2012) stated that the use of static obstacles rather than dynamic ones removes the "critical perceptual variables that performers typically use to control their actions during performance" (p. 1728). Likewise, the differences in a cricket batsmsn's movement kinematics when facing a bowling machine compared to a 'live' bowler (highlighted previously) demonstrate the importance of task-specific practice (Pinder et al., 2011). There are implications for the perceptual training of athletes too. For instance, research has shown that training goalkeepers on where to look can improve penalty saving performance in football (Murgia et al., 2014). However, gaze behaviour in this task has been shown to differ depending on whether it was performed under a video simulation condition or an in-situ condition (Dicks, Button, & Davids, 2010). These examples indicate the practical importance of investigating the concept of task representativeness in sports research.

Whilst the evidence and theory behind employing a task-representative design is considerable, it must be acknowledged that some studies have failed to support such a stance. For example, Meir, Holding, Hetherington, and Rolfe (2013) failed to identify any significant difference in reactive-agility when the stimulus used was a generic arm signal as compared to a more task-representative stepping movement of an opponent. Likewise, the screen size of video projected basketball scenarios did not significantly affect decision making accuracy in a study by Spittle, Kremer, and Hamilton (2010). Participants were just as accurate in determining whether the appropriate action was to pass, shoot, or dribble when viewing the more "ecologically valid" and "near life-life images" (p. 368) on a large screen size as when they viewed them on a much smaller screen.

A possible explanation for the null finding in Meir et al.'s study is that the 'generic' arm signal may have been more task-representative than intended. This arm movement may in fact provide a sufficient amount of the perceptual cues required to respond at a similar level to that of the more specific stepping movement. Together with the fact that the response required was high in perception-action coupling, it may be that a ceiling effect of reactive agility was reached by the participants. Comparisons with a control group would be needed to determine this. With regards Spittle et al.'s (2010) study, it may be that other features of the study design that lacked task representativeness (e.g. the 3rd person perspective, use of videoed stimuli, and a written response method) bore more influence on decision making than the size of the screen. Furthermore, in both studies, it is possible that whilst direct performance measures (i.e. reactive agility and decision making accuracy) did not significantly differ with increasing task representativeness, other variables not assessed – such as visual search strategy – did. This would fall in line with the findings of Lee et al. (2013) and Vignais et al. (2009) previously reported.

With the growing interest in the specificity of the expert advantage in visual, perceptual, and cognitive skills, recent meta-analyses have provided a useful review. For instance, Voss, Kramer, Basak, Prakash, and Roberts (2010) examined 20 studies containing a total of 198 effect sizes and 694 participants. Three cognitive measures were analysed; attentional cueing, processing speed, and varied attention paradigms. The results revealed medium size effects of the latter two in favour of expert athletes (i.e. expert athletes have superior processing speed and attentional ability compared to novice athletes or non-athletes). These findings are interesting in that the approach taken by Voss et al. (2010) was a cognitive component skills one. That is, as opposed to the expert-performance approach, the analysis focused only on studies which included basic measures of cognitive ability, and excluded any that used sport-specific stimuli in their assessments. Thus, this paper appears to provide evidence against a task-representative approach, and rather, supports the view that expert athletes have superior general cognitive functioning.

Another meta-analysis was conducted by Travassos et al. (2013) to specifically examine whether varying degrees of task representativeness used in studies of decision making amongst experts and novices affected the results obtained. In the study, differences in the type of stimulus presentation (slide images vs. video presentations vs. in-situ), and requisite response (verbal report vs. micro-movements vs. sport performance) were compared. A total of 31 papers were analysed and, as predicted according to the task representative approach, the expertise effect was significantly greater when the study design reflected the performance environment to a higher degree. That is, with regards stimulus presentation, studies conducted in-situ generated the greatest expert-novice differences. Similarly, for requisite responses the expert advantage in decision making was more consistent when participants were required to perform an action fitting for the specific sporting context; a result not surprising considering the levels of perception-action coupling involved in each response condition. This meta-analysis illustrates that research investigating expert-novice differences in tasks such as decision making may be undervaluing their results if they employ designs involving slide images, video presentations, verbal reports, and micro-movement responses.

Finally, an interesting extension to the idea of task representative designs is presented by Lorains et al. (2013) in their work using a speeded video paradigm. They showed that elite Australian Football League players had significantly greater decision making accuracy for video footage edited to play at a faster than normal speed, whilst sub-elite players and novices both performed worse with increasing speed. More importantly, the elite and sub-elite athletes rated the videos edited to be 1.25 and 1.5 times the normal speed to be significantly more 'game-like' than any other speed (including real-time), leading the authors to conclude that the speeded video paradigm is the most representative task design and should be used in future research concerning athletic expertise. Considering that the ideas of task representativeness and the EPA both propose that expert-novice differences are most likely to be identified when the tests used replicate the natural environment as closely as possible, this raises the question – what is more important: designs that reflect how the situation *is* or designs that reflect how the situation *feels*?

Summary

Below average vision, then, does not seem to impact an individual's ability to perform a single task, whilst superior visual software is probably – and above-average visual hardware possibly – a characteristic of elite-athletes. The existing literature on vision testing is full of contradictory conclusions, making it difficult to conclude whether or not a specific visual skill influences sporting performance. It may be that enhanced visual abilities are an inconsequential by-product of the countless hours of practice athletes put into their sport. If this is the case, then visual training would not be expected to lead to improved sport performance. The logic underlying vision training programmes in sport is based on three assumptions: that athletes have greater visual skills than non-athletes, that we can improve our visual skills, and that potentially improved visual skills transfer to improved sporting skills. All of these assumptions are not conclusively supported by the literature, though the first two (at least with regards visual software) have more support in the literature than the latter. As in vision testing, the benefits of visual training may be dependent upon the specificity of the methodology employed.

This notion of specificity underpins the idea of task representative (and other related concepts) in the design of experiments investigating differences in human behaviour and sporting performance. Considerable research has shown that the more representative an experiment is of the environment being studied, the greater the opportunity to identify expert-novice differences. Numerous authors have strongly advocated the use of designs which involve matching laboratory conditions with both the perceptual stimuli and natural response behaviours of the environment under investigation. Failure to follow such an approach may lead to inaccurate (or at least, non-generalisable) findings and/or overlooked results.

Aims of Thesis and Study Purposes

Within this introduction numerous areas of the visual skills literature were covered, with an emphasis placed on highlighting the key areas of literature which remain either unexplored or ambiguous. Of chief importance was the consistent employment of testing methods which bear little resemblance to the highly dynamic and 3-dimensional nature of sporting environments. The weaknesses of the current visual training literature was also stressed, with particular attention paid to the lack of sporting measures used in such studies. Next, the resurgent topic of stroboscopic visual training was detailed, along with thoughts on where the next steps of this particular area should head. Finally, the concept of task representativeness was discussed. In particular, it was noted that study designs which implement this approach generally elicit greater expert-novice differences in cognitive and motor skills, though the extent to which this can be applied to our vision and perception is less clear.

Consequently, the aims of this thesis are tied in to these unresolved areas of the existing literature. Specifically, the four studies included in this thesis were designed with the intention to address the following points:

1. The lack of dynamic, 3-dimensional tasks in the testing and training of skilled performance (study one).
2. The transfer of potential stroboscopic training effects to sporting performance in the form of one-handed ball catching (study two).
3. The effects that stroboscopic training may have on simple motor control and its underlying mechanisms (study three).
4. The extent to which visual-perceptual tests of varying degrees of task representativeness can identify differences in sporting experience (study four).

CHAPTER TWO

"Visual perception had been dominated by the employment of squares, triangles, circles and similar figures drawn in two-dimensional form on blank cards, very different in their properties and perceptual demands from the contours, shapes, and meaningful objects of the visual world, and usually with all the vitally important distance and depth characters lacking."

- Sir F. Bartlett (1951)

STUDY ONE: MOTION PERCEPTION AND DRIVING: PREDICTING PERFORMANCE THROUGH TESTING AND SHORTENING BRAKING REACTION TIMES THROUGH TRAINING

Abstract

Purpose: A driving simulator was used to examine the relationship between motion perception and driving performance. Although motion perception test scores have been shown to be related to driving safety, it is not clear which combination of tests are the best predictors and whether motion perception training can improve driving performance.

Methods: In Experiment 1, 60 younger drivers (22.4 ± 2.5 years) completed three motion perception tests [2D motion-defined letter (MDL) identification, 3D motion in depth sensitivity (MID), and dynamic visual acuity (DVA)] followed by two driving tests [emergency braking (EB) and hazard perception (HP)]. In Experiment 2, 20 drivers (21.6 ± 2.1 years) completed six weeks of motion perception training (using the MDL, MID and DVA tests) whilst 20 control drivers (22.0 ± 2.7 years) completed an online driving safety course. EB performance was measured pre- and post-training.

Results: In Experiment 1, both MDL (r=.34) and MID (r=.46) significantly correlated with EB score. The change in DVA score as a function of target speed (i.e., "velocity susceptibility") was most strongly correlated with HP score (r = -.61). In Experiment 2, the motion perception training group had a significant decrease in brake reaction time on the EB test from pre-post whilst there was no significant change for the control group: $t(38) = 2.24$, $p = 0.03$.

Conclusions: Tests of 3D motion perception are the best predictor of EB whilst DVA velocity susceptibility is the best predictor of hazard perception. Motion perception training appears to result in faster braking responses.

Introduction

The ability to detect and discriminate one's own motion and the motion of other vehicles and pedestrians in the environment is critical for driving safety. Examples of driving tasks that depend on precise and accurate motion perception include controlling one's speed and heading when entering a curve (Wilkie & Wann, 2003), judging whether it is safe to overtake and pass another vehicle (Gray & Regan, 2005), responding to a lead vehicle suddenly braking (Lee, 1976), and detecting pedestrian incursions in the roadway (Straughn, Gray, & Tan, 2009). Even relatively small impairments in motion perception are likely to significantly increase crash risk (DeLucia, Bleckley, Meyer, & Bush, 2003). Given the essential role that motion perception plays in driving, it has been hypothesized that simple tests of motion perception may be predictive of driving ability and accident risk (Wood, 2002). Over the past decade a small number of studies have provided strong support for this hypothesis, demonstrating correlations between a variety of motion perception measures and indices of driving performance.

To date, the most commonly used measures of motion perception have involved motion sensitivity i.e., quantifying the smallest amount of movement needed to accurately indicate the direction of movement. An important distinction that has been identified in such tests is the stimulus resolution. Some previous studies have used small, high resolution (i.e., high spatial frequency) moving random dot patterns as test stimuli (Wood, 2002, Wood, Anstey, Kerr, Lacherez, & Lord, 2008) whilst others have used coarse, low resolution (i.e., low spatial frequency) moving gratings (Henderson, Gagnon, Belanger, Tabone, & Collin, 2010). Whilst both sets of tests have been found to be correlated with measures of driving performance/safety such as hazard perception tests scores and self-reported attentional failures during driving, it has recently been shown that the relationship between driving performance and motion perception for high resolution tests can be fully explained by other visual abilities, namely acuity and contrast sensitivity (Lacherez, Au, & Wood, 2012). Therefore, tests using high resolution stimuli may not provide a good means of assessing the role of motion perception in driving.

Another test that has been used previously in this area is dynamic visual acuity (DVA), where an object has to be identified (or object feature localized) whilst the object is in motion. Therefore, both the ability to perceive motion and the ability to track the target with eye movements is assessed. The general finding from this research is that DVA is a better predictor of driving performance than static visual acuity but is weaker than other measures of motion perception (Wood, 2002, Shinar & Schieber, 1991).

One of the limitations of previous research examining the relationship between DVA and driving performance is that the effect of target speed was not analyzed in detail. Previous research in other domains, namely sports, has shown that this may be important for predicting visual-motor performance. For example, in a study of catching performance, it was found that skilled catchers had a DVA that decreased only slightly as target velocity was increased (what the authors' termed "velocity resistance") (Sanderson & Whiting, 1978). Conversely, less-skilled catchers showed a more dramatic decline in DVA as a function of target velocity (what the authors' termed "velocity susceptibility"). A similar relationship between DVA and performance has also been reported for other sports (Ishigaki & Miyao, 1993). One of the goals of the present study was to determine whether velocity resistance/susceptibility relates to driving performance.

Another limitation of previous research in this area is that the relationship between motion perception tests and driving performance has only been examined for fronto-parallel (2D) motion (i.e., up/down or left/right). Very few previous experiments in this area have used tests of motion-in-depth (3D) perception (i.e., towards/away). This is an important omission for several reasons. First, for many of the driving situations in which a large number of accidents occur (e.g., rear-end collisions and across-path turns) the primary type of motion involved is 3D motion. Second, previous research has shown that older drivers can have impairments in their ability to judge approaching motion (DeLucia et al., 2003, Schiff, Oldak, & Shah, 1992, DeLucia & Mather, 2006). Finally, and most critically, it has been demonstrated that 2D and 3D motion are processed in different brain regions and individuals can have a selective impairment for one type of motion (Cynader & Regan, 1982, Regan, 1991). For example, previous research has reported cases of “motion in depth blindness” in which individuals fail to detect approaching/receding motion in certain locations of their visual field whilst detection of 2D motion is normal (Hong & Regan, 1989). These findings suggest that tests of 2D motion perception may not be predictive of driving ability in some tasks.

To this author’s knowledge only one previous study has investigated the relationship between tests of 3D motion perception and driving performance. In this study (Raghuram & Lakshminarayanan, 2006), 2D speed discrimination, 3D speed discrimination, estimation of time to collision for 3D (approaching) motion, and heading discrimination were measured. Scores on these tests were related to self-reported driving difficulties and accidents. Significant relationships between driving difficulty ratings and scores were found for all tests except 3D speed discrimination. However, several participants who reported no driving difficulties also scored poorly on the motion perception tests. As recognized by the authors, the dependent variables used may not have been sensitive enough to pick up differences between these tests and further research measuring actual driving performance is needed. It has also been reported that velocity discrimination for motion in depth (expanding radial pattern) was correlated with several measures of student pilot performance in flight tests as well as flight simulations (Kruk & Regan, 1983, Kruk, Regan, Beverley, & Longridge, 1983). Thus motion perception tests may also have selection and training applications in aviation, as well as for driving.

From this brief review it is clear that more research is needed to identify the combination of motion perception tests that will be most predictive of driving ability. The goal of the present study was to expand on this effort by: (i) directly comparing the relationship between 2D and 3D motion perception tests and driving performance, (ii) investigating the relationship between target speed, DVA, and driving performance, and (iii) directly comparing motion perception tests with other visual tests (with static stimuli) that have been shown to be related to driving safety. Another aspect of the relationship between motion perception and driving performance that has not been studied in previous research is whether motion perception training can improve driving ability. Recent research has shown that training on simple perceptual-cognitive tests can improve driving performance and reduce accident risk (Ball, Edwards, Ross, & McGwin, 2010). Therefore, in Experiment 2 of the present study the goal was to evaluate to what extent training on motion tests can improve driving performance.

Experiment 1

Purpose

The aim of Experiment 1 was to investigate the relationship between performance on a set of motion sensitivity tests and performance on a set of tests of driving performance in a simulator. As discussed above, the experiment included 2D and 3D motion perception tests and a DVA test which required observers to visually track moving targets moving at different speeds. To allow for comparison, tests of visual acuity, contrast sensitivity and the Useful Field of View (UFOV; Ball & Owsley, 1992) were also included. The driving tests included an emergency braking test and a hazard perception test. The experiment was designed to test the following hypotheses:

(i) There would be a significant correlation between the 3D motion test and the emergency braking test because this driving task primarily involves detection of 3D (looming) motion. The relationship between the 2D test and EB and between the DVA test and EB would not be significant.

(ii) The 2D motion and DVA test would be significantly correlated with HP, as has been found in the previous research described above.

(iii) For the DVA test, “velocity susceptibility” (as assessed by the relationship between DVA threshold and target speed) would be significantly related to performance on the HP test.

Methods

Subjects

60 subjects (42 male, 18 female; mean age 22.4 ± 2.5 years) were recruited from the Birmingham UK area. Participants received payment for their participation. All participants had a full valid UK driving license and had no obvious visual deficits that would affect their driving ability at the time of testing. Participants were asked to wear any prescribed lenses (i.e., glasses or contacts) during testing but were not given any additional refractive correction. Driving experience was quantified as the number of years since driving license was awarded. All participants had a minimum of six months driving experience. The work reported here was approved by the Science, Technology, Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham and adhered to the Declaration of Helsinki. All participants signed a consent form.

Apparatus

Motion Perception Tests. The motion perception tests used custom-designed software. Tests were displayed on a Philips Brilliance™ 107P40 VGA 120 Hz CRT monitor which subtended 40 (H) x 36 (V) deg of visual angle at a resolution of 1920 x 1440 pixels. The viewing distance was 57cm. Three tests were used; the motion-defined-letter test (MDL), the motion-in-depth-sensitivity test (MID), and the dynamic visual acuity test (DVA).

The MDL test, 2D motion perception test, was based on the work of Hong and Regan (1989). On each trial the participant is presented with a display of 1200 moving white dots presented on a black background. Each dot was comprised of four pixels and had a luminance contrast of 92%. As illustrated in Figure 1, a letter is made visible by moving the dots inside the letter boundary in the opposite direction to the dots outside of the letter boundary. The entire display of dots subtended 15 x 15 deg of visual angle whilst the letters subtended 7 x7 deg. The dot density was identical inside and outside the letter boundary. The dots inside and outside the letter boundary always moved at the same speed with the direction of motion chosen randomly on each trial. The letter could be made more (or less) visible by increasing (or decreasing) the motion contrast (relative velocity). On each trial the letter was chosen randomly from nine possible alternatives (C, D, E, F, L, O, P, T and Z) and participants were asked to identify the letter by pressing a key on the numerical keypad on a standard keyboard. The standard keys were covered with labels corresponding to each of the letters. The presentation duration was 0.5 sec.

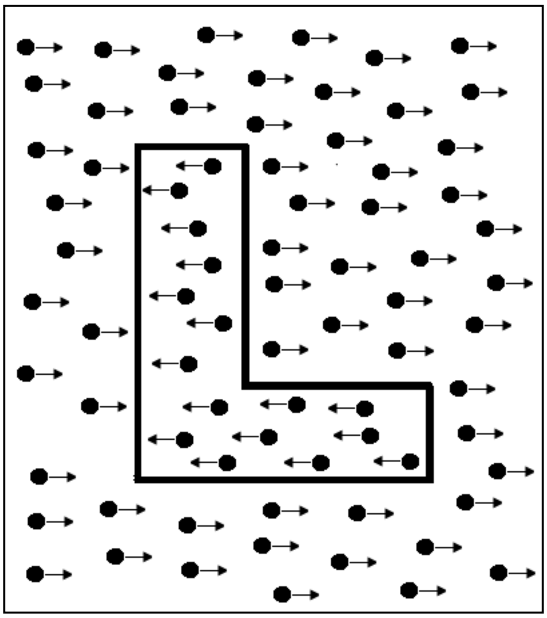

Figure 1. Illustration of a motion defined letter (MDL). The dots inside and outside the boundary of the letter moved in opposite directions at the same speed. Note the solid black border was not visible in the actual test.

A maximum-likelihood adaptive staircase psychophysical procedure (ML-PEST) was used to adjust the speed of the dots on each trial based on the participant's responses. A correct identification resulted in a reduction in dot speed whilst an incorrect response resulted in an increase in dot speed. The initial dot speed was 1 deg/s and the step size was 0.2 deg/s. The step size was halved after the first two reversals. Four staircases were randomly interleaved so that participants could not anticipate the dot speed on each trial. After a minimum of six reversals for each staircase the test concluded, with the average speed of the final four reversals used to calculate the participant's MDL threshold for each letter size. The thresholds for the four staircases were then averaged to generate the observers' MDL threshold in deg/sec.

The MID test, a 3D motion perception test, involved the presentation of two radially expanding flow fields – with differing velocities – on each trial. The flow fields were comprised of 1500 white dots presented on a black background and the duration of each presentation was 1 sec. The inter-presentation interval was 0.2 sec and the inter-trial interval was 0.5 sec. Participants were required to make a two-alternative forced-choice judgement (2AFC) about which presentation the movement velocity was greater by pressing one of two response keys on the keyboard. The velocity of one of the presentations (the reference) was held constant throughout the test and had a value of 5 deg/sec. The velocity on the other presentation (the test) was adjusted in accordance with a ML-PEST staircase procedure. The order of the test and reference presentation was chosen randomly on each trial. The initial difference in velocity of the test presentation was 0.5 deg/s and the step size was 0.1 deg/s. The step size was halved after the first two reversals. Four staircases were randomly interleaved so that participants could not anticipate the dot speed on each trial (i.e., if they indicated the test was faster than the reference the test presentation on the next trial would not necessarily be slower). After a minimum of six reversals for each staircase the test concluded, with the average speed of the final four reversals used to calculate the participant's MID threshold for a given staircase. The thresholds for the four staircases were then averaged to generate the observers' mean MID threshold in deg/sec.

On each trial of the DVA test a white Landolt C target moved across a grey background. The target had a contrast of 50% relative to the background. The orientation of the notch in Landolt C target was chosen randomly for each trial from one of four alternatives (up, down, left, right). The target always initially appeared in the centre of the display and the presentation duration was 1.0 sec on all trials. The movement direction was chosen randomly from the eight cardinal directions. The participant's task was to make a 4AFC judgment about the notch orientation by pressing one of the four arrow keys on the numerical keypad of a standard keyboard. The notch size was adjusted according to a ML-PEST staircase procedure.

The initial notch size was 100 arc min and the step size was 30 arc min. The step size was halved after the first two reversals. Four staircases (corresponding to four target speeds: 5, 10, 15 and 20 deg/sec) were randomly interleaved. Four speeds were used so that "velocity resistance" (Sanderson & Whiting, 1978) could be measured. Speed was constant within a given trial (i.e., the target did not accelerate). After a minimum of six reversals for each staircase the test concluded, with notch size of the final four reversals used to calculate the participant's DVA threshold for each velocity in arc min. An overall threshold (designated DVA below) was also measured by calculating the mean for the four velocities.

Visual Acuity & Contrast Sensitivity Test. Visual acuity and contrast sensitivity were measured using the Freiburg Visual Acuity + Contrast test (Bach, 1996). Visual acuity data was collected in decimal form and transformed to log-MAR units. Contrast sensitivity is based on a single optotype size of varying contrast. The Freiburg software is available at: http://www.michaelbach.de/fract/index.html.

UFOV Test – The commercially available UFOV® test was used (Visual Awareness Research Group, Inc, 2009). Only data from subtest 2 was collected because previous research has shown it to be the most predictive of driving safety (Wood et al., 2008). The UFOV 2 test measures divided attention: the subject is asked to identify a central presented object (an image of a car or a truck) and localize a car that is presented simultaneously in the periphery. The presentation duration is adjusted using a staircase procedure. The score for this test is the presentation duration (in ms) for which 75% correct performance is achieved.

Driving Tests. The driving tasks were carried out on a XPI Simulation Limited™ XPDS-XP300 driving simulator, version 2.2. The simulator was comprised of a Logitech G25 Racing Wheel/Pedals and three Microsoft Plug and Play monitors with 43.2cm displays (2840 x 1025 resolution). The system ran using the NVIDIA GeForce GTS 450 graphics card with a 1024MB memory. Participants positioned themselves so they could comfortably use the steering wheel and pedals and such that their eyes were 80cm away from the computer monitors. Two driving tests were used: Emergency Braking (EB) and Hazard Perception (HP).

In the EB test, the lead vehicle began from a stopped position and accelerated to a speed of 40mph. It then travelled at speed ranging between 35 and 45 mph with speed changes every 5 sec on average. At a random time interval (between 40-180 sec after the beginning of the trial) the lead car braked suddenly with a -6 m/s^2 deceleration rate. Drivers were instructed to accelerate to catch up with the lead vehicle and then maintain a 2 sec time headway. If their time headway was larger than 3 sec the trial was aborted and re-run. The brake lights of the lead vehicle were deactivated. Drivers were further instructed that they must brake to avoid collision with the lead vehicle and must not go out of the lane (any trials for which this occurred were discarded and re-run).

In the HP test participants were required to indicate, using a button on the steering wheel, when they perceived there to be a hazard during three different driving scenarios. Across the three scenarios there were a total of 10 potential driving hazards: (i) construction vehicle pulling out of work site from left, (ii) construction vehicle pulling out of work site from right, (iii) child pedestrian crossing street in school zone from left, (iv) child pedestrian crossing street in school zone from right, (v) adult pedestrian crossing the street from left, (vi) adult pedestrian crossing the street from right, (vii) vehicle emerging from side street on the left, (viii) vehicle emerging from side street on the right, (ix) vehicle ahead waiting to turn across traffic, and (x) vehicle ahead reversing. Each scenario involved driving through an urban environment at a speed of 35 mph for 5 minutes with the hazards randomly placed throughout. If the participant pressed the button when the hazard was visible and correctly verbalized the nature of the hazard to the experimenter it was scored as a correct response. If the participant pressed the button when no hazard was visible it was scored as a false alarm. The HP score for each driver was the number of hazards successfully identified minus the number of false alarms. The score was calculated in this manner so that it provided an unbiased measure of HP performance i.e., the drivers' criteria for indicating the presence of hazards was also taken into account. Drivers were presented with a list of the potential hazards prior to completing the test.

Procedure

Each participant completed the vision tests followed by the two tests of driving ability. The order of driving tests was counterbalanced across participants. Participants were given a practice period of 2 minutes of free driving through a city environment to familiarize themselves with the driving simulator before beginning the tasks. Likewise, a 30 sec practice period was allowed prior to each visual test in order for the participant to fully understand the tests.

Data Analysis

SPSS[M] software (version 19) was used to analyse the data. Initial screening was administered to identify any outliers. Pearson's correlations were first calculated between each of the tests. Stepwise multiple regressions were performed next to determine whether combinations of the motion tests best predicted driving performance. Velocity resistance/susceptibility for the DVA test was determined by plotting DVA threshold as a function of target speed, fitting a linear curve to the data and calculating slope. Slopes were used as an additional variable in the multiple regression analyses.

Results

Table 1 shows the descriptive statistics for the visual and driving tests. Bivariate correlations between visual and driving tests are shown in Table 2. For the EB driving test, better driving performance (i.e., shorter brake reaction time) was significantly associated with better performance on the MDL test (i.e., lower threshold), better performance on the MID test (i.e., lower threshold), higher visual acuity and higher contrast sensitivity. Note that the visual acuity measure is a threshold so a lower score represents higher acuity. The scatterplots for the three strongest predictions of EB performance are shown in Figure 2. The stepwise regression analysis performed on the EB data revealed that three significant predictors accounted for approximately 33% of the variance: [$F(3,59) = 9.5$; $p < .001$]. The three predictors were MID threshold ($\beta = 0.36$, $t = 3.2$, $p < .01$), log contrast sensitivity ($\beta = -0.26$, $t = 2.4$, $p < .05$), and log MAR acuity threshold ($\beta = 0.24$, $t = 2.2$, $p < .05$).

For the HP test, a greater ability to identify hazards (i.e., higher score) was significantly associated with better performance on the DVA test (i.e., lower threshold), a lesser effect of speed on DVA performance (i.e., lower DVA threshold x target speed slope), higher visual acuity, better performance on the UFOV2 test (i.e., lower presentation threshold), being older, having more years of driving experience and higher contrast sensitivity. The scatterplots for the three strongest predictions of HP performance are shown in Figure 3. The stepwise regression analysis performed on the HP data revealed that three significant predictors accounted for approximately 47% of the variance: [$F(3,59) = 17.8$; $p < .001$]. The three predictors were DVA threshold x target speed slope ($\beta = -0.44$, $t = -4.9$, $p < .001$), UFOV2 score ($\beta = -0.44$, $t = -5.0$; $p < .001$), and log contrast sensitivity ($\beta = 0.21$, $t = 2.5$, $p < .05$).

Variable	Minimum	Maximum	Mean	SD
Age	18	26	22.4	2.36
EXP	0.5	8	4.19	2.11
MDL (deg/sec) ↓	0.07	0.20	0.13	0.04
MID (deg/sec) ↓	0.03	0.22	0.12	0.06
DVA (arc min) ↓	7.8	81.6	33.9	17.9
DVA slope↓	0.23	1.72	0.86	0.42
Log MAR acuity↓	-0.21	0.11	-0.07	0.09
Log CS↑	1.6	1.99	1.80	0.12
UFOV2 (ms) ↓	36	89	49.6	14.2
EB (sec) ↓	0.62	1.9	1.09	0.32
HP (/10) ↑	1	10	5.71	3.13
HP hits↑	6	10	8.3	1.52
HP FA↓	0	6	2.81	1.33

Table 1. Descriptive statistics for the visual and driving tests in Experiment 1. EXP = years of driving experience, MDL = motion defined letter test, MID = motion in depth sensitivity test, DVA = dynamic visual acuity test, DVA slope = slope of DVA threshold x target speed fit, Log CS = contrast sensitivity, UFOV = useful field of view, EB = emergency braking test, HP = hazard perception test, HP hits = instance in which the driver correctly identified a potential hazard, HP FA = false alarms, instance in which the driver incorrectly indicated a hazard was present. Note: arrows are used to indicate whether a higher (↑) or lower (↓) score represents better performance for a particular test.

Variable	EB↓	HP↑	Age	MDL↓	MID↓	DVA↓	DVAs↓	VA↓	CS↑	UFOV
HP↑	-.26									
Age	-.15	.27*								
MDL↓	.34**	-0.06	.15							
MID↓	.46**	-.16	.21	.23						
DVA↓	.09	-.33**	.17	.06	-.18					
DVAs↓	.14	-.61**	.12	-.16	.05	.31*				
VA↓	.34**	-.32*	.13	.16	.22	.12	.17			
CS↑	-.33*	.28*	-.19	-.16	-.15	-.19	-.12	-.29*		
UFOV↓	.23	-.60**	.19	-.06	.13	.25	.33**	.20	-.14	
EXP	-.12	.29*	.91**	.06	-.2	-.08	-.04	.01	.01	.02

Table 2. Bivariate correlations between motion perception and driving performance in Experiment 1. *$p < 0.05$; ** $p < 0.01$, all other correlation not significant, EXP = years of driving experience, MDL = motion defined letter test, MID = motion in depth sensitivity test, DVA = dynamic visual acuity test, DVAs = slope of DVA threshold x target speed fit, VA = log MAR acuity, CS = contrast sensitivity, UFOV = useful field of view, EB = emergency braking test, HP = hazard perception test. Note: arrows are used to indicate whether a higher (↑) or lower (↓) score represents better performance for a particular test.

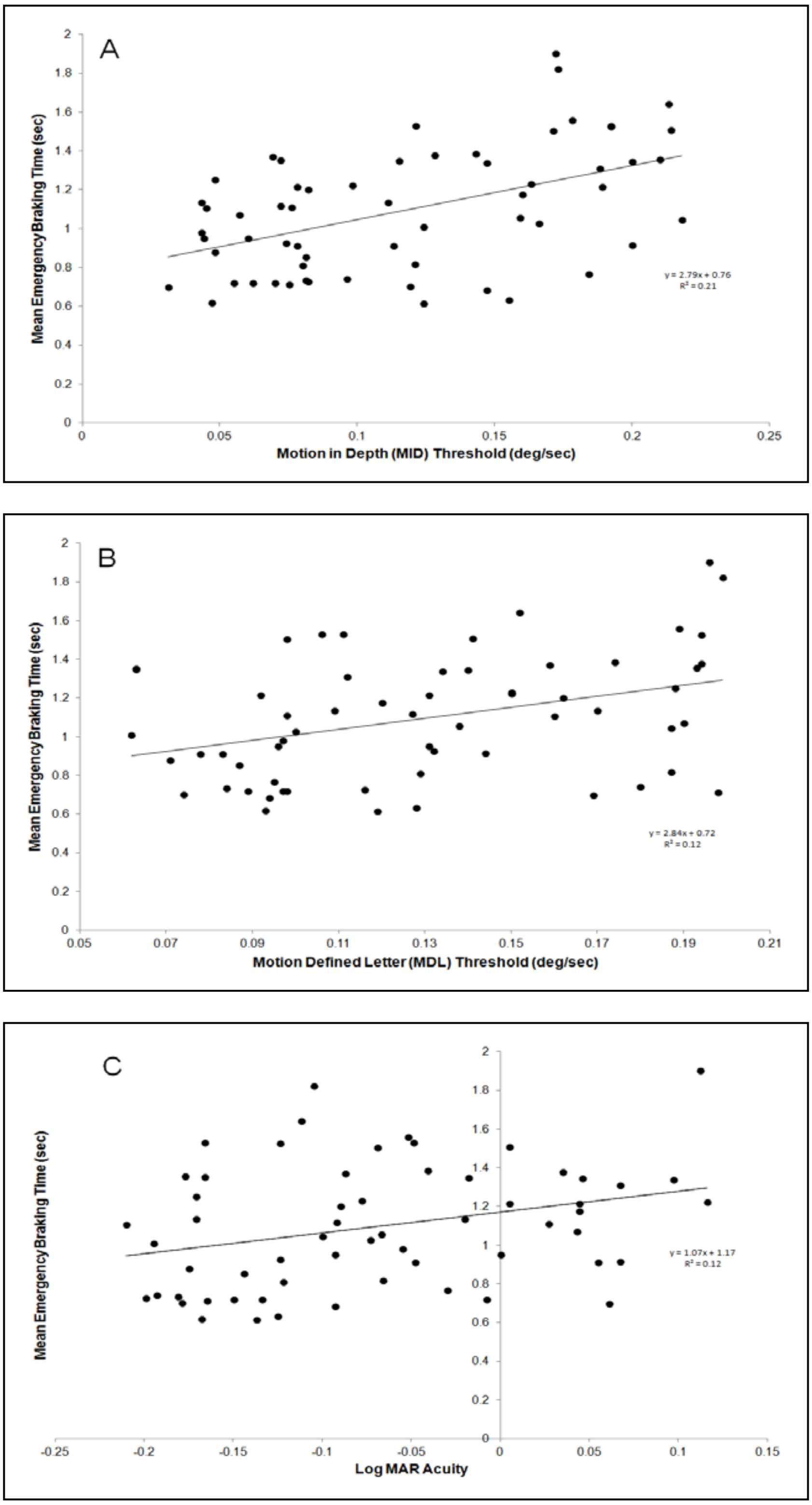

Figure 2. Scatter-plots for test scores most strongly related to Emergency Braking Time.

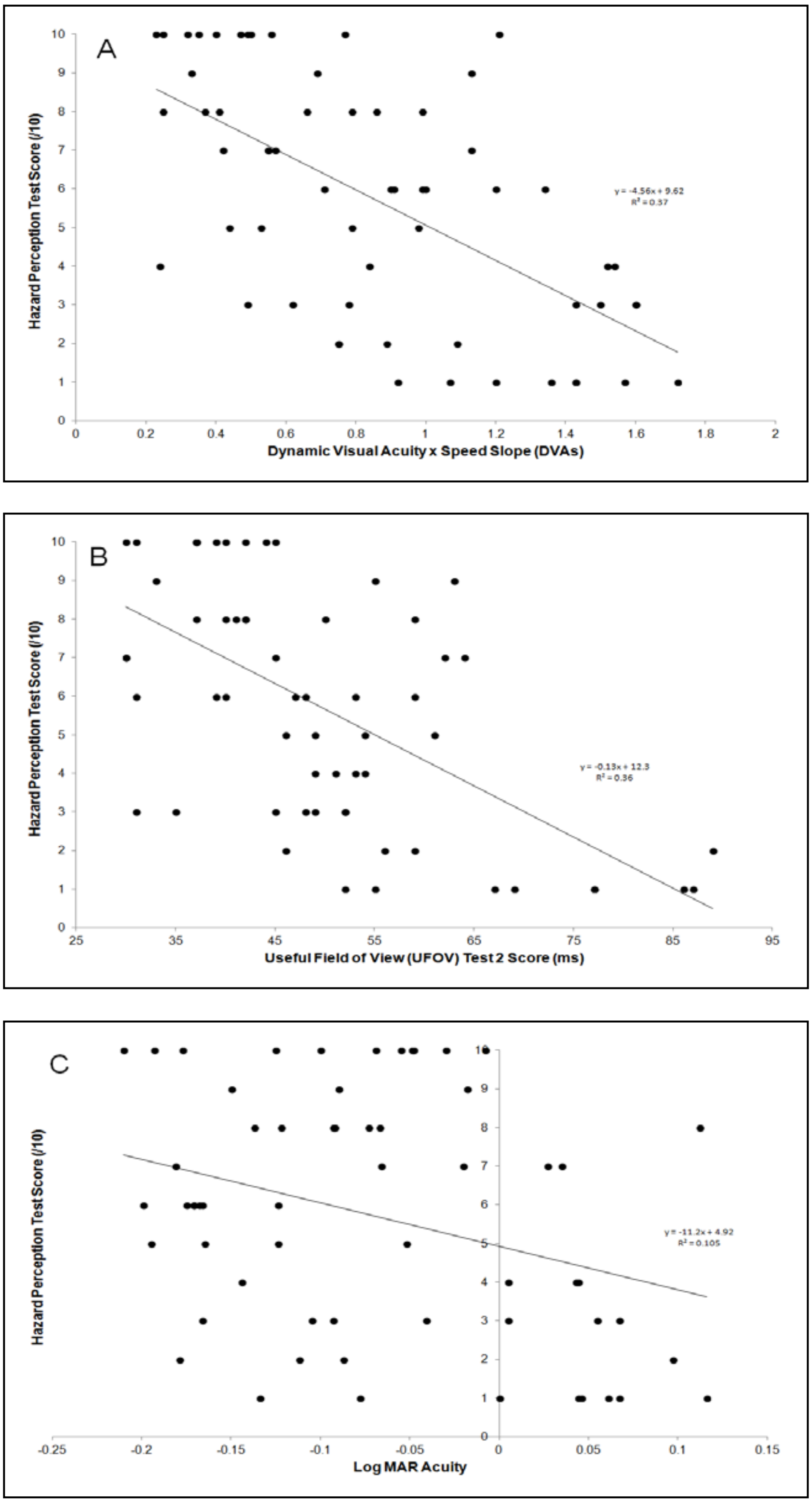

Figure 3. Scatter-plots for test scores most strongly related to Hazard Perception Test score. Hazard perception scores were the number of hits minus the number of false alarms.

Discussion

Experiment 1 was designed to expand on previous research examining the relationship between motion perception and driving performance. The first goal was to directly compare 2D and 3D motion tests. As predicted, scores on the 3D motion test were significantly correlated with performance in the emergency braking task and this test had the highest correlation of all vision tests. It was hypothesized that the 3D motion tests would be more strongly related to driving performance in this case because emergency braking in a car following situation primarily involves the detection of 3D motion, i.e., looming (Lee, 1976). The stronger relationship for the 3D motion test is consistent with previous research in aviation. For example, previous research (Kruk et al., 1983) has examined the relationship between scores on a variety of motion perception tests (including thresholds for MID and motion in the fronto-parallel plane) and the performance of pilots in a flight simulator. MID thresholds were significantly correlated with landing and formation flight performance whilst the relationships were not significant for the 2D motion test. Similar findings were also reported when real flight tasks were used (Kruk & Regan, 1983). Taken together these findings suggest that 3D motion perception tests will be stronger predictors of performance on perceptual-motor control tasks involving approaching or receding motion and should be incorporated in test batteries for driving.

Unexpectedly a significant relationship was also found between 2D motion perception and braking time. As discussed above, previous research has shown that 2D and 3D motion are processed relatively independently – a conclusion that is supported in the present study by the non-significant correlation between MID and MDL test scores. Therefore, it was not expected that these two tests would be related. One possible explanation could be that the 2D motion test used in the present study was effectively a test of static visual acuity because a relatively small (7 x 7 deg), high density stimulus was used whilst in the 3D motion test a large (40 x 36 deg), lower density stimulus was used. As discussed above, when high resolution stimuli are used, the relationship between motion perception and driving performance can be explained entirely by visual acuity and contrast sensitivity (Henderson et al., 2010). However, in the present study there was not a significant correlation between visual acuity and MDL test score and, furthermore, MDL was a significant predictor in the stepwise regression analysis. This issue is discussed in more detail below.

Another unexpected finding of Experiment 1 was the lack of a significant relationship between the 2D motion tests and performance on the HP driving test. Given that the HP test involves lateral movement of objects (cars and pedestrians entering the roadway from the side) and that a significant relationship between 2D motion and HP has been shown in past research (DeLucia et al., 2003, Wood, 2002), it was anticipated that a similar relationship would be observed. Perhaps this effect was due to the complexity of the 2D motion test used. Whilst in previous research 2D motion tests invovle simply indicating the direction of motion, in the present study observers were required to identify letters. It will be interesting for future research to explore this difference. Another possibility is that the lack of relationship was due to the limited experience of the drivers in the present study. It is possible that performance on the HP was more strongly determined by whether or not drivers had developed mental models of hazardous driving situations as opposed to motion perception. The signficant positive correlation between HP test performance and years of driving experience is consistent with this idea.

Turning to the DVA test, a secondary goal of Experiment 1 was to further evaluate a motion perception test with an eye movement component. As predicted, DVA thresholds in the present study were significantly correlated with scores on the HP test. This finding is consistent with previous research (DeLucia et al., 2003). However, expanding on previous research (Sanderson & Whiting, 1978) it was found that “velocity suscpetibility” as quantified by the DVA threshold x target speed slope was actually a stronger predictor of HP test performance than DVA threshold alone.

Consistent with previous research (Ball & Owsley, 1992, Clay et al., 2005) it was also found in Experiment 1 that performance on the UFOV test was a significant predictor of HP performance. However, it should be noted that unlike in previous studies, the subjects in the present study were young and healthy without any cognitive or attentional impairments. One possible reason for this significant relationship is that the majority of the hazards used in the HP test involved a divided attention component (i.e., monitoring the position of other vehicles in central vision whilst also monitoring the location of pedestrians and other vehicles in the periphery) like that assessed with the UFOV2 test. The fact that DVAs and UFOV were significantly correlated is also interesting. It is possible that the characteristics of visual attention measured with the UFOV test are a prerequisite for directing a subsequent eye movement.

Experiment 2

Purpose

In Experiment 1, significant relationships were found between different tests of motion perception and two tests of driving performance. The aim of Experiment 2 was to investigate the effect of motion perception training on driving performance in a simulator in comparison to a control group that received standard, text-based driver training. The experiment was designed to test the following hypothesis: drivers in the motion perception training group should show a significantly greater improvement in driving performance (pre-post training) as compared to the control group.

Methods

Subjects

40 subjects (28 males and 12 females) completed Experiment 2. Participants in the experimental group (15 males, 5 females) had a mean age of 21.2 ± 2.1 years whilst subjects in the control group (14 males, 6 females) had a mean age of 22.0 ± 2.7 years. All subjects had a full valid UK driving license and had no obvious visual deficits that would affect their driving ability at the time of testing. All participants received £20 for their participation. The work reported here was approved by the Science, Technology, Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham. All participants signed a consent form.

Apparatus and Procedure

The apparatus and procedure were as described in Experiment 1 except for the following. The experiment was divided into eight phases: a pre-test, six training blocks (once per week), and a post-test. Participants were randomly allocated to either the experimental or control group. During the pre-test, all participants completed all of the visual tests used in Experiment 1 and the EB driving task. During the post-test all participants completed the EB task. In both the pre- and post- tests the EB task was repeated five times for each participant and the average braking response time was calculated. During each of the training blocks participants in the experimental group (n = 20) completed the three motion tests used in

Experiment 1 in random order. Each block lasted roughly 30 minutes. To create a training scenario, auditory feedback was added to each of the tests in Experiment 2 and the threshold was displayed at the end of each trial. Participants in the control group (n = 20) completed an online driving safety course which involved reading about rules and regulations (https://www.gov.uk/highway-code) and answering multiple choice questions (and receiving feedback about the accuracy of their response) during the training blocks (https://www.gov.uk/practise-your-driving-theory-test). Neither of the groups performed simulated driving during the training blocks.

Data Analysis

Separate repeated measures analysis of variance (ANOVA) was used to examine the changes in the three motion-perception test scores over time for the experimental group. To analyse performance on the EB driving test a 2x2 mixed-factorial ANOVA was used with Group (Experimental, Group) as the between –subject factor and Test Phase (Pre, Post) as the within-subjects factor.

Results

Pre-test Comparison

Table 3 shows the descriptive statistics for the visual tests completed at the pre-test stage. Data are separated for the experimental and control groups. Independent samples t-tests revealed marginally significant differences between the two groups for MDL score [$t(38) = -2.06$, $p = 0.05$] and UFOV score [$t(38) = 1.96$, $p = 0.06$]. All other comparisons were not significant (p all > 0.1).

Variable	Minimum		Maximum		Mean		SD	
	Control Group	Expt Group	Control Group	Expt Group	Control Group	Expt Group	Control Group	Expt Group
Age	18	18	26	24	22.0	21.2	2.71	2.13
Exp	0.5	0.5	5	4	3.9	3.7	2.4	2.2
MDL (deg/sec) ↓	0.06	0.08	0.19	0.22	0.12	0.14	0.05	0.04
MID (deg/sec) ↓	0.05	0.05	0.21	0.18	0.10	0.13	0.05	0.07
DVA (arc min) ↓	10.5	8.4	67.4	74.7	37.0	32.9	16.8	18.1
DVA slope ↓	0.25	0.20	1.82	1.52	0.87	0.83	0.43	0.46
Log MAR acuity ↓	-0.18	-0.21	0.07	0.17	-0.08	-0.03	0.08	0.11
Log CS ↑	1.7	1.5	1.98	1.92	1.84	1.77	0.09	0.11
UFOV2 (ms) ↓	37	30	99	77	55.1	46.4	15.0	12.9

Table 3. Descriptive statistics for the visual pre-tests in Experiment 2. EXP = years of driving experience, MDL = motion defined letter test, MID = motion in depth sensitivity test, DVA = dynamic visual acuity test, DVA slope = slope of DVA threshold x target speed fit, Log CS = contrast sensitivity, UFOV = useful field of view.

Changes in Motion Perception

Figure 4A shows the means and standard deviations for the three motion-perception tests at each of the six weeks of training for the experimental group. The repeated-measures ANOVAs indicated significant effects of training for MDL ($F(5, 95) = 17.4$, $p < 0.001$), MID ($F(5, 95) = 33.2$, $p < 0.001$) and DVA ($F(5,95) = 3.28$, $p = 0 .013$). These findings are generally consistent with previous research demonstrating that motion perception can improve with training (Zanker, 1999).

Effect of Training on Driving Performance

Figure 4B shows the mean EB time for the two groups in the pre-and post-tests. The 2x2 mixed factors ANOVA revealed a significant main effect of test block [$F(1, 38) = 11.9$, $p = 0.01$] and a significant interaction effect between group and block [$F(1, 38) = 4.2$, $p = 0.04$]. As can be seen in Figure 4B, this effect was due to the fact that the motion test training group showed a larger improvement in driving performance. A post-hoc comparison revealed that the mean EB time was significantly lower in the post-test for the experimental group as compared to the control group: $t(38) = 2.24$, $p = 0.03$.

To further investigate the relationship between the training on the motion perception tests and driving performance, the pre-post changes in score for the motion tests were calculated. Following this, bivariate correlations between changes in motion test scores and the change in braking time were run. This analysis revealed a significant positive correlation between change in braking time and change in MID score ($r = .47$, $p < 0.05$). The correlation was not significant for either MDL ($r = 0.26$, $p > 0.05$) or DVA ($r = 0.1$, $p > 0.05$).

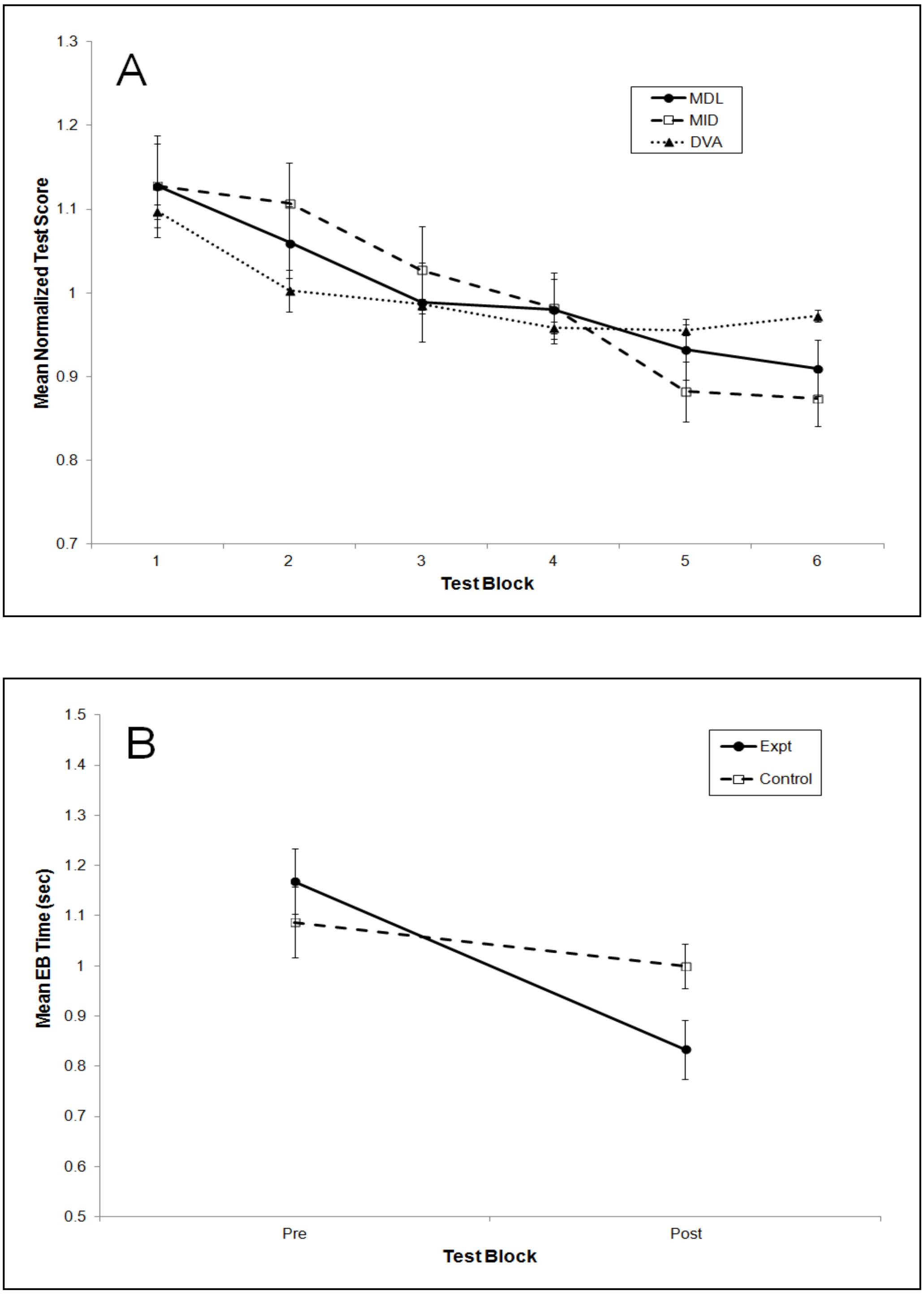

Figure 4. A: Motion test scores as a function of training block. B: Mean total braking time in the pre and post-tests. Error bars are standard errors. Scores were expressed as a proportion of each participant's pre-test mean, in order to make the MDL, MID, and DVA tests comparable.

Discussion

Experiment 2 sought to test whether training on the motion perception tests used in Experiment 1 would improve EB performance. Consistent with the hypothesis, the motion training group had a significantly greater reduction in braking time as compared to the control group that received driving theory instruction. This finding suggests that improving motion perception through training can lead to safer driver behaviour: namely quicker brake reaction time.

The mean difference between the control and experimental groups in the EB post-test was 0.17 sec. Whilst on the surface this may not seem like a large difference, the real world impact of a change of this magnitude can be seen by considering the effect of the Center High Mounted Stop Lamps (CHMSL) intervention. CHMSL, also called the third brake light, has been standard equipment on all passenger cars sold in the U.S since 1986 and all light trucks since 1994. The mandate for CHMSL was based on the technical evidence that braking reaction times were improved by an average of 0.11 sec (range 0.09 – 0.3 sec) (Digges, Nicholson, & Rouse, 1985). Accident analyses have subsequently shown that CHMSL has resulted in a significant reduction in rear end collisions and fatalities, and avoided several million dollars of property damage each year (National Highway Traffic Safety Administration, 1998, 2004). It will be important for future studies to investigate whether the effects on performance observed in the driving simulator in the present study also result in reduced number of accidents in real driving, as has been shown for training designed to increase the speed of processing in a visual attention task (Ball et al., 2010).

One important limitation of Experiment 2 is the possibility that there could have been motivational differences between the experimental and control groups. Because several of the drivers in the present study had only received their driver's license relatively recently (which likely involved completing an online training course and tests similar to those used in the present study), the online training course may not have been particularly motivating. Conversely, the motion perception training is likely to have been more novel for these participants. It will be important for future studies to compare other types of control groups (e.g., training tests involving non-motion perception such as static acuity or UFOV).

General Discussion

The use of motion perception tests as possible predictors of driving performance and safety has been gaining momentum in the past decade with a handful of studies demonstrating relationships between the two (Wood et al., 2008, Lacherez et al., 2012). The goal of the present study was to expand on these efforts in two ways: (i) expanding the content of the motion test battery and (ii) evaluating the feasibility of motion perception training as a possible means to improve driving safety.

Given the importance of 3D motion perception (Gray & Regan, 2005) and eye movements (Lacherez et al., 2012) in driving it was hypothesized that the strength of the relationship between motion perception tests and driving performance would be increased if these two variables were better incorporated into the test battery. As discussed above, the majority of studies in this area have used only tests of 2D motion perception with the one exception being a study in which driving performance/safety was not directly assessed (Raghuram & Lakshminarayanan, 2006). And whilst the motion perception tests that requires eye movements, namely dynamic visual acuity (DVA), have been used in past research in the area (DeLucia et al., 2003) the relationship between DVA threshold and target speed (“velocity susceptibility”), which has shown to be important in other domains (Sanderson & Whiting, 1978), has not been examined in the context of driving.

Consistent with the hypotheses, the 3D motion perception test and velocity susceptibility (the DVA threshold x target speed slope), along with the UFOV test, showed the strongest relationship with driving performance in the present study. The MID test was significantly correlated with emergency braking performance whilst the velocity susceptibility was significantly correlated with performance on a hazard perception test. Consistent with some past research it was also found that 2D motion perception was significantly related to the driving performance measures. Taken together, the present study suggests that a motion perception test battery should incorporate tests of 2D motion, 3D motion and DVA (with target speeds that are systematically varied) to maximize predictability. It is important to assess correlations among visual tests to avoid the use of overlapping/redundant tests in a clinical setting, or for administration of driver testing, where large numbers of individuals must be tested as quickly and efficiently as possible. These results indicate that, whilst most of the vision tests were uncorrelated, VA and contrast sensitivity were significantly correlated, and DVAs and UFOV were also significantly correlated. The correlation between VA and CS is not surprising; however the significant correlation between DVAs and UFOV was not expected. As noted above, it may be that deployment of visual attention to a peripheral location is important preceding an eye movement. This relationship could be of interest in further research.

Experiment 2 of the present study provides evidence to suggest that motion perception training can have a positive influence on the driving behaviour of younger drivers, namely reduced braking reaction times in response to a simulated potential collision. As can be seen in Figure 4B, a training program which involved repeating 2D, 3D and DVA tests for six weeks resulted in a significant reduction in emergency braking reaction time that was not observed in a control group that received training in driver theory. Both groups completed the braking action the same number of times, suggesting that this difference was due to a change at the level of motion processing (e.g., greater sensitivity to looming) rather than at the motor response stage (e.g., faster foot movements from accelerator to brake). However, as discussed above, there may have also been motivational differences between the two groups. Therefore, it will be important for future research to further investigate this type of training (using other types of control/comparison groups) to determine to what extent this effect is due to improved motion perception and to what extent similar effects might be achieved with other types of training (e.g., contrast sensitivity or UFOV).

It should also be noted that the present training study involved young, healthy drivers. It will be important for future research to investigate motion perception training effects in individuals with compromised abilities resulting from ageing, ocular disease, or cognitive impairment. It is reasonable to assume that the training benefits may be even larger in these populations than those observed in the present study but of course that needs to be tested. Consistent with this idea, previous research has shown that one of the tests used in the present study (the MDL test), is sensitive to deficits in a variety of conditions for which standard visual acuity is normal. These include multiple sclerosis, amblyopia (Giaschi, Regan, Kraft, & Hong, 1992), early enucleation (Steeves, Gonzalez, Gallie, & Steinbach, 2002), multiple sclerosis (Giaschi, Regan, Kothe, Hong, & Sharpe, 1992), and glaucoma (Giaschi, Trope, Kothe, & Hong, 1996).

There are some important limitations to the present study. First, it will be important for future research to expand the range of driving tasks used. It will be interesting to examine driving tasks which are associated with a high number of accidents and involve a strong 3D motion component such as overtaking and passing (Gray & Regan, 2005) and across path turns (Gray & Regan, 2007). Second, it will be important for future research to use stimulus speeds that better represent those experienced in real driving. In the present study, stimulus speeds used values similar to that of previous experiments (Sanderson & Whiting, 1978, Kruk & Regan, 1983) (e.g., 0.05 m/s for the MID test and 0.05-0.2 m/s for the DVA test) rather than values similar to those experienced in the driving task (11-15 m/s). Finally, as discussed above, it will be important to determine the effectiveness of motion perception training relative to other types of perceptual and attention training.

Conclusion

Previous research has shown that simple motion perception tests may be effective predictors of driving safety. The goal of the present study was to expand on this work by: (i) evaluating the relative effectiveness of tests of 2D and 3D motion and a motion perception test that involves eye movements, and (ii) evaluating the effect of motion perception training on driving performance. In terms of motion tests, it was shown that a 3D motion perception test was the best predictor of emergency braking whilst DVA velocity susceptibility was the best predictor of hazard perception performance. In a second experiment, training on tests of motion perception resulted in a significantly reduced braking reaction time. This study provides evidence that incorporating motion perception tests in a test battery including contrast sensitivity, colour, and UFOV would be far more predictive than existing screening methods which rely almost exclusively on Snellen acuity, and in some instances, colour and simple visual field tests. This study also provides preliminary evidence to suggest that motion perception training may be a valuable tool in improving driver safety.

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CHAPTER THREE

"Does it mean, also, that it is impossible to train for a particular ability, such as vision, without putting the training in the context of each particular sport in turn, or is it possible to provide a generalized training of vision which will be found to be effective in various sports?"

- Kretchmar et al. (1949)

STUDY TWO: THE EFFECTS OF STROBOSCOPIC VISUAL TRAINING ON VISUAL ATTENTION, MOTION PERCEPTION, AND CATCHING PERFORMANCE

Abstract

It has recently been shown that stroboscopic visual training can improve visual-perceptual abilities, such as central field motion sensitivity and anticipatory timing (Appelbaum, Schroeder, Cain, & Mitroff, 2011; Smith and Mitroff, 2012). The goal of the present study was to test the prediction that such training should also improve a sports skill that relies on these perceptual abilities, namely ball catching. 30 athletes (12 female, 18 male; mean age = 22.5, SD = 4.7) were assigned to one of two types of stroboscopic training groups: a variable strobe rate (VSR) group for which the off-time of the glasses was systematically increased (as was used in previous research) and a constant strobe rate group

(CSR) for which the glasses were always set at the shortest off-time. Training involved simple, tennis-ball catching drills (9 x 20 min) occurring over a six week period. Pre and post training, participants completed a one-handed ball-catching task and two perceptual tests: the useful-field-of-view (UFOV) and motion-in-depth sensitivity (MIDS) tests. Since the CSR condition used in the present study has been shown to have no effect on catching performance (Bennett, Ashford, Rioja, & Elliott, 2004), it was predicted that the VSR group would show significantly greater improvement pre-post training. There were no significant differences between the CSR and VSR on any of the tests. However, changes in catching performance (total balls caught) pre-post training were significantly correlated with changes in scores for the UFOV single-task and MIDS tests. That is, regardless of group, participants whose perceptual-cognitive performance improved in the post-test were significantly more likely to improve their catching performance. This suggests that the perceptual changes observed in previous stroboscopic training studies may be linked to changes in sports skill performance.

Introduction

The importance of visual-perceptual skills in sport has been emphasised on countless occasions (Williams, Davids, and Williams, 1999), indeed, Revien and Gabor (1981) claimed that “visual training might well make the difference between winning and losing’ (p. 21). As a consequence, training programmes designed to improve these skills for athletes have been a target of many studies.

Initial research in this area suggested that the benefits of such programmes for athletes are highly questionable. For example, Abernethy and Wood (2001) investigated the effects of “Sports Vision” (Revien & Gabor, 1981) and “Eyerobics” (Revien, 1987). Both programmes aimed to improve a variety of visual functions – including acuity, accommodation, peripheral vision, and depth perception – though it should be noted only Sports Vision claimed a subsequent effect on sporting performance. This was done through the use of exercises such as the Brock string test and Howard-Dolman apparatus. The effect of these training programmes on the tennis forehand drive and 12 tests of general visual perception (including dynamic and static acuity, accommodation, field of view, and depth perception) were investigated. Participants were assigned to one of four groups: a "Sports Vision" training group, an "Eyerobics" training group, a (placebo) reading group, and a control group. Each training group took part in a total of 320 minutes of visual training and 80 minutes of tennis forehand practice over a four-week period. The reading group and control group also took part in the 80 minutes of tennis practice, though the former also completed 320 minutes of reading/watching tennis matches. No significant differences were found between any of the groups in the post-test measures of visual perception, or in the accuracy of the tennis forehand drive.

In contrast, Rezaee, Ghasemi, and Momeni (2012) found that a combination of Sports Vision training with physical practice improved visual skills (accommodation, saccadic eye movement, eye-hand coordination, and speed of recognition) and table tennis forehand drive performance to a greater degree than physical practice or Sports Vision training alone. Similarly, Revien's Eyerobics training program has been shown to improve hand-eye coordination, balance, and performance on a football dribbling task relative to a control group which did no such training (McLeod, 1991). Whilst Abernethy and Wood (2001) found no training affect using a novice sample group, the positive effects of McLeod's (1991) study were found for a more experienced (varsity level) group. It has been suggested that for visual training programmes to be effective, they must target areas that are limiting factors to performance (Abernethy, Wood, & Parkes 2001). As a result, visual training is likely to be more beneficial for elite athletes than novices. It must be noted, though, that the study by Rezaee et al. (2012) found significant training improvements with a novice sample group.

Rezaee et al. (2012) have suggested that one of the reasons for the current ambiguity in the literature may be due to the differing duration of visual training programmes; their study incorporated 24 sessions of 30 minutes over an eight-week period, compared to 20 sessions of 20 minutes over a four-week period (visual-training only) in Abernethy and Wood's study. The type of visual skill targeted is also likely to affect the results of visual training studies; so called "software-based skills" that rely on task-specific cognitive knowledge are more likely to be sensitive to training effects compared to "hardware-based skills" that are underpinned by the physical characteristics of the eye (Williams, 2000). The participants' stage of learning may also have an influence on the benefits of visual training. Finally, visual training programmes designed to specifically emulate the requirements of the activity/task assessed are likely to result in greater skill transfer (and thus greater training effects) than ones which do not (Schmidt & Lee, 2011).

Interest in visual training programmes for sport has recently been revived in a series of studies focused on the possible benefits of stroboscopic training (e.g., Appelbaum, Schroeder, Cain, & Mitroff, 2011; Clark, Ellis, Bench, Khoury, & Graman, 2012). Stroboscopic training involves intermittently occluding a performer's vision (e.g., by using liquid crystal technology in the lenses that alternate between transparent and semi-opaque states). It is proposed that this stroboscopic training will force an athlete to make better use of the limited visual input that they do receive and become more sensitive to other sources of sensory information involved in skill execution (e.g., proprioception), resulting in improved performance post-training when the glasses are removed (Mitroff, 2013).

The development of this intervention was based on a large body of laboratory research examining the effects of stroboscopic visual presentation on motor performance by Digby Elliot and colleagues (see Elliott, 1990, Elliott, Helsen, & Chua, 2001, for reviews). For example, in one study, participants were required to catch tennis balls projected from a serving machine 10 metres away at a speed of 11m/s and directed towards the shoulder of their catching arm (Bennett, Ashford, Rioja, & Elliott, 2004). This was done under the following visual conditions: continuous, 20/40, 20/80, or 20/120, where the two values in these ratios refer to the duration (in ms) for which the glasses were transparent and occluded, respectively. Catching performance was found to decrease monotonically as occlusion periods increased. However, even in the 20/120 condition, participants caught approximately 50% of balls, indicating that even with very limited vision, people can still perform a complex perceptual-motor task.

The second experiment by Bennett et al. (2004) investigated the effects of training under intermittent visual conditions on catching ability. Using a between-subjects design they had participants perform a catching test before and after practicing in one of four visual conditions (continuous, 20/40, 20/80, or 20/120) or in a control group which had no training. Pre- and post-practice tests were done under a 20/80 intermittent visual condition. The main finding was that all three of the stroboscopic training groups improved catching accuracy in the 20/80 post-test whilst there was no pre-post difference for the control condition. Critically, this study did not include a continuous vision post-practice test and therefore it is not clear whether or not training using stroboscopic vision transfers to performance in continuous vision conditions post-training. This type of transfer is, of course, what is directly relevant to sports training. As predicted by the general principles of transfer of training outlined by

Schmidt and Young (1987), it might be predicted that there would be no such transfer as the training and testing conditions would be too dissimilar.

More recent studies have attempted to address this transfer question by evaluating the effects of stroboscopic vision training on performance when the glasses are subsequently taken off. For example, in a study by Clark et al. (2012) players from the University of Cincinnati baseball team underwent vision training (which included dynavision, brock string, tachistoscope, and strobe glasses) prior to and during their 2011 collegiate season. Numerous batting statistics from the 2010 and 2011 season were then compared (with comparisons also made between other divisional teams, who did not undergo visual training, to act as a pseudo-control). It was found that several key performance statistics increased between the two seasons including batting average, team performance (i.e., wins), slugging percentage, on base percentage, and number of hits. Whilst it is impossible to know whether it was the stroboscopic training aspect of the visual training program that accounted for the improved performance, the findings look promising. However, it should be acknowledged that the University of Cincinnati baseball team continued with the visual training the following season (Clark et al., 2012) and statistics taken from that 2012 season showed reductions of several batting statistics (Cincinnati Season Stats., 2012). This suggests that the training program may have provided only a transient placebo effect, such as a Hawthorne effect (Franke & Kaul, 1978).

Additional research on the effect of stroboscopic training has been carried out by Mitroff and colleagues (e.g., Appelbaum et al., 2011; Appelbaum, Cain, Schroeder, Darling, & Mitroff, 2012; Smith & Mitroff, 2012). Appelbaum et al. (2011) found that stroboscopic training can improve certain aspects of visual perception, namely enhanced sensitivity to changes in motion in centrally presented stimuli, and greater accuracy in the processing ability of central field information. In this study, 157 participants (41 of which were varsity football players) performed between 54 and 300 minutes of sports-related activities, such as simple, tennis-ball catching, Frisbee practice, and speed and agility drills, over multiple sessions whilst wearing the Nike Vapor Strobe glasses. Half wore glasses in which the strobe rate slowed – and therefore the task became harder – at pre-determined intervals throughout training (experimental group) whilst the other half had glasses in which no strobe effect was experienced (the glasses remained transparent throughout) (control group). A number of computer-based visual-perceptual measures were assessed, with it being found that there was a significant increase in sensitivity to changes in motion in centrally presented stimuli, and a greater accuracy in the processing ability of central field information. There was no change between the groups following training for peripheral-field measures. Due to the absence of any type of motor skill or sports performance measure, these findings have limited implications to sports-related performance, especially given the lack of transfer often found between general visual abilities (e.g., acuity, reaction time, etc.) and skilled performance (Abernethy & Wood, 2001; Oudejans, Koedijker, Bleijendaal, & Bakker, 2005).

In a follow up study, Appelbaum et al. (2012) hypothesised that a further effect of the stroboscopic training could be to "force individuals to more robustly engage visual memory for successful motor planning" (p. 1682). The ability to retain visual samples and extrapolate details such as acceleration and trajectory could prove useful in sports, for example, to a quarterback trying to find his receiver between onrushing defenders. Following a similar protocol to their previous study (i.e. training drills, training duration, and group instructions), participants recruited from the varsity soccer and basketball teams, as well as normal students, performed an iconic memory task immediately before and immediately after the stroboscopic training. In this task participants were briefly presented 4 letters ("D", "F", "J", and "K") at eight locations spaced equally around a central fixation point. Presentations lasted 105ms and were followed by a systematic interval period ranging from 13-2560ms, after which a central cue pointed at one of the eight locations. The accuracy in which participants were able to report the letter that appeared at this location was recorded. In an additional experiment, naive participants performed the same procedure but with the post-test occurring after a twenty-four hour delay in order to examine retention effects. The results showed that participants who underwent stroboscopic training did indeed have significantly increased scores for iconic memory performance compared to a control group, with improvements retained for at least 24 hours. However, again this is only suggestive of a link between stroboscopic training and sports performance.

A more performance-related measure was used in a study by Smith and Mitroff (2012). They tested the anticipation timing – an essential ability in many sports – before, immediately after, 10 minutes after, and 10 days after participants completed 5-7 minutes of either stroboscopic training or continuous vision training (control). This task used a four-metre long Bassin Anticipation Timer (Lafayette Instrument Co.) containing 200 evenly spaced red light-emitting diodes (LED). On initiation of a trial, these lights would illuminate in sequence at a rate of 2.25 metres/second. Participants were required to press a button when the lights reached the final LED. Accuracy (absolute error), direction of error (early or late response), and consistency (variability of error) were recorded. The training session was simply further practice of the anticipation timing test. As expected, performance during training was poorer for the stroboscopic training group. In the immediate retest, however, this group were significantly more accurate than the control group, though this difference was not significant in the retention tests. This study suggests that there may be a link between stroboscopic training and performance on perceptual-motor tasks. However, the possible transfer of these effects to sports skills could be questioned given that it involved a button press response; an issue that is further evidenced by the very large difference in the amount of training in the present study relative to the transfer studies described above. Furthermore, as pointed out by one of the reviewers, since both the training intervention (stroboscopic glasses) and the measurement device (anticipation timer) involve intermittent presentation there could have been complex interaction between the frequency of the stroboscopic presentation and frequency of the anticipation stimuli in the experimental task.

Finally, Mitroff, Friesen, Bennett, Yoo, & Reichow (2013) conducted a pilot study that examined the effects of stroboscopic training on ice hockey performance. Six (four forwards, two defensemen) players from the NHL's Carolina Hurricanes performed an ice hockey task before and after 16 days of stroboscopic training (10 minutes per day). The stroboscopic training involved usual training activities (on-ice skills as well as conditioning drills) whilst wearing the stroboscopic eyewear. A further five players (three forwards, two defensemen) acted as a control group and continued normal training activities without the stroboscopic eyewear. For the forwards, the task involved skating a figure-of-eight pattern with the puck before taking a shot at an empty net (total 20 trials). For the defensemen, the task involved skating in a circle then around the goal with the puck, where they then made a long pass to an 'X' marked near the halfway mark on the opposite side of the rink. In both cases, accuracy of the shot/pass was measured only. The ice hockey task corresponded to the position played and thus, performance for attackers was based on their success in taking a slapshot on goal whilst performance for defenders was based on their accuracy in making a long pass to the opposite side of the ice. It was found that the experimental group significantly improved their ice hockey performance (average 18% increase) compared to a control group who did not wear the stroboscopic glasses (average 2% decrease). Whilst this study benefits from using an elite (professional) sample and examining directly the impact of stroboscopic training on a sports skill there are a number of limitations to the methodology including a possible placebo effect and lack of measures of visual perception to establish a link between changes in visual processing and sports performance following training. It is also somewhat unclear how professional athletes (who are presumably performing at an asymptotic level due to extensive hours of practice) could achieve such a large improvement in performance.

Aims of the Present Study

To summarize, research on stroboscopic training has: (i) provided strong evidence for improvements in visual perception skills such as motion perception and visual memory following training, and (ii) provided some suggestion that there are associated improvements in motor skill and sport performance following training, however these findings are clouded by several methodological limitations. The goal of the present study was to provide a stronger test of the basic predictions underlying the logic of proposed stroboscopic training benefits.

More specifically, to measure the effect of stroboscopic training on sports skill a one-handed ball catching task was employed. This was chosen for three reasons. First, it involves some of the basic visual skills that have been shown to be influenced by stroboscopic training in the previous research described above (e.g., central field motion sensitivity and anticipatory timing). Second, it is a skill that is directly involved in several sports (e.g., baseball and cricket), whilst the requirements involved in performing the skill – such as correctly timing and intercepting the moving object – are essential to many others, such as football, tennis, and hockey. Finally, it is a task that has been used in several previous studies (e.g., Bennett et al., 2004) including several that have used stroboscopic viewing conditions.

The measures of perceptual-cognitive skills included a modified version of one of the tests found to be significantly influenced by stroboscopic training in previous research; the useful-field-of-view (UFOV) and a test that has not been studied in the context of stroboscopic training previous; motion-in-depth-sensitivity (MIDS). The MIDS was chosen because the ability to effectively process the motion of approaching objects is essential for many sports and the MIDS has been shown to be predictive of performance for other complex perceptual-motor tasks including flying an aircraft (Kruk, Regan, Beverley, & Longridge, 1983) and driving (Wilkins, Gray, Gaska, & Winterbottom, 2013).

One of the challenges of conducting research on interventions like stroboscopic training is deciding on the appropriate control group. As discussed by Appelbaum et al. (2012), if a stroboscopic training group is compared to a control group training under normal, continuous vision conditions one runs the risk of introducing motivational differences between groups (i.e., a placebo effect) as one is training with a new technology whilst the other is following a commonplace training regimen. To address this possible confound, the present study compared two different stroboscopic training groups: a constant strobe rate (CSR) group and a variable strobe rate (VSR) group. For the CSR group, the off time of glasses was set to the shortest value (25ms). Under such conditions, it has previously been shown that there is no significant difference between catching performance in stroboscopic and continuous vision conditions (Bennett et al., 2004). Therefore, it was predicted that the stroboscopic glasses would have no effect on performance in this condition – allowing it to act as a pseudo control condition. For the VSR group, the off time of the glasses was systematically increased from 25-900ms in a manner identical to that used in the previous studies by Mitroff and colleagues (Smith & Mitroff, 2012; Mitroff et al., 2013). Based on the previous research group described above, it was anticipated that the stroboscopic presentation would influence performance in this condition.

The present experiment was designed to test the following hypotheses:

(i) Based on previous research which suggests that stroboscopic training can improve sports performance (e.g., Clark et al., 2012; Mitroff et al., 2013) and previous research demonstrating that stroboscopic training can improve perceptual skills related to catching [e.g., anticipation timing (Smith & Mitroff, 2012) and motion perception (Appelbaum et al., 2012)], it was predicted that improvements in catching performance would be significantly greater for the VSR group as compared to the CSR group.

(ii) Based on previous research showing improvements in visual-perceptual abilities following stroboscopic training (e.g., Appelbaum et al., 2011; Smith and Mitroff, 2012), it was predicted that improvements on the UFOV and MIDS tests (pre-post training) would be significantly greater for the VSR group as compared to the CSR group.

(iii) Based on the proposal that stroboscopic performance can improve performance by improving the underlying perceptual skills (Mitroff, 2013), it was predicted that there would be a significant correlation between the change (pre-post training) in UFOV score and change in catching performance and a significant correlation between the change in MIDS score and change in catching performance.

Methods

Participants

30 participants (12 female, 18 male; mean age = 22.5, SD = 4.7) were recruited from a subject pool in the Sport and Exercise Science undergraduate department of the University of Birmingham. All participants had normal or corrected to normal vision and received partial course credit for participation. All participants were members of sports clubs/teams and had between 5-20 years (mean 9.1 years) experience in their sport. There were no other exclusion criteria. Ethical approval was granted by the Science, Technology, Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham.

Apparatus

The ball projector used in the study was a Prince Professional II projector machine. It was set to project balls out at approximately 22mph and at a frequency of once every 3 seconds. Prince 'Play and Stay 2' tennis balls were used for the ball-catching task whilst standard tennis balls were used in the training sessions. This differentiation ensured that any post-test improvement in catching performance was not due to increased familiarity with the equipment. It also adhered to ethical considerations of the ball-catching task, as the 'Play and Stay 2' tennis balls are designed for junior tennis and move slower and bounce lower than standard tennis balls.

The UFOV and MIDS tests were performed on a Toshiba C660-28T (47.7 V x 78.9 H deg display running at 1366 x 768 resolution and 100 Hz display refresh rate). The viewing distance was 23.5 cm.

The stroboscopic glasses used in the study were the *PLATO Visual Occlusion Spectacles* (Milgram, 1987). These have been used in previous investigations of the effects of intermittent vision (Bennett et al., 2004). The glasses were set so that the VSR group could progress through the eight levels shown in Table 1. These settings were based on the Nike Vapor Strobe glasses as reported in Holliday (2013) to allow for comparison with previous studies (Appelbaum et al., 2011, 2012; Smith & Mitroff, 2012). The CSR group remained on Level 1 in Table 1 throughout the whole of the training programme. The last of the seven training sessions, as well as the 5 minute session prior to the post-test, all began at level 5 for the VSR in order to increase the exposure participants had at the later levels.

Level	On time (ms)	Off time (ms)
1	100	25
2	100	43
3	100	67
4	100	100
5	100	150
6	100	233
7	100	400
8	100	900

Table 1 – On/Off durations for the different levels in the Variable Strobe Rate group.

Procedure

All participants attended the lab on 10 separate occasions over a five week period, with consecutive sessions no more than a week apart. The first session consisted solely of pre-testing. Sessions 2-9 were training sessions lasting 20 minutes each. The final session consisted of 5 minutes training followed by the post-testing. This follows a similar program to that used by Appelbaum et al. (2011, 2012). Participants were randomly assigned to either the VSR or CSR group (15 participants per group) upon arrival at the first session. The mean age of each group was: VSR; 23.5 (6 female), CSR; 22.8 (6 female).

The pre- and post-testing sessions involved the performance of a ball-catching task and two perceptual-cognitive tests (UFOV and MIDS). The training sessions comprised of four simple tennis-ball catching drills taken from the *NikeVaporStrobeGoggles* uploaded videos on *Youtube,* and which use the Nike Vapor Strobe eyewear in a manner that aims to improve both visual and sporting performance. These drills included: the wall-ball catch, the front catch, the turn and catch, and the power ball drop (Athletic Republic, 2011a). In the wall ball catch, the participant catches the ball after it has rebounded off a flat wall situated four metres in front of them. The front catch involves catching the ball thrown from the experimenter standing five metres away. The power ball drop requires the participant to start with their hands behind their back and catch a ball dropped (at eye height) from in front of them before it touches the ground. Finally, in the turn and catch, participants must catch the ball after starting with their back to the experimenter from five metres away (the experimenter shouts “go” on release of the ball). The power ball drop was altered to use a standard tennis ball so as to reduce any potential influence of strength on the training drill. Each drill lasted 10 minutes. Participants completed two drills each session, and therefore each drill on four occasions. The front catch drill was performed on a fifth occasion in the five minutes of training prior to the post-testing. As each drill lasted 10 minutes, between 60 and 100 repetitions were typically performed.

For participants in the VSR, the strobe level was increased (i.e. the strobe rate became slower, and in theory, the task became more difficult due to experiencing fewer visual samples) when 10 successful catches were made during each training drill. For participants in the CSR the strobe level remained the same throughout the whole of training – at the lowest (quickest) and therefore easiest level. Again, in an attempt to maintain motivation levels, each training drill was made progressively more difficult for participants from the CSR when they made 10 successful catches. This was done by reducing the throwing distance by 25cm (wall-ball, front, and turn and catch drills) or lowering the starting position by 5cm (ball drop drill), as opposed to changing the off time of the stroboscopic glasses. Motivation, enjoyment, and effort during the training program were measured via a custom-made questionnaire that was administered prior to the post-testing session. This consisted of 12 questions answered on a 7-point scale ranging from 1: not at all to 7: very much so.

Ball-Catching Task

Participants were required to cleanly catch (i.e. not to "parry" the ball and then catch it) the tennis ball in one hand from a distance of between five and nine metres. This distance was dependent on performance in a practice phase carried out upon arrival to the lab. The starting distance at practice was seven metres; if participants successfully caught seven or more tennis balls (out of 10) then they would move forward a metre. If they caught three or less tennis balls they would move back a metre. In both instances this process would be repeated, thus allowing participants to be tested at distances ranging from five to nine metres. This process was used so that participants' pre-test scores were around a 50% successful catch rate; ensuring the task was not too difficult, but also providing room for improvement. The practice phase also allowed for familiarisation with the task.

The test phase totalled 100 attempts split into four sections of 25. Participants were instructed to use their dominant hand for the first and third sections, and their non-dominant hand for the second and fourth sections. Each attempt was classified as either a successful catch, a timing error (an unsuccessful catch when the hand made contact with the ball but was unable to grasp it), or a positional error (an unsuccessful catch when no contact was made between hand and ball). This classification for catching performance has been used in previous, similar studies (e.g., Savelsbergh & Whiting, 1992).

In all trials participants started with their arms to the side and their feet 30 centimetres from the centre plane of the ball projector so that the balls travelled directly towards the shoulder of the catching hand (without bouncing).

Perceptual-Cognitive Tests

During the ball-catching task rest intervals of approximately 3 minutes were given between the practice phase and the test phase, and between each of the four sections of the test phase. In each of these intervals participants performed three computer tests: the MIDS test, the UFOV single-task, and the UFOV dual-task.

The MIDS Test: The MIDS test used custom made software and was identical to that used in a previous driver training study (Wilkins et al., 2013). This test, a 3D motion perception test, involved the presentation of two radially expanding flow fields – with differing velocities – on each trial. The flow fields were comprised of 1500 white dots presented on a black background and the duration of each presentation was 1 sec. The inter-presentation interval was 0.2 sec and the inter-trial interval was 0.5 sec. Participants were required to make a two-alternative forced-choice judgement (2AFC) about which presentation had a greater movement velocity by pressing one of two response keys on the keyboard. The velocity of one of the presentations (the reference) was held constant throughout the test and had a value of 5 deg/sec. The velocity on the other presentation (the test) was adjusted in accordance with a ML-PEST staircase procedure. The order of the test and reference presentation was chosen randomly on each trial. The initial difference in velocity of the test presentation was 0.5 deg/s and the step size was 0.1 deg/s. The step size was halved after the first two reversals. Four staircases were randomly interleaved so that participants could not anticipate the dot speed on each trial (i.e., if they indicated the test was faster than the reference the test presentation on the next trial would not necessarily be slower). After a minimum of six reversals for each staircase the test concluded, with the average speed of the final four reversals used to calculate the participant's MIDS threshold for a given staircase. The thresholds for the four staircases were then averaged to generate the participant's mean MIDS threshold in deg/sec.

The Team Sports UFOV Test: The test was comprised of two separate subtests which increased in the level of difficulty. These subtests are the single-task and the dual-task and are analogous to those used by Appelbaum et al., (2011). Both subtests began with the presentation of a fixation cross in the centre of the screen for 1.5 sec. After a 200ms delay a cartoon image of a basketball player dribbling a ball (size 3.6 x 2.7 deg) was presented inside a 5 x 5 deg black square positioned at the centre of the display (termed the *central player* throughout). Note, a test involving basketball players was chosen as it is a team sport which involves both a large role for attention (e.g., shifting between teammates and opponents) and intercepting a ball with the hand. The central player had two possible variants (chosen randomly from trial to trial): the player dribbling the ball to the participant's left or the player dribbling the ball to the right. The central player always had a blue jersey and was displayed for a variable duration determined by a staircase procedure as described below. For all subtests, the participant's primary task was to make a two-alternative forced choice (2AFC) judgment about the direction the central player was facing/dribbling. Responses were made by pressing one of two keys on the keyboard. For both subtests, no response feedback was given. For both subtests, participants were given 10 practice trials before the experimental trials began. The other particulars of the two subtests were as follows.

Single Task: In this subtest the participant was only required to make the judgment about the central player and no other stimuli were presented. The player direction was chosen randomly on each trial. The presentation duration for the central player was varied according to staircase procedure used in the UFOV test developed by Ball and Owsley (1992). Namely, after two correct responses, stimulus presentation time for the next trial was shortened; whereas stimulus presentation time for the next trial was lengthened if the response was incorrect. This was continued until six reversals occurred. The threshold presentation time (equivalent to 75% correct) was calculated by taking the mean of the final four reversals. The initial presentation duration was 120ms. The initial step size was 10ms and was halved after the first two reversals.

Dual Task: In the second subtest, an additional image of a basketball player was presented on the screen at the same time (and for the same duration) as the central player on every trial. The image of the second player was identical to the central player except that the player shown was not dribbling a ball and appeared to be stopping to receive (or intercept) a pass. Following the procedure developed by Sekuler and Ball (1986), the player could appear on one of 24 different locations on the screen representing all possible combinations of three eccentricities (10, 15 or 20 deg measured from the centre of the display) and eight directions (N, NE, E, SE, S, SW, W, and NW). Peripheral players were presented in small black squares that were located on radial arms extending from the centre of the display.

Participants were asked to make two judgments on every trial: a 2AFC judgment about the dribbling direction of the central player using the keyboard, and to click on the location of the peripheral player using the computer mouse. They were informed that they should always make the judgment about the central player first followed by the judgment about the peripheral player. The presentation duration was again varied according to a staircase procedure as described above, however, correct responses for both the central and peripheral tasks were required before the duration was shortened. Three separate staircases (corresponding to the three peripheral player eccentricities were randomly interleaved). Peripheral player direction was chosen randomly on each trial. The test was completed once a minimum of six reversals occurred for each of the three staircases. The initial presentation duration for each staircase was 150ms.

Data Analysis

Data analysis was performed using IBM SPSS software (version 20). Data were analysed using a series of 2x2 mixed ANOVAs with a between-subjects factor of group (CSR and VSR) and a within subjects factor of testing period (pre- versus post-training). The alpha level for these tests was adjusted for each subset of performance variables (see Mullen & Hardy, 2000). For the three catching dependent variables (successful catches, positional errors, and timing errors) the adjusted alpha was 0.017. For the two UFOV subtests (single task and dual task) the adjusted alpha was 0.025. Finally, for the MIDS variable there was no adjustment. Partial eta squared was used as a measure of effect size.

Following these analyses, Pearson's correlation analyses were also performed to investigate whether the changes in catching performance (pre to post) were significantly related to the changes in perceptual test score (pre to post). Finally, independent samples t-tests were run on the post-training questionnaire data to examine whether motivation, effort, and enjoyment during the training program differed between the CSR and VSR groups. The alpha level for these t-tests was adjusted to 0.017.

Results

The first hypothesis tested in the present study was that there would be a significantly greater improvement in catching performance (from pre-post training) for the VSR group as compared to the CSR group. Figure 1 shows the percentage of successful catches (A) and percentage of temporal and positional errors (B) in the pre and post sessions for the two training groups. It is clear from this figure that the result did not support this hypothesis and there were little if any training improvements for either group. For the percentage of successful catches the main effects of training group [F(1, 28) = .29, p = .59, η_p^2 = .01] and testing period [F(1, 28) = .12, p = .73, η_p^2 = .004] and the group x testing period interaction [F(1, 28) = .52, p = .48, η_p^2 = .02] were all not significant. Similarly, for the percentage of positional errors the main effects of training group [F(1, 28) = 2.01, p = .16, η_p^2 = .07] and testing period [F(1, 28) = 1.31, p = .26, η_p^2 = .05] were non-significant, though the group x testing period interaction [F(1, 28) = 4.99, p = .034, η_p^2 = .15] was significant and had a medium effect size (Cohen, 1988). Finally, for the percentage of temporal errors the main effects of training group [F(1, 28) = 0.62, p = .43, η_p^2 = .02] and testing period [F(1, 28) = .06, p = .94, η_p^2 = .00] and the group x testing period interaction [F(1, 28) = 2.13, p = .15, η_p^2 = .07] were all not significant. Clearly, these data do not support the first hypothesis.

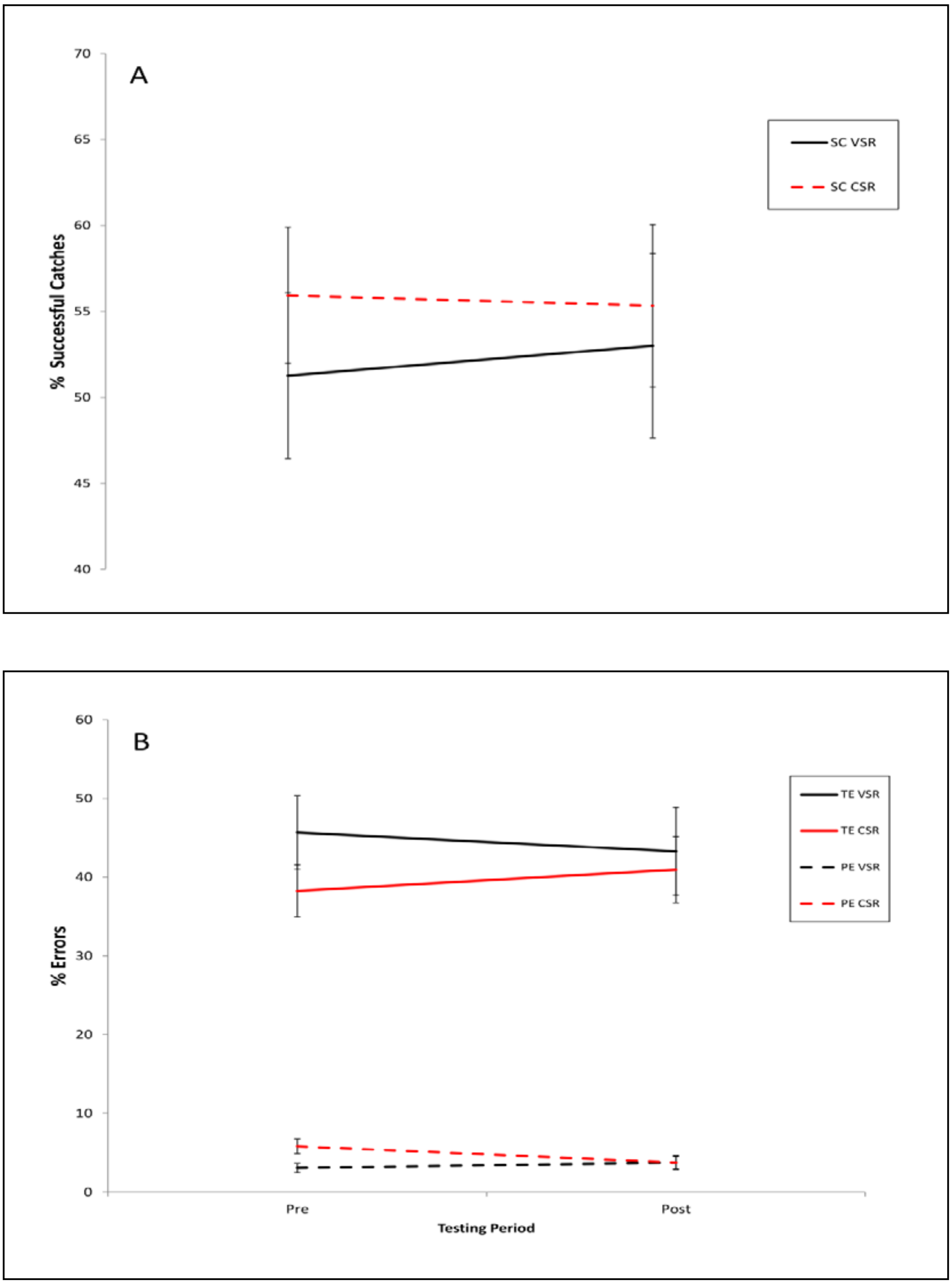

Figure 1 – Catching performance (A = % of successful catches, B = % of errors) for the variable (VSR) and constant (CSR) strobe rate training groups. Error bars are standard errors.

The second hypothesis tested in the present study was that improvements in visual-perceptual tests (UFOV and MIDS) would be significantly greater following training for the VSR group as compared to the CSR group. Figure 2 shows the mean threshold presentation times for the two UFOV subtests. Again, it is evident that there was little evidence of a training effect for either group. For the single task, the main effects of training group [F(1, 28) = .00, p = .95, η_p^2 = .00] and testing period [F(1, 28) = .38, p = .54, η_p^2 = .01] and the group x testing period interaction [F(1, 28) = .00, p = .98, η_p^2 = .00] were all not significant. For the dual task, the main effects of training group [F(1, 28) = 3.73, p = .06, η_p^2 = .12] and testing period [F(1, 28) = .00, p = .99, η_p^2 = .00] and the group x testing period interaction [F(1, 28) = 1.09, p = .30, η_p^2 = .04] were all not significant.

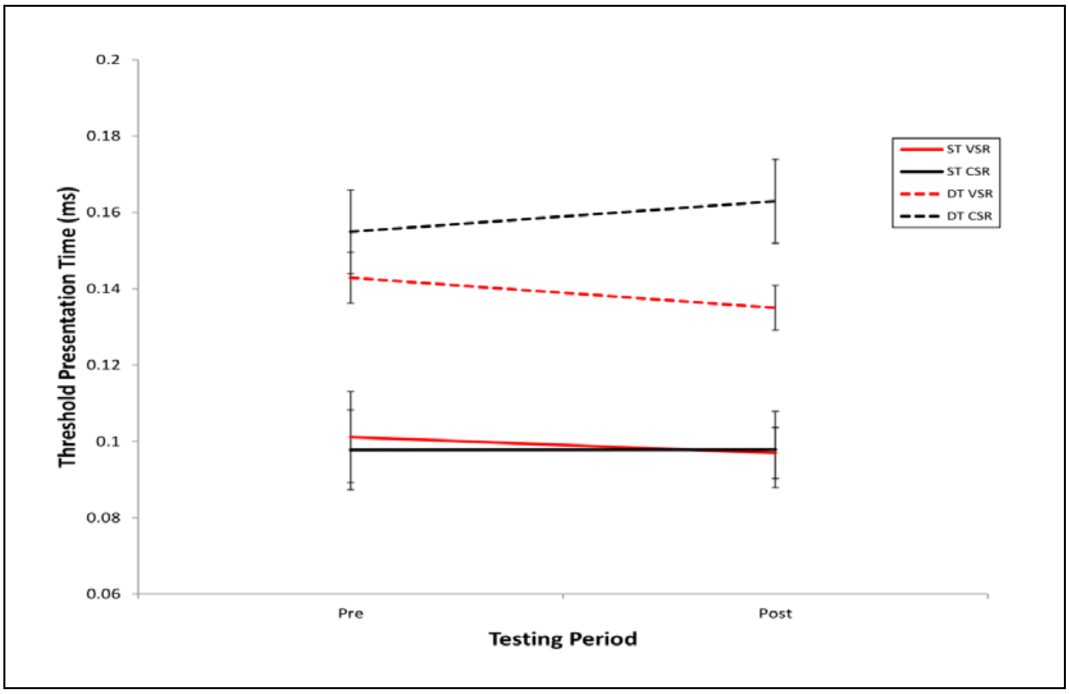

Figure 2 – Mean Scores from the single task (ST) and dual tasks (DT) subtests of the Useful Field of View. Error bars are standard errors.

Figure 3 shows the mean thresholds for the MIDS test. For this dependent variable it does appear that there was an improvement following training, an effect that was born out in a significant main effect of testing period and large effect size [F(1, 28) = 12.64, p = .001, η_p^2 = .31]. However, both the main effect of group [F(1, 28) = .96, p = .33, η_p^2 = .03] and the group x testing period interaction [F(1, 28) = 2.51, p = .12, η_p^2 = .08] were not significant. Therefore, both the UFOV and MIDS data do not support the second hypothesis.

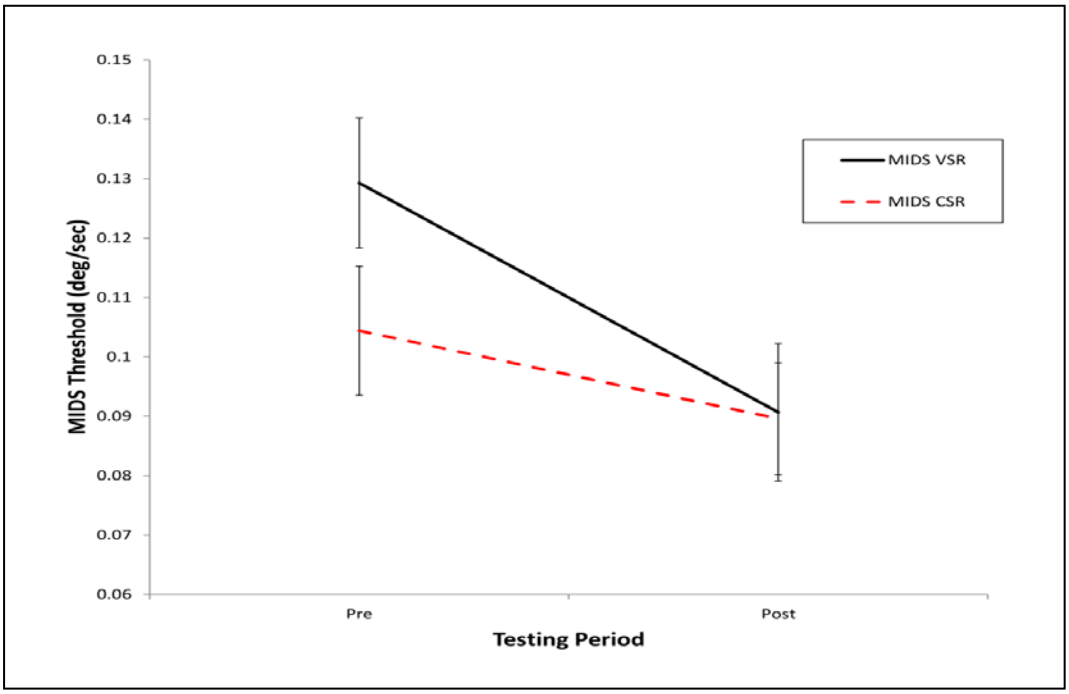

Figure 3 – Mean Scores from the Motion in Depth Sensitivity (MIDS) test. Error bars are standard errors.

The final hypothesis was that there would be significant correlations between the change in performance on the perceptual tests and the change in performance in the catching tasks. Figure 4 shows the change in number of successful catches plotted as a function of the change in threshold presentation time for the single task subtest of the UFOV. For both the VSR [r(15) = -.69, p = .00] and the CSR [r(15) = -.59, p = .02] groups there was significant negative correlations indicating that a larger increase in the number of successful catches post-training was associated with a larger decrease in the required threshold presentation time. For the dual task subtest, correlations were not significant for either the VSR [r(15) = .11, p = .67] or the CSR [r(15) = .28, p = .30] group. Figure 5 shows the change in number of successful catches plotted as a function of the change in threshold speed for the MIDS test. Again for both the VSR [r(15) = -.51, p = .04] and the CSR [r(15) = -.61, p = .01] groups there was significant negative correlations indicating that a larger increase in the number of successful catches post-training was associated with a larger decrease in the MIDS threshold. Therefore, the results were largely consistent with the third hypothesis.

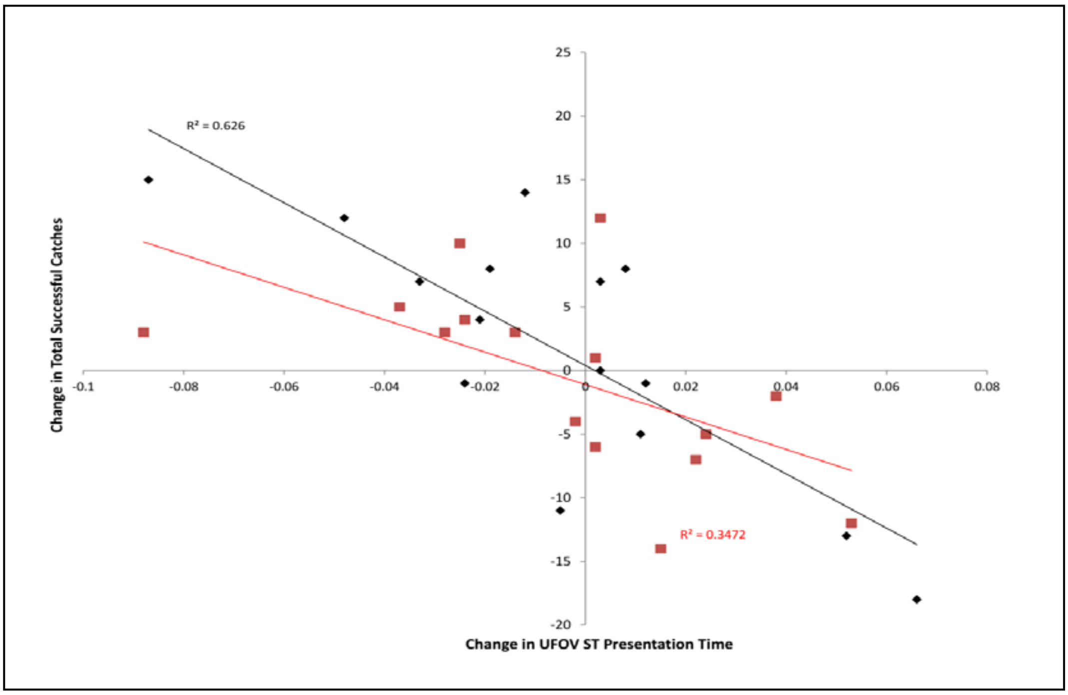

Figure 4 – Relationship between the change in the number of sucessful catches (pre-post training) and the change in the single task score of the UFOV test. VSR = black line, CSR = red line.

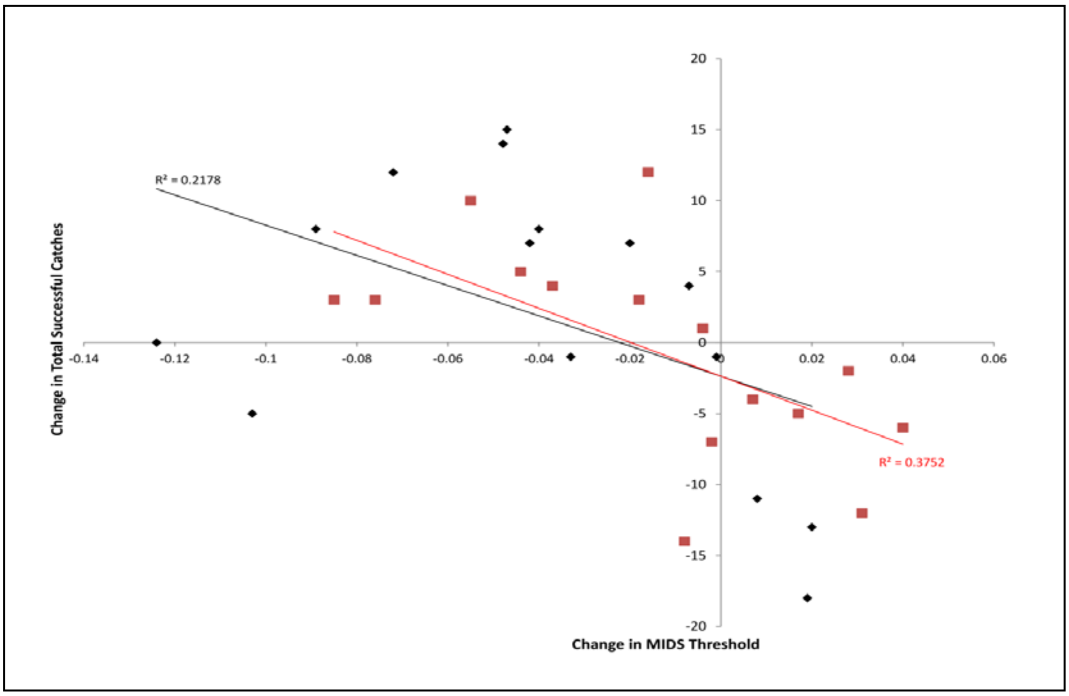

Figure 5 – Relationship between the change in the number of sucessful catches (pre-post training) and the change in MIDS threshold. VSR = black line, CSR = red line.

Finally, one of the design goals of the present study was to ensure that there were no motivational differences between the two training. To test whether this was achieved levels of enjoyment, motivation and effort (as measured via a questionnaire) were compared. Analysis of these data revealed no significant group differences: enjoyment ($t(58) = 0.69$, $p = 0.49$), motivation ($t(58) = -0.38$, $p = 0.70$), or effort ($t(58) = 0.67$, $p = 0.50$).

Discussion

Previous research suggests that certain perceptual and cognitive abilities can be enhanced through stroboscopic training, such as central field motion sensitivity, transient attention (Appelbaum et al., 2011), short-term memory retention (Appelbaum et al., 2012) and anticipation timing (Smith & Mitroff, 2012). Although there are anecdotal claims of large improvements in sporting ability from elite (NFL) American football players (Athletic Republic, 2011b), the few studies which have attempted to examine this have provided inconsistent results (Holliday, 2013; Mitroff et al., 2013). The present study directly compared training with variable strobe rate (VSR) and constant strobe rate (CSR) and tested the following hypotheses: i) improvements in catching performance (pre-post training) would be significantly greater for the VSR group as compared to the CSR group, ii) improvements on the UFOV and MIDS tests (pre-post training) would be significantly greater for the VSR group as compared to the CSR group, and iii) there would be a significant correlation between the change (pre-post training) in UFOV score and change in catching performance and a significant correlation between the change in MIDS score and change in catching performance.

The results of the present did not support hypothesis (i) as there were no significant effects of group (or group x test phase interactions) for any of the measures of catching performance used. This result is inconsistent with previous research which has shown benefits in sports performance (though, not catching) following stroboscopic training (e.g., Clark et al., 2012; Mitroff et al., 2013 – however, see Holliday, 2013, for another study which found no training benefits). Possible differences between the present study and previous research may have contributed to this discrepancy and are discussed next.

First, unlike the previous studies, the present study did not have a pure control group (i.e., a group that received no stroboscopic training). As discussed in detail above, the main design goal of the present study was to compare training groups that would have similar motivational levels in a manner that could rule out placebo/Hawthorne effects. Consequently, the design compared a training method hypothesized (based on a large body of previous research examining the effects of stroboscopic viewing) to have no effect on catching behaviour during training (a constant, high frequency strobe rate, CSR) with a training method that has been shown to effect catching behaviour (a variable strobe that involves systematic decreases in frequency, VSR). The lack of significant group differences in the present study leaves open the possibility that it is the mere interruption of visual input, regardless of whether it is constant or variable, that is sufficient to produce advantageous training effects. Finally, it is possible that the training drills used have more of an effect on performance changes pre-post than the use of stroboscopic glasses. That is, it was decided to physically alter the training drills for the CSR group (i.e. by shortening the distance between the experimenter and the participant after every 10 successful catches), in order to maintain motivation between the two groups, though it is possible that this increased difficulty may have acted as a confound in any performance changes. However, the lack of an overall training effect even when the data for the two groups are combined (i.e., a significant testing period main effect on catching performance) in the present study would argue against these ideas.

Another importance difference is the equipment used to produce the stroboscopic effect. In the present study, the PLATO glasses (Milgram, 1987) were used; which alternate between conditions of full-vision and completely occluded vision. In contrast, in the Mitroff and Clark studies, the Nike Vapor Strobe eyewear were used, which alternate between a full-vision condition and a semi-transparent condition. This attenuated vision condition may be a key requisite in exploiting the potential effects of stroboscopic training, rather than the fully stroboscopic condition used in the present study. For example, being able to partially see the hand/ball during the semi-transparent phase provides greater feedback than full occlusion. A further difference in methodology is in the choice of participants; much of the recent research in stroboscopic training has focused on elite athletes (Smith & Mitroff, 2013, Clark et al., 2012), whereas the present study did not. Perhaps, stroboscopic training is only effective for highly experienced athletes. It will be important for future research to explore these issues.

A final explanation for the lack of any effects on catching performance in the present could be simply that the perceptual-motor changes that occur whilst performing under conditions of stroboscopic training simply do not transfer to full vision conditions. As discussed above, the evidence for transfer in this type of training (or any other vision training) is highly inconsistent. Indeed, there is a large body of research showing a high level of specificity in transfer of training (reviewed in Schmidt & Lee, 2011).

Somewhat surprisingly, given the large and more consistent body of evidence for changes in perceptual-cognitive abilities following stroboscopic training (reviewed), the results of the present study also did not provide support for hypothesis (ii). There were no significant group differences in training effects for either the UFOV or MIDS tests. For the UFOV test, there was also no significant main effect of testing phase (i.e., there was no overall improvement in UFOV performance following training). This result conflicts the previous training effect for UFOV found by Appelbaum et al. (2011). However, there was an important difference between the UFOV tests used in the two studies. In the Appelbaum study, generic shapes were used whilst in the present study sports stimuli (images of basketball players) were used. Since some (but not all) of the participants were not basketball players, it is possible that within group differences (due to expertise effects) masked any potential training effects. It has been previously shown that the domain specificity of stimuli used in simple cognitive/attentional tests can have large effects on performance (e.g., Memmert, Simons & Grimme, 2009). Although there were no group differences for the MIDS test there was an overall training effect for this perceptual test. Therefore, it is possible that VSR and CSR training produce similar benefits for this particular ability, as discussed above.

Despite the lack of any group differences in stroboscopic training for either catching performance or the perceptual tests, an interesting pattern emerged when the pre-post changes in score were examined; a technique that has been used in other performance studies (e.g., Gray, Allsop, & Williams, 2013; Allsop & Gray, 2014). Significant negative correlations were found between changes in catching performance and changes in both MIDS and UFOV ST scores. That is, participants that showed an increase in the number of successful catches from pre-post tended to show an improved ability to judge motion in depth (lower threshold) and improved performance in the UFOV single task (lower required presentation time). In other words, the findings of the present study did support hypothesis (iii). This finding suggests that there may be some link between the perceptual changes that have been reported in previous research and changes in catching performance; however, the nature of the effect is highly variable. Whilst some participants seemed to clearly show training effects for both the perceptual and catching tests others clearly did not. Further evidence in support of this link can be seen in the specificity of the effects. Only the single-task subtest of the UFOV, which measures processing speed in central vision, had a significant relationship with catching performance, whilst the dual-task subtest did not. The ball-catching task employed in the present study involved the projection of a tennis ball almost straight along the medial plane of the body. As previously mentioned, the MIDS test involved assessing the speed of radially expanding dots presented in central vision, whilst the UFOV single-task required quickly judging the orientation of a centrally presented stimuli. Both of these tests presumably tap into some of the same perceptual/cognitive abilities involved in the ball-catching task.

Conversely, the UFOV dual-task subtest, which involves being able to shift attention between central and peripheral stimuli, share much less with the demands of the ball catching task.

To summarise, the present study failed to support previous research which has found stroboscopic training to have beneficial effects on sporting performance (Mitroff et al., 2013). Whilst MIDS test performance did significantly improve post-training, there was no difference between the VSR and CSR groups. Given that visual and perceptual abilities have been shown to improve with stroboscopic training (Appelbaum et al., 2011, 2012; Holliday, 2013; Smith & Mitroff, 2012), these findings may indicate that the mere interruption of visual input, regardless of stroboscopic frequency, is sufficient to produce advantageous effects. This is further supported by the significant correlations between pre-post changes in catching performance and pre-post changes in UFOV processing speed and MIDS test performance.

CHAPTER FOUR

"Although full vision normally provides for the most precise motor control, humans are able to achieve reasonable movement accuracy and consistency when provided with only brief visual samples of the movement environment"

- Elliott et al. (1994)

STUDY THREE: THE EFFECTS OF STROBOSCOPIC VISUAL TRAINING ON MOTOR PLANNING AND ONLINE CONTROL

Abstract

Recent research has suggested that stroboscopic training may enhance sports performance. The present study was designed to investigate whether i) stroboscopic visual training improves manual aiming performance, and ii) whether any improvements are primarily due to changes in movement planning or online-control. 32 participants were randomly divided into either an experimental group (EG) or a control group (CG) and performed an upper limb computer-based manual aiming task under both full-vision (FV) and no-vision (NV) conditions. During the training session, the EG wore stroboscopic glasses whilst the CG did not. Performance was assessed in terms of target hits and the variability in limb trajectories at different stages of the kinematic profile. Variability (at the end of the

movement) significantly decreased in the FV condition for the EG from pre-post training. Significant reductions in variability were not present early in the limb trajectory indicating that the increased performance associated with stroboscopic training occurred as a result of improved online control rather than enhanced movement planning. The present study indicates that stroboscopic training improves the precision of manual aiming as a result of improved online control.

Introduction

Stroboscopic training is a form of visual training that aims to improve an array of perceptual, motor, and cognitive functions by exposing individuals to conditions of intermittent vision (Smith & Mitroff, 2012). Most often this is through the use of specialised eyewear (Elliott, Chua, & Pollock, 1994), though in some instances it can be achieved by the manipulation of light sources in the environment (extinguishing environmental light; Elliott, 1990, optically reversing prisms; Melvill-Jones & Mandl, 1981). It has been proposed that by reducing the amount of visual input an individual receives, a performer learns to use these limited visual samples, as well as their other sensory inputs (such as those from kinaesthetic, proprioceptive and auditory senses), more efficiently (Appelbaum, Schroeder, Cain & Mitroff, 2011). The anecdotal evidence for the benefits of stroboscopic training are many, with individuals often reporting that objects, such as tennis balls, appear bigger or move slower, and actions such as catching become easier (Mitroff, 2013). Indeed, the anecdotal evidence is such that Nike designed, produced and released the Vapor Strobe Eyewear in 2011 as an ‘off the shelf’ visual training aid. However, because the empirical evidence surrounding stroboscopic training is limited, the purpose of the present investigation was to conduct a rigorous experimental design study to further investigate the benefits of stroboscopic training

Nike's Vapor Strobe Eyewear use liquid-crystal lenses that alternate between transparent and semi-occluded states at rates varying from 1-6 hertz. The rationale is that the stroboscopic effect these lenses produce improves a variety of visual and cognitive functions including attention, focus, anticipation, visualisation, reaction time, visual balance, and peripheral vision (Pinkman, Pinkman & Pavlovich, 2012). Previous research has shown that training using stroboscopic eyewear can improve short-term visual memory (Appelbaum, Cain, Schroeder, Darling, & Mitroff, 2012), central field motion sensitivity and the ability to divide attention (Appelbaum et al., 2011), anticipatory timing (Smith & Mitroff, 2012), and dynamic visual acuity (Holliday, 2013). Furthermore, there have also been a small number of studies which have demonstrated that stroboscopic training can improve performance in perceptual-motor tasks.

For example, Bennett, Ashford, Rioja, and Elliott (2004), revealed that practicing under stroboscopic conditions significantly improved catching performance compared to practicing under full-vision conditions. In this study, participants performed pre- and post-test trials of a one-handed catching task under a 20/80 intermittent condition (where the values in the ratio refer to the times for which the glasses are open and closes during each cycle, respectively). They were then assigned to one of five practice groups: continuous vision; 20/40 intermittent; 20/80 intermittent; 20/120 intermittent; and a control that did not practice. Whilst practice performance was as expected (continuous group achieved approximately 100% of catches; with each decrease in the time of available intermittent visual information resulting in fewer successful catches), it was found that all three intermittent groups significantly improved in the post-test, whilst the continuous and control groups did not. Note, that although this finding has important theoretical importance for understanding visual-motor control, it has limited relevance to visual skills training in sport as the effect demonstrated was between stroboscopic training and stroboscopic performance, not stroboscopic training and normal (continuous) vision performance.

In an attempt to further investigate stroboscopic visual training in catching, Holliday (2013), asked 16 elite-level American football players to perform a catching task in either a strobe training group or a control group. Participants performed a range of dynamic visual acuity tests before and after a two-week training period which consisted of 30 minute sessions across eight different days. Results revealed that stroboscopic training did not result in performance increases above those of normal control training conditions since both groups demonstrated similar catching performance following training. Nevertheless, whilst catching performance did not differ between the two groups, stroboscopic training did result in a significant improvement in dynamic visual acuity; a visual ability that has previously been linked to superior sporting performance (Ishigaki & Miyao, 1993).

In contrast to the null performance findings of Holliday's (2013) stroboscopic training experiment, Clark, Ellis, Bench, Khoury, and Graman (2012) revealed significant baseball batting performance increases following stroboscopic training. Specifically, batting performance of the University of Cincinnati baseball team was compared for the 2010 and 2011 seasons, in between which the team had undergone a visual training programme. A number of performance measures including batting average, on-base percentage, and slugging percentage all significantly improved relative to other teams in the same division (who had not undergone any visual training). However, it must be noted that stroboscopic training was just one of eight different visual training methods used during the training programme and therefore it is not possible to conclude how much of the benefits reported, if any, are due solely to stroboscopic visual training.

Finally, Mitroff, Friesen, Bennett, Yoo, and Reichow (2013) recently conducted a pilot study investigating the effects of stroboscopic training on ice hockey performance using athletes from the NHL's Carolina Hurricanes team. Whilst only a small sample, the use of these participants provides an insightful examination of solely stroboscopic training on a truly elite-level population in a practical environment. It was found that the experimental group significantly improved their ice hockey skills (shooting and long passes) by 18% whereas a control group showed no significant change in performance. However, there are a number of limitations to the methodology including a possible placebo effect and lack of measures of visual perception to establish a concrete link between changes in visual processing and sports performance following stroboscopic training.

Aims of the Present Study

From the research reviewed above it can be seen that there is some initial evidence that stroboscopic visual training can improve motor performance in sporting tasks. An interesting question to ask, that is the focus of the present study, is which part of the movement does stroboscopic training effect: offline motor planning, online movement regulation or both? For example, were the improvements in shooting and passing accuracy following the stroboscopic training of Mitroff et al. (2013) due to (i) an improved ability to program the parameters (amplitude, direction) of movement before it was initiated (i.e., offline planning), (ii) an improved ability to adjust the direction and velocity of stick movement after the movement was initiated (i.e., online control), or (iii) both.

To address this question the present study employed a task that has long been known to involve a combination of online and offline processes (Woodworth, 1899) and has been studied extensively in motor control research (Lawrence, Khan, Buckolz, & Oldham, 2006). Specifically, participants were required to make a fast, goal directed upper limb aiming movement to stationary targets. To address the relative contribution of motor planning and online control the variability method developed by Khan and colleagues (for a review see Khan et al., 2006) was used. In this method, the within subject standard deviation in the distance travelled at four separate kinematic markers (i.e., peak acceleration, peak velocity, peak negative acceleration, movement end) is calculated. Variability of markers that habitually occur early in the movement, such as peak acceleration and peak velocity, are deemed to reflect the "planning" component of an aiming task, whilst those that occur later in the movement, like peak negative acceleration, are deemed to reflect the "online control" component of an aiming task (Khan et al., 2006; Lawrence et al., 2006).

In the present study, participants performed manual aiming trials pre and post training. Two groups were compared: an experimental group which received stroboscopic training and a control group which trained under continuous vision conditions. The study was designed to test the following hypotheses: 1) based on the studies showing the benefits of stroboscopic training, the experimental group would improve manual aiming performance to a significantly greater extent than a control group, and 2) based on the proposal that stroboscopic training improves the ability of a performer to use visual and other sensory information, the experimental group would have a greater decrease in the variability for the later kinematic markers as compared to the control group (indicative of improved online control).

Methods

Participants

32 participants (16 female, 16 male) were recruited from the School of Sport, Exercise and Rehabilitation Sciences undergraduate department at the University of Birmingham. Participants signed a consent form, had normal or normal-to-corrected vision, had not previously received visual training, and were all self-declared right-handed. Participants received partial course credit for taking part and were randomly allocated (though gender matched) to one of two groups: an experimental group (EG) which received stroboscopic training (mean age = 21.44, *SD* = 3.56) or a control group (CG) which received continuous vision training (mean age = 21.13, *SD* = 3.95). Ethical approval was granted by the Science, Technology, Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham. Prior to commencing the study, all participants signed a general health questionnaire ensuring they were fit to take part, were not susceptible to seizures, and did not suffer from epilepsy.

Apparatus

Participants sat at a desk in a well-lit lab with a SummaSketch III Professional digitizing tablet (model: MM III 1812) in front of them. This was linked to a 555mm ViewSonic monitor situated approximately 600mm away, and an Intel Core 2 duo processor with Windows Vista. To ensure participants could not see their aiming hand during the experiment, a wooden frame was assembled and placed over the top of the SummaSketch tablet (see Figure 1). A plastic “track” measuring 470mm in length and 10mm in width was fixed to the tablet to guarantee that the hand-held stylus could not vary along the longitudinal plane during the aiming movement; as such the task involved only extent control (also see

Lawrence et al., 2006). The hand-held stylus used was 165mm long and 10mm in diameter, with a nib measuring 2mm in diameter.

The portable liquid crystal Apparatus for Tachistoscopic Occlusion (PLATO) spectacles (Milgram, 1987) were used to create the stroboscopic effect in the study. These have been used in previous intermittent-vision based research (Bennett et al., 2004; Elliott, Pollock, Lyons & Chua, 1995) and allow "an experimenter accurately to control the timing of presentation of visual information to an experimental subject" (http://www.translucent.ca/plato.html). For the current study the glasses were set to a consistent rate of 4Hz throughout. This value was chosen as it equates to the value used by Smith and Mitroff (2012) in their stroboscopic training study of anticipatory timing.

Figure 1. Picture indicating the layout of a trial (shown in the EG's training phase).

Procedure

Each trial consisted of the participant moving the hand-held stylus along the track way fixed to the SummaSketch III graphic tablet. Movement of the stylus was represented by a correlated movement of a cursor (2mm in diameter) on the computer screen from its "start position" towards a target square situated 200mm away along the horizontal axis. This correlation was set at a 1:1 ratio. At the start of each trial, participants were required to align the cursor on the start position. Once steadily aligned, the target box (10mm × 10mm) appeared on the monitor screen. This was then followed by a tone that informed participants they could begin the aiming movement. All trials were initiated by the experimenter and participants were explicitly aware that reaction time was not important. Participants were informed that the aim of each trial was to stop the cursor in the centre of the target box with a movement time of 400ms[1]. Successfully doing so resulted in seven points being awarded, with points diminishing dependent on how far the movement end point diverged from both the target box and the target time (400ms). Trials in which the movement time fell outside the range of 350-450ms were not saved for analysis and were repeated (this amounted to < 5% of trials in all participants). The number of trials used in each phase of the experiment is described below.

The manual aiming task was performed in three different visual conditions. In the full vision (FV) condition, the cursor representing the position of the stylus and the target box were visible throughout the whole of the trial. Therefore, online regulation of the movement based on visual information was possible. In the no vision (NV) condition, the target box remained on the screen for the duration of the trial but the cursor representing the position of

[1] Movement time was restricted to the 400msec criterion to ensure participants did not strategically redistribute planning and control processes (Khan, Sarteep, Mottram, Lawrence, & Adam, 2011).

the stylus disappeared at the onset of movement and did not re-appear until the trial was complete, thus preventing any online regulation of the movement based on visual information. Finally, in the stroboscopic vision (SV) condition, the cursor representing the position of the stylus and the target box were presented on the screen throughout the whole of the trial but the participant's vision of the screen was intermittently occluded via the PLATO glasses. In this condition, online regulation based on visual information is presumably possible (i.e., see Elliot, 1990), however the information is impoverished relative to the FV condition.

The feedback given to participants was kept consistent and was delivered in two forms; from the experimenter, and on-screen. On all trials, a reminder appeared on-screen reading "movement time should be 400ms". On "good trials" (those in which the movement time was between the 350-450ms range), the participants' screen would show information regarding that trials trial number, reaction time, movement time, and points scored, together with total points accrued during that experimental phase thus far and either the words "target hit" or "target miss". On "bad trials" (those in which movement time fell outside the 350-450ms range) none of this feedback was presented and the experimenter would inform participants only of that trials movement time.

The training procedure used in the present study was directly modelled after the anticipatory timing study described of Smith and Mitroff (2012). The experiment consisted of four phases in the following order: a practice phase of 30 trials (15 FV, 15 NV), a pre-test phase of 60 trials (30 FV, 30 NV for both groups), a training phase of 50 trials (SV for the experimental group and FV for the control group), and a post-test phase of 60 trials (30 FV, 30 NV for both groups). The order of the FV and NV conditions in pre- and post-test phases were counterbalanced across participants. All participants were given a one minute break after every 15 trials. The total duration of the experiment was approximately 80 minutes.

Data reduction, dependent measures and analyses

The displacement data for each trial were filtered using a second-order dual-pass Butterworth filter with a low-pass cut-off frequency of 10 Hz. Instantaneous velocity data were obtained by differentiating the displacement data using a two-point central finite difference algorithm. This process was repeated to obtain acceleration data. In order to locate the beginning of the movement, peak velocity was first obtained. The velocity profile was then traversed backwards in time until the velocity fell below 1 cm/s. The end of the movement was defined as the first point in time following peak velocity in which the absolute velocity of the pen fell below 1 cm/s. Hence, movement trajectories could not contain a reversal in direction.

Aiming performance was quantified using three dependent measures (calculated by using the 30 trials for condition in the pre- and post-test phases): total number of target hits, average positive error (distance missed *after* the target), and average negative error (distance missed *before* the target). All errors (+ve and –ve) were taken from the centre of the target box.

To evaluate the effect of stroboscopic training on movement kinematics, the within subject standard deviation in the distance travelled at peak acceleration (dPkA), peak velocity (dPkV), peak negative acceleration (dPkNA), and movement end (dEnd) was calculated. The mean values for these four kinematic markers (calculated from the 30 trials in each block) were then used as the primary dependent variables.

A 2x2x2 ANOVA was run to examine each aiming performance measure, with group (experimental/control) as a between subjects factor, and phase (pre/post) and vision (full/no) as within subjects factors. Movement variability data were analysed using a 2x2x2x4 mixed

ANOVA with group (control/experimental) as a between-subjects factor and phase (pre/post), vision (full/no), and kinematic marker (dPkA, dPkV, dPkNA, dEnd) as the within-subject factors. In this analysis, the kinematic markers are treated as independent variables as they are acting as different points of time during the aiming movement. This method has been used in previous research (Khan et al, 2011). All analyses were run using SPSS version 20.

Results

Following initial data screening, no outliers were identified and thus, all results are based on data from all 32 participants.

Aiming Performance

Figure 2 displays the mean performance measure scores for each group. The 2x2x2 ANOVAs performed on these data revealed significant main effects of vision on total target hits ($F_{(1,29)}$ = 4.56, p = 0.04, η^2 = .14), and average negative error ($F_{(1,29)}$ = 4.99, p = 0.03, η^2 = .15). There was also a significant main effect of experimental phase on average positive error ($F_{(1,29)}$ = 4.19, p = 0.05, η^2 = .13). None of the interactions were significant (p all > 0.10). Critically there was no significant effect of group found for any of the performance measures.

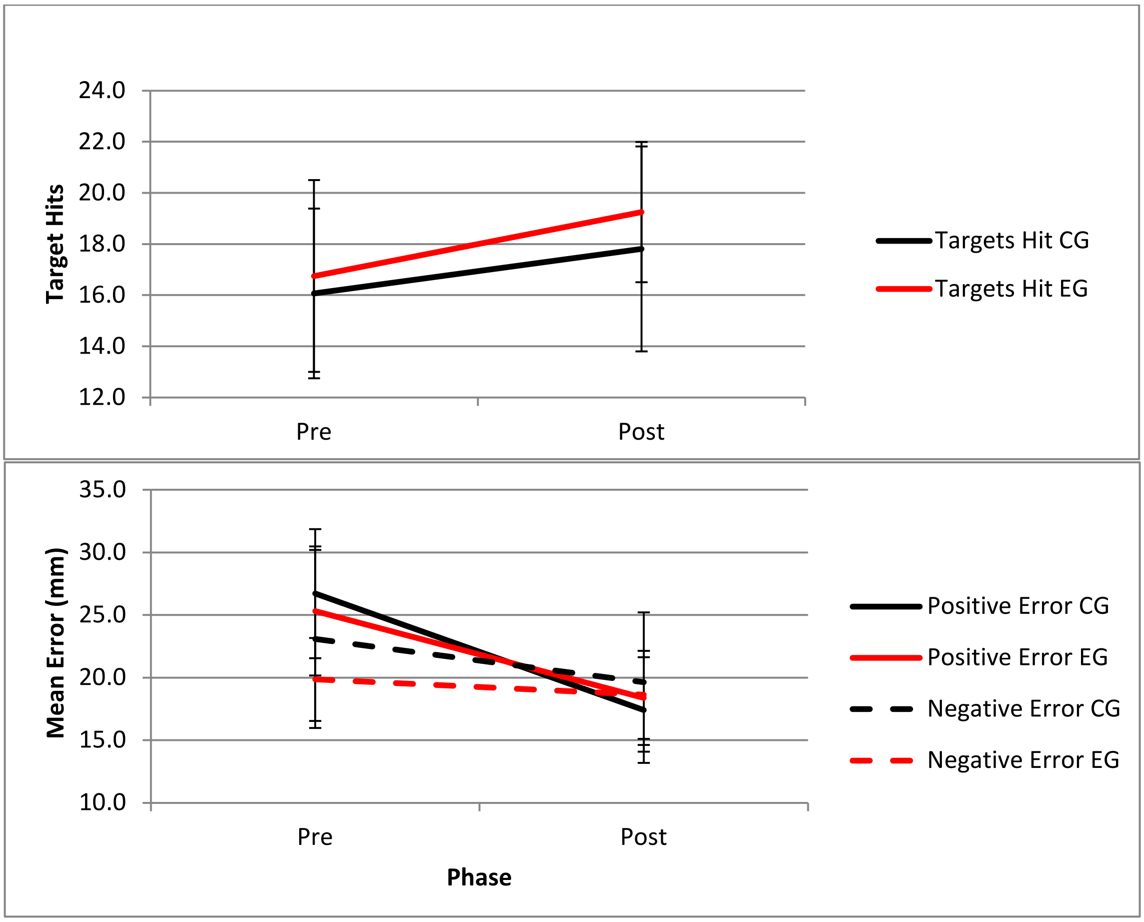

Figure 2. Manual aiming performance in terms of a) target hits, and b) mean error (mm) for both the control group and the experimental group, pre and post-training.

Kinematic Markers

Figure 3A & B show the mean variability for each of the kinematic markers for the experimental and control groups, respectively. The 2x2x2x4 mixed ANOVA performed on these data revealed a significant phase x vision x group x kinematic marker interaction ($F_{(1,29)}$ = 9.98, p = 0.004). In order to interpret this significant four-way interaction a simple effects analysis using separate 2 (phase) x 2 (vision condition) x 4 (kinematic markers) repeated-measures ANOVA's for the EG and CG was performed.

For the experimental group, the 2x2x4 ANOVA revealed significant main effects for vision condition ($F_{(1, 15)}$ = 11.60, p = .004, η^2 = .44) and kinematic marker ($F_{(3, 45)}$ = 5.14, p = .004, η^2 = .26). An interaction effect was also found for phase x vision condition ($F_{(3, 45)}$ = 4.78, p = .045, η^2 = .24). As can be seen in figure 3A , this was due to that fact that movement variability was significantly reduced for the full vision condition, pre-post training whilst there were no differences pre-post training for the no vision condition. There was also a marginally significant phase x vision condition x kinematic marker interaction ($F_{(3,45)}$ = 27.70, p = .06, η^2 = .15). To further analyse these data a series of paired-samples t-tests with Bonferroni correction (comparing the variability at each kinematic marker, pre-post training in the FV condition) were conducted. These tests revealed that dEnd variability was decreased significantly from pre-post training: ($t_{(15)}$ = 2.55, p = 0.01). There were no significant differences for any of the other kinematic markers (p all > 0.05). Furthermore, a significant difference between PkNA and dEnd was found in the post-test phase ($t_{(15)}$ = 3.07, p = 0.01) but not the pre-test phase ($t_{(15)}$ = 1.29, p = 0.22).

For the control group, significant main effects were found for vision condition ($F_{(1, 15)}$ = 39.00, p = .00, η^2 = .72) and kinematic marker ($F_{(3, 45)}$ = 3.56, p = .02, η^2 = .19). Interaction effects were additionally found for block x vision condition ($F_{(1, 15)}$ = 5.78, p = .03, η^2 = .28). As shown in figure 3B, the significant block x vision condition interaction occurred because there was a decrease in movement variability for the no vision condition when comparing pre-post training, but there was no change for full vision. None of the other main effects or interactions was significant (all *p's* > .05).

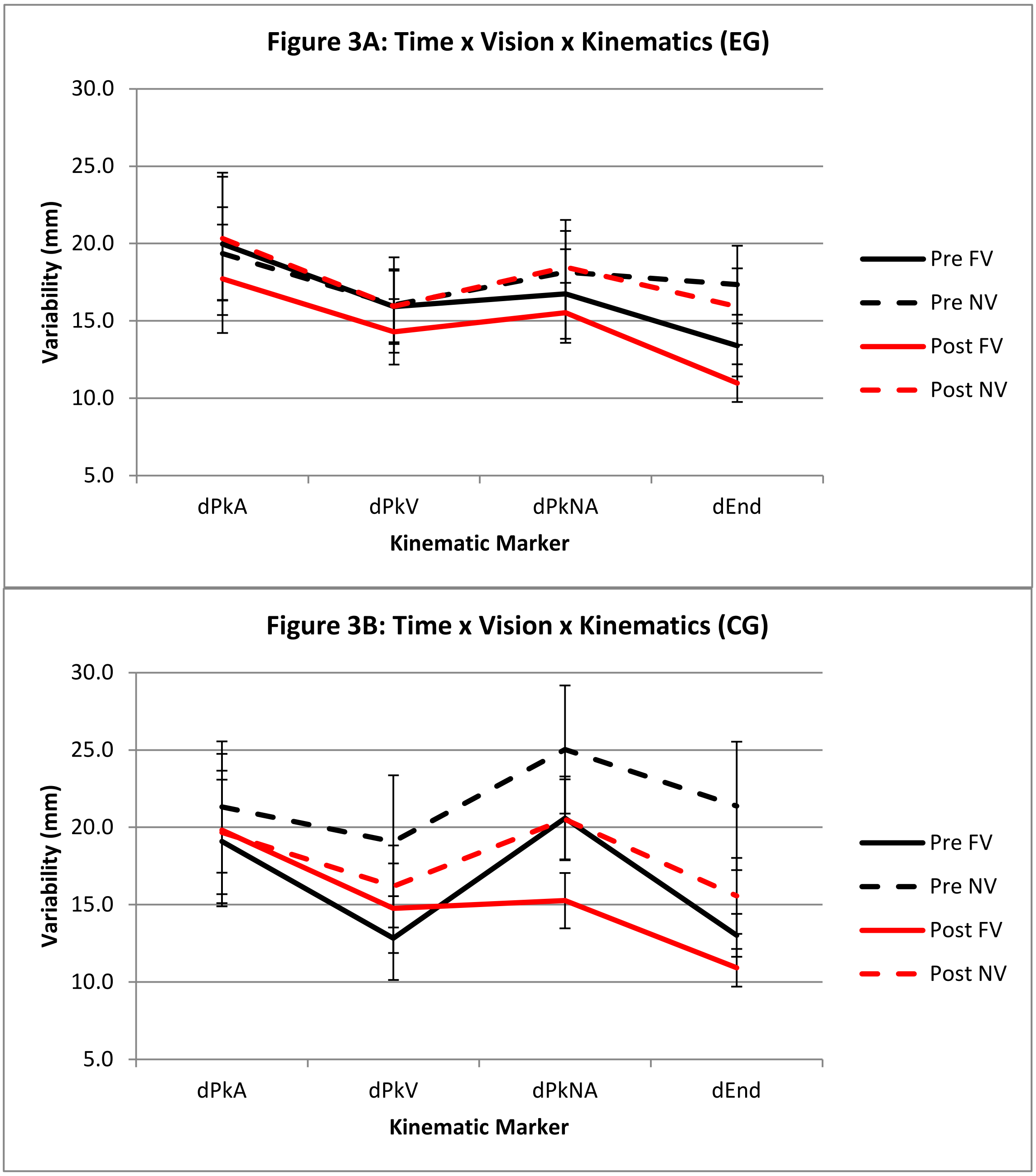

Figure 3. Mean variability (mm) of each kinematic marker for a) the experimental group, and b) the control group, under both full vision and no vision conditions and for pre and post-training.

Training phase

Finally, data from the training phase was analysed to see if participants changed their manual aiming technique during training (Figure 4). Paired-samples t-tests with Bonferroni correction were performed on the kinematic marker variability between the first 25 trials and the last 25 trials. Significant decreases in variability were found between the first half and the second half of training for the PkNA ($t_{(31)}$ = 2.83, p = 0.01) and End ($t_{(31)}$ = 2.56, p = 0.01) kinematic markers. No significant difference was found for the PkA or PkV.

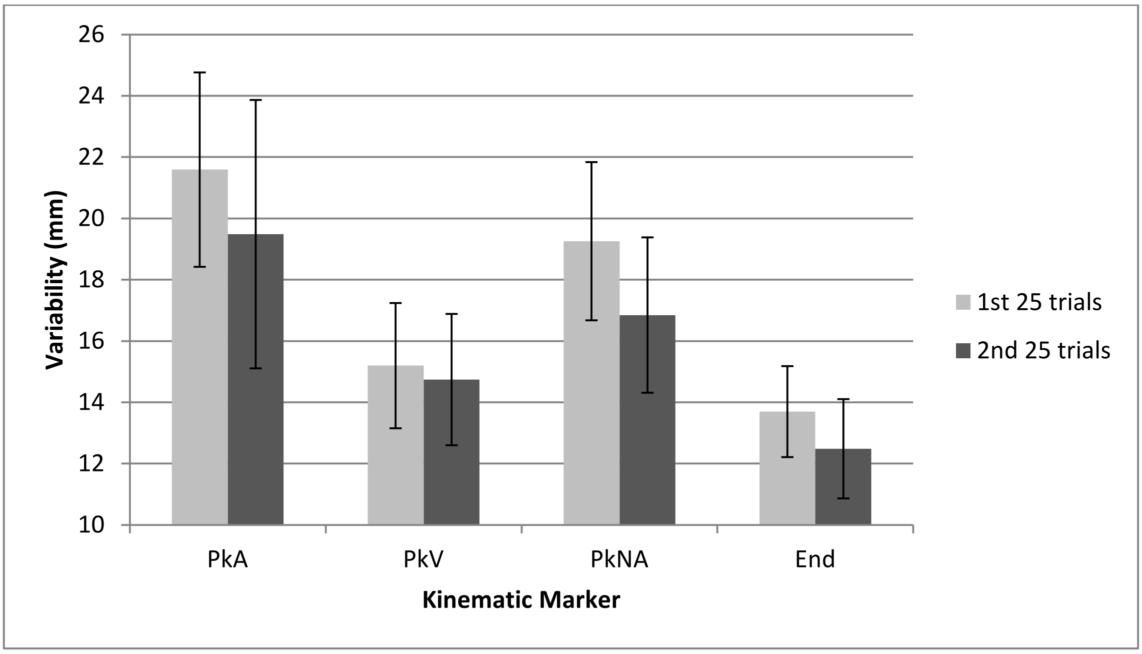

Figure 4. Changes in variability (mm) for each kinematic marker during the training phase.

Discussion

The present study aimed to investigate two things; first, whether stroboscopic visual training could improve manual aiming performance, and second, whether any improvements were due to changes in planning or online control. The mixed ANOVA's indicated no effect of training on targets hit, however, a significant phase x vision x group interaction was found for the kinematic variables. When this interaction was broken down it was found that variability in the dEnd kinematic marker decreased significantly in the FV condition for the EG from pre- to post-training. Furthermore, the decrease in variability for the EG from peak negative acceleration to movement end was also greater in the FV condition post-test compared to pre-test. Since, significant reductions in variability were not present early in the movement, and reduction later in movement is said to reflect online control (Khan et al., 2006; Lawrence et al., 2006; Lawrence, Khan, & Hardy, 2012), the performance changes following stroboscopic training are likely caused by an improvement in online control rather than enhanced planning. These results suggest that stroboscopic training may not improve the accuracy of manual aiming but may improve its precision, and that these improvements are due to enhanced online-control of movement, rather than enhanced motor planning.

These findings support the hypotheses set and the previous literature which show stroboscopic training to bring about a variety of improvements in both our visual and cognitive functioning (Appelbaum et al., 2011; Appelbaum et al., 2012). In addition, the improvement in online control emphasises the importance of the latter stages of aiming movements asserted in other research (Carlton, 1981; Elliott et al., 1995). However, as in much of the research, there remain reservations about stroboscopic training benefits, particular with regards to absolute or outcome motor performance. Given the simple and controlled nature of the task, and the non-significant finding regarding absolute aiming performance, it is difficult to argue that the benefits of stroboscopic training may extend to more complex sporting situations which are dependent on numerous factors, though research should experimentally investigate this before concrete conclusions are drawn. One particular task which may be of interest when investigating this is golf putting; given its closed nature and reliance on consistent movement kinematics.

Whilst no increases in target hits were found for the EG, the significantly reduced kinematic variability indicates that whilst participants may not be improving their *accuracy*, they are improving their *ability to process and utilise afferent information to make trajectory adjustments during movement execution*. This finding (that it is online control that is improved during stroboscopic training) is logical considering the mechanics of the stroboscopic eyewear. By allowing only intermittent visual samples, participants are forced to make online corrections with each sample received. Although a possible alternative is to wait for feedback at the end of the movement and use this to alter the planning mechanics, it seems unlikely that individuals adopted this strategy since the results of the early kinematic markers did not reveal any significant differences pre and post stroboscopic training (i.e., participants did not utilise the intermittent vision offline to enhance the planning of subsequent actions). Thus, it appears that the intermittent visual samples available in stroboscopic conditions force participants to make continuous online trajectory adjustment that result in greater use of this online correction strategy in subsequent full vision conditions.

By contrast, CG participants are able to learn these online adjustments, but without the same deprived visual conditions, and therefore it is not a strategy that is imposed upon them. A sporting analogy could be that of two golfers; one with a choice of clubs, the other with only 3, 5, 7, and 9 irons available. Whilst both in theory have the opportunity to learn to hit "half a club", the latter is *forced* to given the constraints set. The lack of significant findings with regards to the NV condition supports this idea, as online-control is no longer possible. In a related manner, Bennett et al. (2004) suggest that extrapolation of an object's future trajectory may be possible under intermittent vision conditions and it is possible that participants in the present study employed a similar strategy to make the improved online adjustments in manual aiming performance.

An alternative explanation for the improved online adjustment processes in manual aiming following stroboscopic training could be the effects that the reduced visual input has on an individual's kinaesthetic knowledge. Kretchmar, Sherman, and Mooney (1949) state as much when referencing a study by Griffith (1928) in which individuals learned to drive a golf ball in differing visual conditions: "when visual cues are absent, the individual is forced to rely more heavily upon kinaesthetic cues. He becomes increasingly conscious of muscular feel" (p. 240). Though the learning in Griffiths' study involved no visual input whatsoever, the implications for reduced vision are apparent, and may have contributed to the enhanced precision found in the present study. That is, the reduction in the available visual information during stroboscopic conditions results in participants utilising kinaesthetic afferent information to make online trajectory adjustments; a strategy not typically adopted under full vision aiming conditions (Khan & Franks, 2000; Khan, Franks, & Goodman, 1998; Mackrous & Proteau, 2007; Proteau & Cournoyer, 1990; Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau, 1992).

The implications of these results can be related to studies which have inferred improved catching ability from stroboscopic training (Holliday, 2013) or ones which have suggested such improvements via transfer from enhanced visual/cognitive skills (Smith & Mitroff, 2012). Greater ability to make spatial corrections (i.e. use online control) has been proposed as a key determinant of catching success due to a "more precise orientation of the hand in space" (Mazyn, Lenoir, Montagne, & Savelsbergh 2004, p. 389).

It is important that any inferences made from these findings are considered alongside the training protocol used. As in Smith and Mitroff's (2012) study, participants took part in only one, approximately 20-minute session, situated immediately after pre-testing and immediately before post-testing. Therefore the effects found may be understated compared to programmes which entail considerably more training, or overstated compared to programmes where post-testing is performed with a delay following training. On this note, it is important for future research to identify whether extended periods of stroboscopic training lead to outcome performance improvements and how long the benefits found surrounding stroboscopic training will last. Much of the research to date has been ambiguous over the retention capabilities of any learned skills from stroboscopic training, with some studies showing benefits lasting at least 24 hours (Appelbaum et al., 2012) and other showing only immediate effects (Smith & Mitroff, 2012). From an athlete's standpoint this is an essential element to the results, and could define how and when he or she prepares for training and competitions.

An interesting difference between studies which have found sizeable differences in motor performance following stroboscopic training (Clark et al., 2012; Mitroff et al., 2013) and the present study lies in the population sample. In both of the former cases, truly-elite level athletes participated, whereas the current study used a novice to intermediate population sample. The efficacy of a training program is dependent upon whether the area targeted is the limiting factor in performance (Abernethy, Wood, & Parks, 1999). Given that the differences between novice athletes (or novices on any task) are generally larger than the differences between elite athletes, the limiting factors for motor performance may not extend to areas as narrow as visual and cognitive function. Consequently, it may be that the benefits of stroboscopic training are greater for expert performers. This may also explain the abundance of anecdotal support for stroboscopic training, as much of it comes from elite-level athletes (Athletic Republic, 2011). Future research should investigate this by directly comparing elite and novice athletes whilst rigorously controlling the experimental design of the stroboscopic training.

The present study is not without its limitations. First, given that the aiming task required both spatial (target box) and temporal (350-450ms) aspects, it could be argued that participants may have differed in any potential prioritisation of one over the other. In an attempt to control for this, all participants were given them same instructions throughout the experiment, and provided with a points score that was a combination of both MT and error accuracy. Additionally, results revealed that all participants produced comparable MT's (as such no speed-accuracy trade-off was observed). However, one cannot completely rule out the possibility that participants might have been prioritising MT over accuracy or vice versa, together with the effects it might have had on aiming performance. It is possible that had the focus been solely on accuracy, the findings may have been more pronounced (Elliott, Carson, Goodman, & Chua, 1991). Second, given the repetitive nature of the task, maintaining motivation levels throughout the study is problematic, and as such, performance may have been affected. However, participants were provided with a point score designed to keep task engagement high, whilst the number of trials decided upon throughout the study was also kept to a minimum; any fewer trials would have likely resulted in more considerable methodological issues.

To conclude, the present study aimed to investigate the effects of stroboscopic visual training on manual aiming performance. By employing both a FV and a NV condition and analysing the variability in kinematic markers, any potential changes found could be attributed to either the planning phase or the online-control phase which governs aiming behaviour (Khan et al., 2006; Woodworth, 1899). The results showed that stroboscopic training can enhance the utilisation of online control mechanisms during manual aiming; that is; performers are better able to make adjustments to movements during task execution following a period of stroboscopic training. The implications of which are highly relevant to tasks where perturbations are possible during performance (i.e. ball flight changes due to environmental factors such as wind, previously unperceived 'spin' on the ball, or both). To further enhance our understanding of the benefits of stroboscopic training, future research should address areas such as retention times, elite versus novice samples, and ecologically valid sports based aiming tasks.

CHAPTER FIVE

"Psychology has only recently entered the experimental field. It is most doubtful if the social sciences will ever become truly experimental in the sense of the controlled experiment. This is no reflection on social scientist; it is a comment on the extreme complexity and uncontrollability of all but the simplest social phenomena."

- Arthur H. Steinhaus (1949)

STUDY FOUR: TASK REPRESENTATIVENESS IN COMPUTER TESTS OF PERCEPTION AND COGNITION: CAN THEY ELICIT DIFFERENCES IN SPORTING EXPERIENCE?

Abstract

Research in sports psychology has shown that the more a test reflects the domain in which performance is being predicted in, the greater the likelihood that differences in skill level will be elicited (Mann, Williams, Ward, & Janelle, 2007). The present study aimed to address this by modifying the useful-field-of-view (UFOV) and motion-in-depth speed discrimination (MIDSD) tests by incorporating sport-specific stimuli, and utilising a novel test (motion-in-depth direction discrimination; MIDDD) in a similar manner. 55 athletes were recruited from the following sports: cricket, hockey, rugby, football, and tennis. Participants

performed associate (in which the test stimuli matched the sport in which they were experienced in) and dissociate (in which the test stimuli matched a sport in which they were not experienced in) versions of the UFOV, MIDSD, and MIDDD tests. In addition, the MIDSD test included both fast and slow subtests, and the MIDDD test included both vertical and horizontal subtests. It was hypothesised that participants would perform significantly better on the associate version of each test compared to the dissociate version, whilst for the MIDSD and MIDDD tests, participants would perform better on the tests that were more reflective of their sport (i.e. cricket players would perform significantly better on the fast and vertical tests compared to the slow and horizontal tests, and rugby players vice versa). In the dual-task with distracters subtest of the UFOV, duration threshold were significantly lower in the associate condition as compared to the dissociate condition. For all other tests no significant differences were found. There were no significant effects of speed or direction in the motion perception tests. In conclusion, the present study provides limited evidence that a task-representative approach with regards computer tests of attention and motion perception are able to elicit differences in experience between athletes.

Introduction

A considerable amount of research effort has been put into studying the differences in perceptual and cognitive skills of athletes of different skill and experience levels. A general finding of this line of research has been that tests which better incorporate the context of an athlete's specific sport show more pronounced expertise differences. For example, significant differences in dynamic visual acuity for athlete and non-athletes are only present for fast-moving, small objects (Ishigaki & Miyao, 1993), elite Australian football league players only demonstrate superior decision making accuracy over their sub-elite counterparts when responding to videos played at a speed rated most representative of games situations (Lorains, Ball, & MacMahon, 2013), and response times for interceptive sport experts are quicker than for strategic sport experts (Mann et al., 2007). The goal of the present study was to further investigate the role of task representativeness in developing computer-based tests of perceptual-cognitive skills for sport.

The use of customised, sport-specific tests in sports science research is growing and is in large part a response to calls that claimed much of the previous research in this area has failed to implement designs that represent the environmental stimuli adequately enough (Dunwoody, 2006). Although the ideas of representative design and ecological validity in the field of behavioural sciences date back to Brunswik's seminal work (1956), it is only in recent years that they have been applied extensively to perceptual and cognitive skills in sport. For example, Araujo and colleagues (Araujo & Kirlik, 2008; Araujo & Davids, 2009; Davids, 2008; Pinder, Davids, Renshaw, & Araujo, 2011) highlight how "in sport studies, small changes in task constraints can lead to substantial changes in performance outcomes and movement responses" (Pinder et al., 2011, p. 149), and as such, any implications are undermined when there are differences between the experimental and real task. The importance of task representativeness is incorporated in the 'Expert Performance Approach' (EPA) – a theoretical approach proposed in 1991 by Ericsson and Smith, and meant as "a guiding framework for those interested in furthering knowledge and understanding of expertise and expert performance" (Williams & Ericsson, 2008, p. 654). It argues that in order to obtain the most accurate reflections of human behaviour (such as in expert performance), scientific experiments must employ designs that replicate the natural environment as closely as possible. In doing this, we ensure that the numerous, complex and interacting sources of information – and our individual perceptions of them – which we use to make our decisions and base our actions upon, are still relevant in the experimental context (Ericsson & Williams, 2007). Ericsson and Lehmann (1996) further claimed that future research needs to "develop a collection of standardized laboratory tasks that capture the essential aspects of a particular type of expert performance", and go on to emphasise that it is "essential to preserve all of the relevant constraints in the tasks studied" (p. 281).

Since the EPA was first proposed there have been a handful of studies that have looked at the effect of task representativeness in sport testing. For example, Lee et al. (2013) compared participants' performance of a sidestep movement response to either a 3-dimensional (3D) or 2-dimensional (2D) video opponent. Whilst no differences were found between reaction times for the two conditions, they did show that the number of visual fixations on the opponent was significantly higher in the 2D scenario. The authors concluded that 3D visual stimuli may enable athletes to gather greater information per fixation than 2D visual stimuli due to the added depth component.

In another study, athletes were found to have significantly superior dynamic visual acuity (DVA) to non-athletes only under conditions which allowed for free eye movement and not when target fixation was required – the former being akin to situations commonly found in sport (Uchida, Kudoh, Murakami, Honda, & Kitazawa, 2012). Varying the screen size (from a 43cm computer monitor to a 180 x 145cm screen that reflected the natural environment more closely) however, did not produce performance differences in the decision making accuracy of basketball players (Spittle, Kremer, & Hamilton, 2010). Furthermore, it has been shown that increasing the level of detail of a virtually animated handball thrower did not improve response times and accuracy of goalkeepers, though the kinematics of motion did significantly differ – a factor that suggests the goalkeepers are using different sources of information in the more detailed conditions (Vignais et al., 2009). Finally, Memmert (2006) found that experienced basketball players were less prone to inattentional blindness than novice basketball players when the inattentional blindness task involved a basketball scenario, but that this difference disappeared when the task involved a neutral scenario (Memmert, Simons, & Grimme, 2009).

The nature of the required response has also been shown to mediate the extent of the expert-novice difference in motor performance. The degree to which an action is related to the stimulus that triggers it is termed the stimulus-response compatibility (SRC) and a highly representative design should also seek to maintain the appropriate SRC. Mann, Abernethy, and Farrow (2010) demonstrated this idea in their study on skilled and novice cricket batsmen. Response accuracy (determining whether the ball was directed towards the leg side or the off side) was recorded for four different response situations, each with increasing SRC: 1) verbal report, 2) foot movement, 3) shadow batting (full movement without the use of a bat), and 4) normal batting. This was done under three occlusion conditions; occlusion at ball release, occlusion 50ms after ball release, and no occlusion. For the first condition, the skilled batsmen showed increasing accuracy with each level of stimulus-response compatibility. That is, skilled batsmen were significantly better at predicting the direction of a delivery when required to produce a normal batting response as opposed to when they were shadow batting (which in turn was significantly better than a verbal response). Novice batsmen, on the other hand, showed no change in response accuracy amongst the different response situations. Similar results were found under the 50ms after ball release occlusion condition, though for the no occlusion condition novices also improved with increased SRC. These findings seem to emphasise the importance of utilising experimental designs that replicate an athlete's natural environment as closely as possible.

A similar finding was reported by Dicks, Button, and Davids (2010) with regards football goalkeepers. As well as comparing penalty saving performance and gaze behaviours between different types of responses (verbal, small movement, and interceptive action) they also made comparisons between a video simulation and an in-situ condition[2]. The results showed that goalkeepers saved significantly more penalties in the in-situ (interceptive and movement) conditions than in the video conditions, and also had significantly fewer fixation locations in the in-situ interceptive condition than in the video conditions. Furthermore, the percentage of time fixated on particular aspects during the penalty kick (torso, lower non-kicking leg, and ball) also significantly differed between the in-situ and video conditions. This suggests that it may be erroneous to generalise findings from passive, perception-based tasks (video simulations) to other, more action-based tasks, such as the in-situ environments of performing athletes.

Taking a different approach, a recent study by Huttermann, Memmert, and Simons (2014) investigated attentional breadth in a series of novel experiments in which the participants' sporting experience varied, rather than the nature of the task. In the first experiment, 22 participants (12 sports "experts", 10 novices) performed an experiment measuring their attentional breadth. This attention task required participants to correctly identify the amount of light-grey triangles appearing in a cluster of shapes at varying degrees along either the horizontal, vertical, or diagonal meridian. The degree to which participants

[2] For the video simulation condition, the small movement was performed using a handheld joystick, whilst in the in-situ condition it was a simplified side-step. The interceptive action response was performed in the in-situ condition only as it was not possible under the video simulation condition.

achieved 75% accuracy in triangle identification was considered their “attentional breadth”. It was found that experts had greater attentional breadth for both the horizontal and diagonal meridians, but not the vertical. To investigate this discrepancy, experiment two recruited 56 participants: 30 from sports requiring predominantly horizontal attention (e.g. soccer and handball), and 26 from sports requiring predominantly vertical attention (e.g. basketball and volleyball). The data revealed a significant meridian x expertise interaction, such that the shape of the attentional breadth of athletes is dependent upon the sport in which they participate. Finally, experiment three incorporated a novice group along with a greater number of trials per distance. Again, horizontal-experts had a greater attentional breadth in the horizontal median compared to the vertical, though interestingly vertical-experts showed no such difference. Both groups did have greater total attentional breadth than the novice group. The present study looks to adopt this sports-classification approach in assessing other aspects of attention, as well as motion-sensitivity.

To summarize, the answer to the question of whether more task-representative tests are more sensitive to expertise difference in sport is somewhat ambiguous. However, there are methodological limitations which may account for the lack of performance differences found. For example, Lee et al. (2013) acknowledge that the use of an interceptive task over an avoidance one may have removed the potential for any response time differences, whilst in Vignais et al.’s study (2009) the inclusion of a more novice participant group may have produced the significant differences that the expert group did not. The present study is therefore important in furthering this existing literature and contributing to the question of whether a more representative task design can elicit performance differences in sport.

Aims of the Current Study: The goal of the current study was twofold. First, it sought to expand on the previous work on attentional span in sport (described above) using a sport-specific useful field of view test (UFOV) test. The UFOV test measure an individual's processing speed, divided attention, and selective attention based on the successful identification of images appearing in both the central and peripheral fields (Mathias & Lucas, 2009). In the commercially available version of this test these images are very simple, 2D, silhouettes of a motor vehicle, with the participants required to judge the direction of the vehicle in the central field (processing speed), the location of a target in the peripheral field (divided attention), and the location of a target amongst several distracter stimuli (selective attention) (Lunsman et al., 2008). To adopt a task representative design, the images used in the present study were photographs of athletes in various sporting situations. Ryu, Abernethy, Mann, Poolton, and Gorman (2013) have suggested that expert-novice differences in such a task should be present due to information in the central field being more familiar to the experts, and as such, allowing more attentional resources for peripheral stimuli.

The second goal of the present study was to measure a perceptual ability that is highly relevant for many sports but which has not been studied extensively in previous studies in this area: motion in depth perception. The ability to judge the speed or direction of an object moving towards oneself is critical to performance in many sports; be it to identify a "slower" ball in cricket, return a tennis serve, or intercept a pass in football. In the present study two tests of motion-in-depth perception were used: the motion-in-depth speed discrimination (MIDSD) test and motion-in-depth direction discrimination (MIDDD) test. Previous research has shown similar tests to be able to predict performance in skills such as simulated aircraft flying (Kruk, Regan, Beverley, & Longridge, 1983) and driving (Wilkins, Gray, Gaska, & Winterbottom, 2013). In order to investigate task representativeness, the present study varied the stimuli used in these tests (i.e., the ball type), the object speed, and compared MID in the vertical and horizontal dimensions (similar to Huttermann et al., 2014)

The MIDSD test measures an individual's threshold for determining differences in the velocity of motion along the sagittal plane. In previous research the velocity of the reference presentation (a fixed trial with which comparisons are made) was set at 5°/s (Wilkins et al., 2013). By incorporating two versions of the MIDSD test – one with a fast reference presentation and one with a slow reference presentation – and by recruiting participants from sports with substantial differences in the velocities of motion experienced (i.e. tennis and rugby), the present study sought to investigate the idea of task representativeness with regards to motion thresholds.

In a similar manner, it is possible to adapt the MIDSD test to examine thresholds in determining the direction of motion (termed MIDDD). In classifying the sports that participants played as either reliant on judging predominantly vertical motion (cricket and tennis) or predominantly horizontal motion (football and rugby) and by using two versions which reflect likewise, task representativeness can again be tested.

With this in mind, the present study aimed to investigate the idea of task representativeness by testing participants of differing levels of sporting experience on a number of sports-modified versions of the UFOV, MIDSD, and MIDDD tests. Participants were recruited from various sports teams and completed two versions of each test: an associate version – with stimuli from the sport in which they compete – and a dissociate version – with stimuli from another sport. Based on the assumptions of the task representativeness and on the findings of studies by Memmert et al. (2006, 2009) and Uchida et al. (2012), the present study was designed to test the following hypotheses:

i) UFOV duration thresholds will be significantly lower in the associate condition as compared to the dissociate condition.

ii) MIDSD threshold will be significantly lower in the associate condition as compared to the dissociate conditions.

iii) MIDDD threshold will be significantly lower in the associate condition as compared to the dissociate conditions.

iv) athletes who are experienced in sports which involve relatively fast moving stimuli will perform better on the MIDSD subtest with a faster reference stimulus (associate) than the MIDSD subtest with a slow reference stimulus (dissociate), and vice versa.

v) following the classification of Huttermann et al. (2014), athletes who are experienced in sports which involve more frequent motion in the horizontal plane will perform better on the MIDDD horizontal subtest (associate) than the MIDDD vertical subtest (dissociate), and vice versa.

Methods

Participants

55 participants recruited from the University of Birmingham took part in the study (17 female, 38 male). Partial course credit was given on completion of the study. Two criteria needed to be met for inclusion in the study: i) that the participant currently played for either a cricket (n = 3), football (20), hockey (8), rugby (14), or tennis club (10), and ii) that the participant has normal or normal-to-corrected vision. The mean age (and S.D.'s) of the participants were as follows: cricket (19.7, 1.5), football (20.5, 1.9), hockey (20.9, 3.9), rugby (19.6, 0.7), tennis (20.8, 3.3). Participants had an average of 11.4 years (S.D. = 3.8) experience in their main sport. Ethical approval was obtained from the Science, Technology,

Mathematics and Engineering (STEM) Ethical Review Committee at The University of Birmingham.

Apparatus

All tests were run on a Toshiba Portege R700-184 laptop with 33.8cm, non-reflective screen and a 1366 x 768 resolution. The viewing distance was roughly 25cm. Each participant performed three different computer tests created using custom-designed software: the UFOV, MIDSD, and MIDDD.

The Useful-Field-Of-View (UFOV) Test: In the present study, a modified version of the UFOV test developed by Ball and Owsley (1992) was used. The UFOV test was comprised of three sub-tests; the single-task (ST), the dual-task (DT), and the dual-task-with-distracters (DTWD), which measure processing speed, divided attention, and selective attention, respectively (Ball, & Owsley, 1992). Separate versions of the UFOV test were created representing the three different team sports used in the present study: football, hockey, and rugby.

In the first subtest (the single-task; ST), the image of a player was presented within a 5x5 deg area in the centre of the screen and the participant was required to make a two-alternative forced choice (2AFC) judgement whether the player was headed to the right or left and indicate their response by pressing one of two keys on the keyboard (see Figure 1). The player's heading direction was chosen randomly on each trial and the initial presentation duration was 150ms. This duration was then was varied according to a staircase procedure; if the participant selected the correct response twice in a row, the next image would be displayed for a shorter amount of time; if they responded incorrectly, the next display time was lengthened. Durations were initially changed in 10ms increments. After the first two reversals step size was halved to 5ms to improve the precision of threshold estimate. This trial ended after six reversals. The average of the final four reversals was used as the perceptual threshold. This value corresponds to the duration required for 75% accuracy.

Figure 1. Images of the central player, heading left and heading right, for the football version of the UFOV test.

The second subtest (the dual-task; DT) required the participant to make a judgment about a player presented in the centre of the screen and then asked them to localize a player presented in the periphery. The display was identical to that described for the single task except that an image of a teammate, wearing the same coloured shirt as the central player, was displayed in the periphery. The participant's task was to use the mouse to click on the location of the peripheral player then judge the heading direction of the central player (as described above). The initial duration of this presentation was 200ms and the same identical staircase procedure was used.

The third subtest (the dual-task-with-distracters; DTWD) was identical to the dual task except distracter/opponent images were also presented in the periphery. The requirements were identical to that described for the DT. In both the DT and DTWD subtests the position of the team mate and the distracters in the periphery could be any one of 24 different locations. The location was randomly selected on each trial, the locations themselves represented the eight possible combinations of compass direction (N, E, S, W, NE, NW, SE, SW), and the three different eccentricities, or distances from the central point of the display, that were used (10, 15 or 20 degrees).

Participants undertook the three UFOV subtests under both associate and dissociate conditions with the order counterbalanced across participants. Because the stimuli involved only the team sports, the cricket and tennis player did not complete these tests.

Motion Perception Tests

Motion in Depth Speed Discrimination (MIDSD) Test. The MIDSD test was used to determine a participant's ability to judge the speed of simulated approaching objects. During each trial participants viewed two presentations of a simulated approaching object each with a presentation duration of 1sec. The inter-presentation interval was 0.3 seconds and consisted of a blank screen. Participants had to make a 2AFC judgment about which of the presentations was the faster moving by pressing the appropriate response key. The trials were separated by 0.5 seconds. During this test, the speed of one of the presentations (called the reference) was held constant whilst the speed of the other (called the test) was adjusted. This adjustment was made in accordance with the ML-PEST staircase procedure. The order of presentation for the test and reference was randomized. Initially the velocity difference between the test and reference was 0.5 deg/s with the step size of 0.1 deg/s. After the first two reversals the step size was halved. Participants were prevented from anticipating the speed of the next trial due to the random interleaving of four staircases. The test ended after a minimum of six reversals for each staircase. The participants speed threshold was calculated by obtaining an average speed from the final four reversals. This value represents the speed difference (i.e., between the test and reference) with a 75% correct response rate.

Participants completed four versions of the *MIDSD* test. Two versions involved associate stimuli (i.e., the simulated approaching objects were images of the balls from their sport) and two involved dissociate stimuli. There were also two speed conditions: one with a relatively slow reference speed of 10 deg/s (aiming to be analogous to the slower speed sports like rugby and football) and one with a relatively fast reference speed of 30 deg/s (aiming to be analogous to faster speed sports like tennis and cricket). The same procedure was followed for each test.

Motion in Depth Direction Discrimination (MIDDD) Test. The MIDDD test was identical to the MIDSD test except that participants were now asked to make judgements about the direction of travel of simulated approaching objects. Specifically, there were asked to make a 2AFC judgment about which presentation passed further from the midpoint between their eyes. The initial direction difference was 1 deg and the step size was 0.1 deg. Step size halved after the first two reversals. The final four reversals were averaged to provide the participant's mean direction discrimination threshold level. There were four staircases randomly interleaved to prevent the participant from anticipating the direction on the next trial. Once there had been six reversals the test concluded with the final four reversals being averaged to provide a threshold for the participant which was the equivalent of 75% of answers correct. This signalled the end of the experimental procedure and all data was stored in an output file to be analysed.

Each participant completed four *MIDDD* tests representing all possible combinations of sport type (associate/dissociate) and motion axis (horizontal/vertical). The justification for horizontal and vertical is based on experiment one of Huttermann et al. (2014), in which the size of the playing surface is deemed to convey the amount of time attended to objects; larger areas necessitate more horizontal views and smaller areas necessitate more vertical views. As such, rugby (100mx70m) and football (90-120 x 45-90) differ to tennis (24x11) and cricket (pitch only) (22x4). These classifications also represent this author's subjective judgement that football and rugby require greater judgement of slower, horizontal motion, whilst cricket and tennis require greater judgement of faster, vertical motion.

Procedure

On arrival to the lab, participants were given an information sheet and consent form to sign. They then completed a 'Sports Experience' questionnaire, which asked them of their main sports, years playing each sport, the highest level they had played at, and the position they played in each sport. This information was then used to determine which visual and motion perception tests the participant was eligible for.

Due to the team based nature of the UFOV, cricket and tennis players were not eligible for this test. Similarly, hockey players were not included in either the MIDSD or MIDDD tests either (hockey could not be classified as either fast/slow or horizontal/vertical). All participants completed the tests in the same order: UFOV first, MIDSD second, and MIDDD third.

For each test participants performed an associate version (where the stimuli corresponds to their main sport), and a dissociate version (where the stimuli corresponds to a different sport) in an order that was counterbalanced throughout. The versions chosen for each individual was dependent upon their responses in the 'Sports Experience' questionnaire. No participants reported that they had any experience in the dissociate sports chosen.

Data Analysis

SPSS version 20 software was used in the analyses and all data was checked to identify any outliers. The mean UFOV presentation duration scores were analysed using a 2x3 repeated-measures ANOVA; with sport type (associate, dissociate) and sub-test (ST, DT, DTWD) as factors. The mean thresholds for the MIDSD test were analysed using a 2x2 repeated-measures ANOVA with sport type (associate, dissociate) and reference speed (slow, fast) as factors. Finally, the mean thresholds from the MIDDD were analysed using a 2x2 repeated-measures ANOVA with sport type (associate, dissociate) and motion axis (horizontal, vertical) as factors.

Results

UFOV Test

Figure 2 shows the mean presentation times for the UFOV test. The 2x3 ANOVA performed on these data revealed a significant main effect for subtest ($F(2,80) = 119.541$, $p < 0.001$) The subtest x version interaction approached significance ($F(1.56, 62.36) = 2.619$, $p = 0.093$). To test the prediction that there would be an expertise effect for the selective attention subtest a paired samples t-tests comparing the associate and dissociate conditions was performed. This test revealed a significant difference for the dual task with distracters subtest: $t(40) = -2.455$, $p = 0.019$.

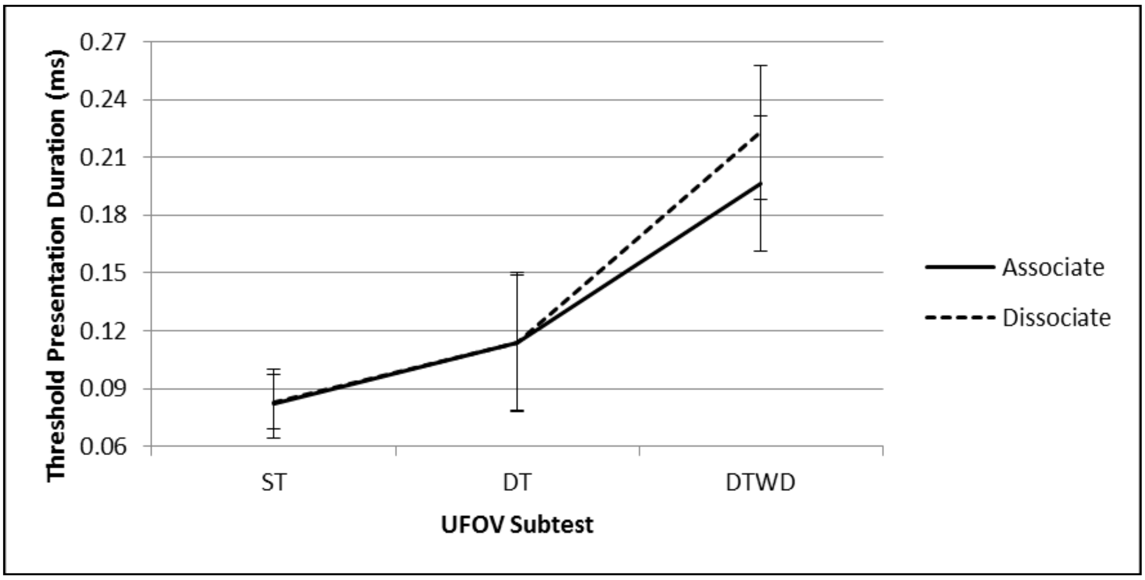

Figure 2. UFOV performance when performing the associate version and dissociate version of the test.

MIDSD Test

Figure 3 shows the mean MIDSD scores for the associate and dissociate versions of both the fast and slow subtest. For the MIDSD test, there were no significant differences between fast-sport individuals (cricket and tennis) and slow-sport individuals (football and rugby) in any of the subtests: associate fast ($p = 0.124$), associate slow ($p = 0.450$), dissociate fast ($p = 0.539$), dissociate slow ($p = 0.965$). Furthermore, when the associate and dissociate versions were collapsed together, the results remained non-significant (fast; $p = 0.497$, slow; $p = 0.654$).

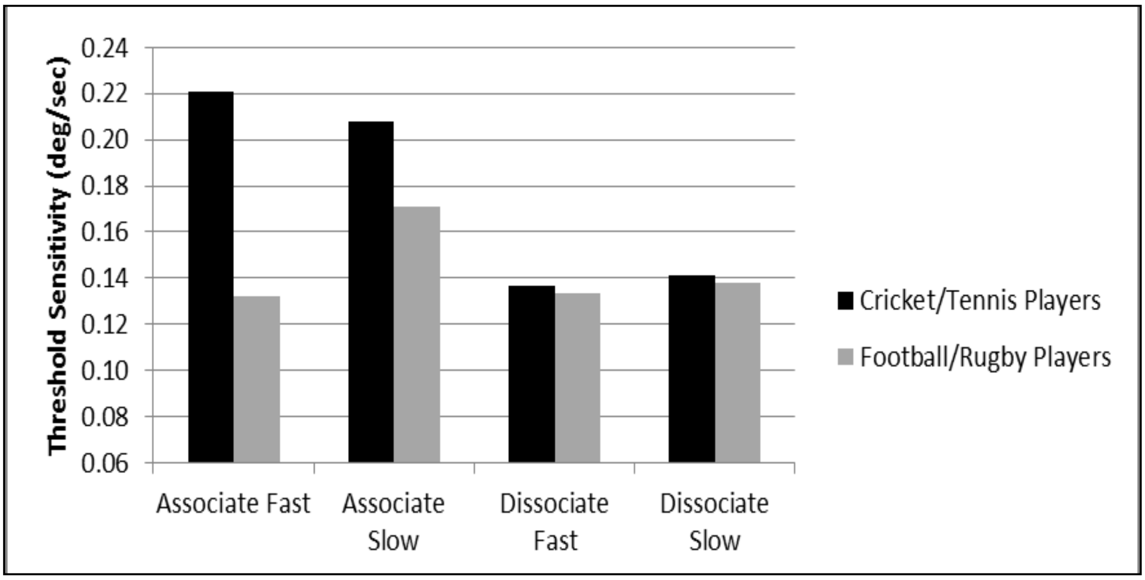

Figure 3. MIDSD threshold for 'fast sport' participants (cricket/tennis players) and 'slow sport' participants (football/rugby players) for both the associate and dissociate versions of the fast and slow subtests of the MIDSD test.

MIDDD Test

Figure 4 shows the mean MIDDD scores for the associate and dissociate versions of both the horizontal and vertical subtest. For the MIDDD test, there were no significant differences between vertical-sport individuals (cricket and tennis) and horizontal-sport individuals (football and rugby) in any of the subtests: associate vertical ($p = 0.537$), associate horizontal ($p = 0.958$), dissociate vertical ($p = 0.283$), dissociate horizontal ($p = 0.182$). Again, when the associate and dissociate versions were collapsed together, the results remained non-significant (vertical; $p = 0.771$, horizontal; $p = 0.336$).

Post-hoc paired sample t-tests were conducted to investigate any within-subject differences between the sub-tests of the MIDSD and MIDDD tests. No significant differences were found (all $p > 0.259$).

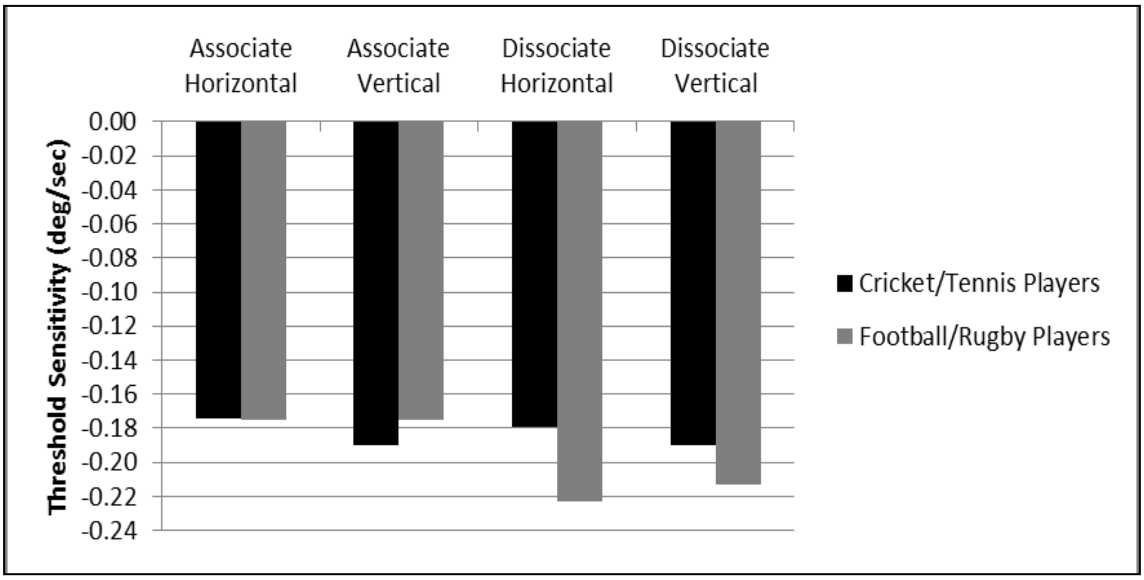

Figure 4. MIDDD threshold for ‘vertical sport’ participants (cricket/tennis players) and ‘horizontal sport’ participants (football/rugby players) for both the associate and dissociate versions of the horizontal and vertical subtests of the MIDDD test.

Discussion

The present study aimed to investigate the idea of task representativeness using computer tests of visual perception and cognition. That is, through using multiple adapted versions of the UFOV, MIDSD, and MIDDD tests, it was examined whether individuals showed greater processing speed, divided attention, selective attention, and thresholds for both velocity and direction of motion, in tests where the stimuli matched their particular sport, as opposed to ones where it did not.

For the UFOV test, a subtest x version interaction approached significance, with the paired samples t-test showing a significant difference in performance for the DTWD subtest (selective attention) between the associate and dissociate versions. In other words, when the UFOV stimuli matched the sport in which the participant was experienced, selective attention was greater than when the stimuli matched a sport in which the participant was a novice. As no significant differences in performance were found on the ST and DT subtests, hypothesis (i) was only partially supported.

With regards the MIDSD test, there were no significant differences between individuals from fast sports and those from slow sports in their threshold for determining differences in both fast motion and slow motion, for both the associate and dissociate versions of the test. The results for the MIDDD test also showed no significant differences between individuals from horizontal sports and those from vertical sports in their threshold for determining differences in both horizontal motion or vertical motion, for both the associate and dissociate versions of the test. Thus, participants' ability to discriminate differences in both speed and direction of motion in depth were equal regardless of whether the velocity and dimension (horizontal/vertical) was set to reflect the sport they were experienced in or reflect a sport in which they were a novice. In sum, results from the two motion perception tests did not support hypotheses (ii)-(v).

The findings for the UFOV test may be reasonably explained by the relative difficulty of the different subtests (Wood & Owsley, 2014). It has been suggested that our perceptual processing has a limited capacity, with any tasks in which there is surplus capacity used to attend to less relevant information (Lavie, 1995, Furley, Memmert, & Schmid, 2013). It is reasonable to assume that the central stimuli in the UFOV test acted as the primary task, after which participants moved their attention to the peripheral ("less relevant") stimuli. It is plausible then, that for the DTWD subtest, the dissociate version exhausted the perceptual processing capacity of individuals whereas the associate version (because of the increased experience) did not; resulting in the ability to attend to the peripheral stimuli for the former.

The justification for the classification of sports used in the MIDSD and MIDDD test was based on both subjective opinion and the size of the playing surface – the larger it is, the more horizontal perspective is required – a similar method to one used by Huttermann et al. (2014). Though this seemed reasonable initially, it may have contributed to the null finding. It is possible that experienced-novice differences do exist in the ability to discriminate differences in both speed and direction of motion, given a more accurate selection of sports.

Another possible explanation is in the participants recruited. All participants were deemed "experienced" in their sport, and the term "novice" was simply applied to them when they completed a dissociate test. It could be that the concept of transfer of skills was at work here, with the perceptual and cognitive skills assessed in the present study shared amongst the sports in which participants were recruited from. It is not unreasonable to suggest that high levels of horizontal motion detection acquired by football and rugby players could transfer to the vertical plane, and likewise for detecting differences in slow and fast motion. A study comparing athletes with non-athletes would be needed to investigate this. Additionally, our sample consisted of *experienced* athletes, not necessarily *expert* athletes. As Ericsson (2014) has pointed out; "in many domains of expertise longer experience does not by itself lead to higher levels of performance" (p. 509). Many studies which have found differences in visual, perceptual, and cognitive skills have done so with expert and novice populations (Huttermann et al., 2014), and it may be that this distinction is key in the contrasting findings. Indeed, it is possible that it is these superior perceptual and cognitive skills that take an athlete from being merely experienced, to being an expert.

Whilst it may seem contradictory to be examining the importance of replicating the natural environment in scientific research through the use of computer testing, it is of fundamental importance given the often logistical-based priorities under which studies are conducted. As a consequence, it is imperative that we formulate a method which allows potential significant effects to be found. How many studies may have produced significant findings had they adopted a more task representative design? Lee et al. (2013) state as much in their study comparing the use of 2D and 3D visual stimuli when they question whether an alternative choice of task may have produced different results. Countless decisions – from training methods to talent identification – are based upon scientific research that may be missing (or indeed, obtaining) crucial information simply because of the methodology employed (Kingstone, Smilek, Ristic, Friesen, & Eastwood, 2003). It may be that computer tests cannot and should not be used to assess certain perceptual and cognitive skills, particularly the discrimination of motion. Future research needs to investigate this, and other possible sources of task representativeness in experimental designs.

Such work could include an investigation into response specificity. This, in particular, is a topic that has been stressed in recent research, with numerous authors highlighting the need for studies to ensure that the perceptual-action coupling of a 'real-world' task is maintained in order to find the full extent of performance differences (Mann et al., 2010, Ryu et al., 2013). Recently, Reed-Jones, Reed-Jones, and Hollands (2014) found that differences in UFOV performance are dependent on the postural conditions under which the tests were taken. Not only may this account for the partial lack of effect found in this study, it further emphasises the need for methodologies to reflect the task at which they are attempting to predict. Future studies could, for example, employ a think aloud protocol indicating estimated speed and deviance after each cricket delivery to examine the cognitive and perceptual differences between experienced and novice cricket batsmen.

There is a myriad of other areas that could also be explored, from incorporating numerous decision making processes in each trial (akin to the numerous processes occurring at any one moment during sport) to the corroboration of work on 2D vs 3D stimuli, computer monitors vs life-size projector screens, and levels of image detail. Furthermore, comparisons with a non-athlete population could also be carried out to investigate any possible differences here. Studies should look to test participants under the conditions with which they participate their sport (where possible) as even the differences in fatigue not often matched in the laboratory have been shown to produce contrasting key findings with regards attention (Huttermann & Memmert, 2014).

A noteworthy point in relation to these findings is made by Thomas and Thomas (1994), who report that the ability to perceive stimuli may be related to the ability to act accordingly on this perception. Thus, whilst the novices in this study appear to have similar perceptual and cognitive skills as experienced athletes, it cannot be inferred (and is probably unlikely) that they can also produce the required motor actions in response. As previously mentioned, examining this particular point through different methods of response may be an interesting route for future studies.

Future studies may also seek to address some of the limitations of the present study. In particular, the participant sample used is relatively small and unevenly distributed amongst the sports. A stronger focus on recruiting athletes from vertical sports should be targeted. In addition, the classification of athletes to such sports may have contributed to some of the null findings. Whilst the method has been established in previous research (Huttermann et al., 2014), it is plausible that the level at which the athletes participate in their sport may have also influenced the results. That is, the majority of the athletes were not of a national or international standard, and therefore, whilst very experienced, may not be ‘expert’. Related to this, whilst it was ensured that the dissociate test used a sport in which the participant was not involved in, it is not inconceivable to suggest that many of the ‘vertical’ participants would have some experience playing other ‘horizontal’ sports, and vice versa. Such instances may have diffused any potential expert-novice differences in their perceptual and cognitive skills.

In conclusion, the present study found little support for the idea of computer tests of perception and cognition requiring increased task representativeness through sport-specific stimuli. Selective attention may be one area in which adopting a task representative approach can elicit differences between experienced and novice athletes, though there is no evidence that the same is true for processing speed, divided attention, and the ability to discriminate differences in motion speed or direction. These findings go against a number of studies which emphasise the need for scientific experiments to incorporate designs which replicate the natural environment as closely as possible in order to obtain performance differences (Mann et al., 2007). A number of potential explanations for this have been given. More studies are needed to examine this essential topic to ensure that future research in sports science does not deprive itself of producing important findings.

CHAPTER SIX

"There is much more to perfect vision than having normal eyesight. While the term 'sight' emphasizes the clarity of image on the retina, vision encompasses a broader meaning as the mental process of deriving meaning from what is seen and is the output of visual pathway integrity, visual efficiency and visual information processing."

- Safal Khanal (2015)

GENERAL DISCUSSION

This thesis has aimed to enhance our understanding of the visual testing and training procedures currently employed in sports research, whilst also exploring alternative methods that may provide a more valid and representative approach. The general introduction gave an overview of the existing literature and highlighted the critical gaps that were to be targeted. Specifically, the key issues of the lack of tests of motion in depth were addressed (study one), the potential benefits (study two) and mechanisms (study three) of stroboscopic visual training were investigated, and the concept of task representative designs in sports vision testing was examined (study four). These studies are not unrelated. The training element of study one motivated a more specific and in-depth analysis for study two, whilst the findings of study two directly warranted further exploration in study three, and stimulated the hypotheses behind study four.

Summary of Results

Chapter two consisted of two experiments; the first assessed the correlation between motion perception ability and driving performance of a young cohort of 60 drivers, whilst the second investigated the effect of training on these motion perception tests on an emergency braking task. The motion perception tests involved the judgement of dynamic stimuli (dynamic visual acuity (DVA) test) and 3-dimensional stimuli (motion-in-depth sensitivity (MID), and motion-defined-letter (MDL) tests). These tests share many common features inherent in driving performance, though have rarely been used in the existing literature. It was found that MID and MDL scores significantly correlated with emergency braking reaction time, whilst changes in DVA scores as a function of target speed (termed 'velocity susceptibility') significantly correlated with performance on a hazard perception task. Furthermore, six weeks of training on these tests produced a significant decrease in emergency braking reaction time that was not found for a control group. These results suggest that aspects of driving performance can be predicted from 3-dimensional and dynamic tests of motion perception, and may even be improved with further training on these tests. This has substantial implications for traditional stationary, 2-dimensional screening methods currently common in driving licensure.

Chapter three built on this training component through the use of a stroboscopic training protocol. Previous research on the topic has often failed to evaluate both perception and sporting performance, thus it is not clear how changes in the former may be related to improvements in the latter. As such, this study involved participants completing a one-handed ball-catching task and the useful-field-of-view (UFOV) and MIDS tests, before and after six weeks of stroboscopic training. Furthermore, many studies are limited by the lack of an adequate control group. Consequently, participants were assigned to either a variable stroboscopic training (VSR) group or a constant stroboscopic training (CSR) group; the latter chosen in an attempt to achieve similar levels of motivation. A significant, positive correlation between changes in catching performance and scores on both the processing speed element of the UFOV test and the MIDS test were observed. As this occurred across both groups, it suggests that sensitivity to the benefits of stroboscopic training may vary between individuals; even minimal levels of stroboscopic effect (CSR group) may provide some benefit.

Chapter four took a manual aiming task to explore the mechanisms behind any potential benefits of stroboscopic training. 32 participants were assigned to either an experimental group (EG), which underwent stroboscopic training, or a control group (CG), which did not, and performed a manual aiming task under both full-vision and no-vision conditions. Under full-vision conditions the EG showed a significant decrease in variability at the end of the movement, post-training. No significant changes were found for the CG. Furthermore, the lack of a decrease in variability at the start of the movement, post-training, for the EG suggests that stroboscopic training altered the online control component of the movement, rather than the planning component. Thus, tasks which require adjustments to be made during the movement (i.e. hitting a spinning ball) may profit from a period of stroboscopic training.

Finally, chapter five investigated the idea of task-representativeness with regards tests of visual attention and motion perception. Given the findings of study two (where changes in performance on tests of centrally presented stimuli correlated with changes in performance on a task involving the interception of a centrally located object), study four examined whether athletes performed better on attention and motion perception tests that reflected their specific sport. Participants performed versions of the UFOV, MIDSD, and MIDDD tests that were modified with stimuli representing either their sport (associate version), or an unfamiliar sport (dissociate version). Only one significant result was found: athletes performed significantly better on the selective attention element of the UFOV when completing the associate version compared to the dissociate version. In all other tests, athletes performed no better when the test reflected their sport than they did when the test reflected an unfamiliar sport. This finding provides limited support for the implementation of task-representative approaches, at least with regards to computer tests of visual and motion perception.

Theoretical Implications

A primary focus of this thesis was to provide evidence for the benefits of employing visual and motion perception tests that replicate the natural environment to a greater degree than the traditional methods currently employed in much of the research on driving, sport, and other areas. In particular, the use of static, 2-dimensional tests such as the Snellen Test and the UK's driver number plate test are likely to be unsuitable for tasks which require the judgement of objects moving in depth (i.e. driving and sport). Despite this, little research exists on alternative methods.

The idea of a task-representative approach has gained substantial support in recent years, despite being first proposed by Brunswik almost sixty years ago (Brunswik, 1955). Numerous studies have shown performance differences to be augmented with the use of protocols that follow this approach. However, study four of this thesis failed to provide substantial support for this. This may be linked to the categorisation of visual skills as either visual hardware or visual software. Though efforts were made to make each test more specific to the domain in question (a characteristic of visual software), most of the skills being measured in this study would still be classified as visual hardware. Given what the extensive review of visual hardware literature in Chapter One concluded, subsequent null findings in differentiating sporting experience may not be a surprise. Thus, it seems that tests of visual hardware may not be conducive to sport-specific stimuli, in terms of their predictive ability.

A key theme emphasised in this thesis has been the ambiguity in the existing literature. In particular, it is still unclear whether athletes and non-athletes differ in their visual hardware abilities, and whether visual training programmes are effective in enhancing both vision and sporting performance. Much of this ambiguity may be due to the lack of a universal approach in testing and training the visual and perceptual skills of athletes and individuals. The increased adoption of task-representative and expert-performance approaches in sports-science research over the past twenty years seems a cogent step in solving this issue. However, when related to computer-tests of vision and motion perception, logical inferences are not sufficient and empirical evidence must yet be obtained. Thus, the aims of this thesis are fitting, and therefore the findings of the studies serve to contribute to these topics. Specifically, the literature surrounding visual testing and training has been enhanced, with input into the concepts of visual hardware and visual software as well. The first steps into understanding the underlying mechanisms behind potential stroboscopic benefits was also established, whilst this thesis also has implications for the generality versus specificity of testing and training in visual and perceptual research.

Practical Implications

The findings from study one have clear practical implications with regards driving licensure and driver training, and these have been discussed in more detail in chapter two. To reiterate, however, the UK Driver and Vehicle Licensing Agency's (DVLA) current standards of vision for normal driving includes having "a visual acuity of at least decimal 0.5 (6/12) measured on the Snellen scale (with glasses or contact lenses, if necessary) using both eyes together or, if you have sight in one eye only, in that eye" and to "also have an adequate field of vision" (Driving eyesight rules, 2015). Given the criticisms directed towards static visual measures, and the results obtained in study one, the current standards used by the DVLA appear both outdated and unsuitable in determining whether an individual has the visual ability necessary to drive. As such, it is hoped that these findings may contribute towards a change in licensing and training procedures that better reflect the nature of driving.

It is possible that study one can also have implications in the field of sports. In particular, the findings from the second experiment demonstrate that a motion perception training regimen can lead to decreased thresholds, which can transfer to a related motor task. Similar findings in sport would open up countless opportunities for training interventions. For example, if repeated testing on the UFOV test were to improve attention ability, and therefore catching performance, the implications for athletes from sports such as cricket and baseball would be great. Moreover, training programmes such as these would be very simple and cost-effective, and would have the advantage of being able to be used indoors and by injured athletes.

The potential applied benefits of the findings from studies two and three with regards stroboscopic training have been mentioned in their respective chapters, though they warrant additional detail here. Many sports involve some form of catching, and whilst the benefits in performance achieved by stroboscopic training may have large individual differences, this may be sufficient to warrant a significant investment in stroboscopic training for some coaches and athletes. In a similar vein, athletes from the majority of sports would benefit from an improvement in online control of movements. For example, the slightest correctional changes in movement mid-swing for cricket batsmen and tennis players could be the difference between edging a delivery to the wicketkeeper and not edging it at all, or between a serve landing on the line or a serve landing out. At the highest levels of sport these minute differences could be the difference between winning and losing.

Finally, the fact that study four provided minimal evidence for a task representative approach with respect to motion perception, can be seen to add to the growing idea that tests of visual hardware (even when made more representative) may be insensitive to expertise differences.

Limitations

Limitations with regards the specifics of each study have been covered in their corresponding chapters, and as such, this section will focus more on any over-riding weaknesses that exist across the thesis as a whole.

First, one of the primary aims of this thesis was to examine the effects of using more task-representative measures of visual performance, be it the 3-dimensional, dynamic tests of study one, or the incorporation of sport-specific stimuli in study four. However, it could be argued that merely using computerised visual-perceptual tests themselves are far removed from the optimal (in-situ) methodologies encouraged to obtain the most reliable and accurate research data. Whilst there is a growing body of evidence that suggests this to be true (Mann, Williams, Ward, & Janelle, 2007; Travassos et al., 2013), it should not escape from the fact that research is more often than not conducted under logistical constraints. Finances and participant involvement are two key areas that need to be considered when designing a study, and particularly for visual research, in-situ methodologies can often be implausible logistically. The question then, should not be "is a more task-representative design better than a less task-representative design?", but rather, "to what extent can logistically viable study designs reflect the expert-novice differences found in the real world?"

Linked to this is another limitation of the thesis as a whole: that of participant recruitment. Given its ease and accessibility, all four studies recruited the majority of participants from subject pools in the Sport, Exercise and Rehabilitation Sciences department of the University of Birmingham, often in return for course credit. This raises the obvious issue of the generalisability of these results. Indeed, it has been noted before that the findings of psychology-based studies are often only representative of 'weird' (western, educated, industrialised, rich, and democratic) individuals, and may offer little information about the behaviour of the majority of the population (Heinrich, Heine, & Norenzayan, 2010). In response to this, emphasis needs to again be placed on the logistical priorities in carrying out such studies. Furthermore this method of recruitment is commonplace in much of the existing literature; for example, 67% of American participants from leading psychology journals are undergraduates studying psychology (Heinrich et al., 2010). In addition, the contribution of study one to the driving performance of this age group (~18-21) is an important one given that the existing literature stresses the distinctive skill-sets of this population (Olsen, Shults, & Eaton, 2013). Likewise, studies two and four were designed with potential implications for sporting performance, and therefore again, this age group could be seen as an appropriate one to use given that research has shown sporting participation to decline with age (Baker, Fraser-Thomas, Dionigi, & Horton, 2010).

If the results of studies two and four are to have implications on sporting performance, caution must be taken. In an International Society of Sport Psychology position stand, Lidor, Côté, and Hackfort (2009) highlighted the need for skills tests to be performed under fatigued conditions so as to replicate the conditions that athletes are under during most sports participation. Whilst this was in reference to physical skills, it would not be unreasonable to suggest the same should be true of visual, perceptual, and cognitive skills. Indeed, Williams, Davids, and Williams (1999) stated that aspects such as peripheral awareness are influenced by an individual's stress, fatigue, or arousal and this may have links with the attentional abilities measured by the UFOV test. Currently the majority of studies – including the ones in this thesis – involve participants performing tests under rested conditions. Again, this relates back to the idea of making study designs as representative of real-life scenarios as possible, and though this may be true of the driving task in study one, studies two and four could be seen to fail in this regard (study three is not applicable given it examines the underlying mechanics of a simple motor skill). This is an area in which it is felt future studies could, and should, investigate.

Finally, whilst a training intervention may produce significant changes in post-tests, it is not always the case that these changes persist in time; be it hours, days, months, or even years. This factor is important to consider, given that from a practical perspective, improvements (or mere differences) in performance need to be retained long-term in order for inferences to be made about an intervention's effectiveness, and therefore whether it is worthwhile implementing. As such, the lack of retention tests employed in the first three studies of this thesis acts as a limitation on their findings, or at least, their implications. In all three studies only immediate post-test measures were conducted (though in the first two this followed the last of multiple training sessions over a number of days or weeks), and consequently, the results may only reflect transient changes in performance. Once more, the justification for such a protocol lay partly with the logistics of maintaining participant adherence over the longer time-frame that would be needed with the addition of retention tests. Another reason, though, lay in the fact that each of these studies contains novel elements in their respective methodologies, and therefore an initial, almost exploratory, investigation of any effects was deemed sufficient. This particularly point is considered a strength of the thesis and will be discussed in detail next.

Strengths

The most important strength of this thesis is in the design of each study to add something novel to the existing literature. Specifically, study one tackles the essential need to extend the research on driving performance and training using tests which better simulate the characteristics of driving. That is, when trying to predict and improve ability in a dynamic and 3-dimensional environment, it is logical for the tests and training methods used to incorporate these features. However, there is limited existing evidence that does this. The findings from study one are some of the first to show that this is a viable and superior procedure to the currently more common 2-dimensional, static methods. This is best summed up by Pinder, Davids, Renshaw, and Araujo (2011), who state that “static tests lack functionality and do not successfully represent the constraints of performance environments” (p. 151).

One particularly novel idea actually resulted in being a potential weakness of study two: the use of a pseudo-control stroboscopic training group. This control group – one in which the level of stroboscopic effect used was kept at minimal levels previously shown to induce no changes in performance – allowed for the maintenance of motivation across the training intervention. Given the role that motivation and adherence play in training programmes, it is essential that the experimental group and their respective comparison groups are equal in this factor. This was identified as a major limitation of previous stroboscopic training studies, and further emphasised the need for a novel and innovative design that avoided this problem. Whilst there were limitations identified with the approach used in study (see the Discussion section in Chapter Three), the importance of such a procedure for the development of future study designs should far outweigh the lack of clarity afforded when attempting to compare this group with the experimental group.

In addition to this, study two added to the small body of literature that has measured the effects of stroboscopic training on both visual and perceptual skills, and motor skills. Much of the literature previously has focused on solely the former (Appelbaum, Schroeder, Cain, & Mitroff, 2011; Appelbaum, Cain, Schroeder, Darling, & Mitroff, 2012; Smith & Mitroff, 2012) or the latter (Bennett, Ashford, Rioja, & Elliott, 2004; Mitroff, Friesen, Bennett, Yoo, & Reichow, 2013). The lack of studies in which aspects of both are measured prevents any connections or inferences to be made between the two. From an applied perspective the lack of motor skill measures is of major concern; any improvements in visual or perceptual abilities may be deemed irrelevant if they do not transfer to enhanced sporting performance. The reverse is also problematic, as any improvements in motor performance may be due to the novelty effects of stroboscopic training (and thus, the issues regarding unequal motivation between study groups, previously mentioned).

Whilst research on intermittent vision has been conducted by Elliott and colleagues since the 1980s (Elliott, 1986; Elliott & Madalena, 1987), the idea of using it/stroboscopic effects as a training method has only been considered to a sizeable degree in recent years. Consequently, the potential mechanisms that underpin the adaptations identified in the latest research on the topic (such as enhanced anticipatory performance; Smith & Mitroff, 2012, or improved ice hockey performance; Mitroff et al., 2013) have not been explored. Thus, study three's aim to investigate whether changes in manual aiming performance are as a result of changes in motor planning or online control provides an original approach to a growing area of literature.

Finally, study four attempts to examine the extent to which a task representative approach can be applied to computer tests of attention and motion perception in order to identify differences in experience level between athletes. To do so, the UFOV and MIDSD tests were modified to incorporate sport-specific stimuli with the aim of eliciting greater skill differences than would occur for generic, non-specific stimuli. Both tests have previously been used to differentiate performance in domains similar to sport, such as driving (Clay et al., 2005) and aircraft flying (Kruk, Regan, Beverley, & Longridge, 1983), yet they have never, to the author's knowledge, been adapted to reflect a more task-representative design. Furthermore, both tests used photographic images as stimuli, rather than cartoon images (UFOV) or basic shapes (MIDSD); again, a novel approach that is in-line with recent recommendations regarding study designs (Roca, Williams, & Ford, 2014). The study also devised a completely novel test to measure threshold values for the detection of the direction of motion in depth (MIDDD test). This was done for both horizontal and vertical motion and again, used sport-specific, photographic stimuli.

Another strength of the thesis as a whole is the applied nature of much of the findings. This has been explained in more depth in the 'Practical Applications' section above, however, it should be noted that this is a notable asset of the work. Whilst theoretical implications are important, it has been suggested that too often in sports psychology research, the practical significance of results are either neglected, or at least not emphasised (Hagger & Chatzisarantis, 2009). Findings that have the clear potential to contribute to society, be it in driving licensure in the public domain or athletic performance in the sporting domain, are key aspects of research. Indeed, it has been argued that a greater relevance paid to the applied implications of sports science could increase athlete and coach acceptance of research studies, and may even influence funding opportunities (Bishop, Burnett, Farrow, Gabbett, & Newton, 2006).

A final strength of this thesis is the contemporaneity of the studies. In the UK in 2009, for those aged 15-19 years, 25% of all fatalities were attributable to driving accidents, whilst it was nearly 20% for those aged 20-24 years (Mortality Statistics, 2011). These numbers (chosen as these ages would have reflected the majority of participants represented in study one) demonstrate that driver safety is still a primary concern for society. Consequently, any measures – such as those identified in study one – which may be beneficial in tackling this issue would be of particular importance currently. Likewise, the resurgence of stroboscopic training in sports research has been frequently mentioned (the Nike Vapor Strobe eyewear of which much of the latest research is based was only released in 2011), and thus, studies two and three stand on the forefront of the current literature in this topic too. Finally, whilst the ideas of task representativeness date back to Brunswik in the 1950s (Brunswik, 1955), it wasn't until the 1990s that Ericsson and Smith devised the 'Expert Performance Approach' (1991). Even now the topic remains a cause for concern; "a principled theoretical analysis has yet to be articulated in detail to guide research and practice in sport psychology and sport science" (Pinder et al., 2011, p. 147).

Directions for Future Research

Of chief importance for future research investigating the effects of visual testing and training on sports performance is the adoption of study designs which represent the environment that the skill being measured is routinely performed in. Though this was one of the aims of the present thesis, much more work is needed in order to answer certain questions. Perhaps most important is an issue that was touched upon in the 'Limitations' section above: visual performance under fatigue. Too many studies are conducted testing athletes under rested conditions – situations that are not relevant given that the knowledge we wish to obtain often regards how they perform in a match or training (and thus, fatigued) situation. Whilst measuring the dynamic visual acuity, visual attention, or motion perception of a footballer as they sprint across the pitch may be all but an impossible task, other methods are possible. For example, it would be simple enough to induce fatigue using a laboratory-based cycle ergometer, or to test athletes immediately following a training session. Though there are limitations to this (not least, the task representativeness of the former and the quick recovery times of an athlete negating any fatigue in the latter), these exploratory studies would provide initial steps into an area that has received minimal attention.

Another topic of interest for future research was briefly mentioned in Chapter One of this thesis. A recent study by Lorains et al. (2013) has found that expert athletes perceive video clips that are played at 1.25 and 1.5 times normal speed to be more 'game-like' than real time. This finding brings with it an interesting question concerning the topic of task representativeness; is it better for tests (such as those used to assess an athlete's visual and perceptual skills) to be as close to real speed as possible, or as close to what is perceived to be real speed? This small distinction may not be an insignificant one, and should it be replicated (the author currently knows of no such study), it opens a whole new avenue for research on task representativeness within visual skills and sport. Given the close relationship between judgements of speed and the judgement of differences in both frontal and directional motion, an exploration of this area may help explain the (mostly) null findings of study four.

Conclusions

To conclude, this thesis has primarily investigated two concepts: i) whether tests of vision and perception can predict performance in driving, and differentiate between athletes of different skill levels, and ii) can performance in a range of tasks be improved, either through repeated training on computerized perception tests, or through the use of stroboscopic training. A key theme throughout the thesis has been the idea of task-representative designs and the importance of studies which encapsulate the key features of the environment in which they are attempting to predict performance. Each study was designed with a novel element, and it is hoped that the findings from these studies can contribute to important and contemporary topics; be it driver safety, stroboscopic training, or the concept of task representativeness. In particular, study one provides evidence that 3-dimensional tests of motion perception can predict driver performance, whilst repeated testing can also improve it. Study two suggests that stroboscopic training may be effective in improving visual perceptual performance, and that this may be linked to changes in catching ability. Study three identifies an improvement in online control as a potential underlying mechanism behind the changes in the precision of manual aiming following stroboscopic training. Finally, study four failed to elicit any expert-novice differences when adopting a task-representative approach to computer tests of vision and perception.

REFERENCES

1. Abernethy, B. (1990). Anticipation in squash: Differences in advance cue utilization between expert and novice players. *Journal of Sports Sciences, 8*(1), 17-34.

2. Abernethy, B., & Neal, R.J. (1999). Visual characteristics of clay target shooters. *Journal of Science and Medicine in Sport, 2*(1), 1-19.

3. Abernethy, B., Neal, R.J., & Koning, P. (1994). Visual-perceptual and cognitive differences between expert, intermediate, and novice snooker players. *Applied Cognitive Psychology, 8*(3), 185-211.

4. Abernethy, B., & Russell, D.G. (1987). The relationship between expertise and visual search strategy in a racquet sport. *Human Movement Science, 6,* 283-319.

5. Abernethy, B., Schorer, J., Jackson, R.C., & Hagemann, N. (2012). Perceptual training methods compared: The relative efficacy of different approaches to enhancing sport-specific anticipation. *Journal of Experimental Psychology: Applied, 18*(2), 143-153.

6. Abernethy, B., & Wood, J.M. (2001). Do generalized visual training programmes for sport really work? An experimental investigation. *Journal of Sports Sciences, 19*(3), 203-222.

7. Abernethy, B., Wood, J.M., & Parks, S. (1999). Can the anticipatory skills of experts be learned by novices? *Research Quarterly for Exercise and Sport, 70(3),* 313-318.

8. Allard, F., Graham, S., & Paarsalų, M.L. (1980). Perception in sport: basketball. *Journal of Sport Psychology, 2,* 14-21.

9. Allard, F., & Starkes, J.L. (1980). Perception in sport: volleyball. *Journal of Sport Psychology, 2,* 22-33.

10. Allsop, J. & Gray, R. (2014). Flying under pressure: Effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition, 3(2),* 63-71.

11. Alves, M., Spaniol, F., & Erichsen, O. (2014). Visual skills of elite Brazilian soccer players. *European Journal of Sports Science, 4,* 1-9.

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

13. 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, & Psychophysics, 74(8),* 1681-1691.

14. Applegate, R.A., & Applegate, R.A. (1992). Set shot shooting performance and visual acuity in basketball. *Optometry and Vision Science, 69,* 765-768.

15. Araujo, D., & Davids, K. (2009). Ecological approaches to cognition and action in sport and exercise: Ask not only what you do, but where you do it. *International Journal of Sport Psychology, 40*, 5-37.

16. Araujo, D., Davids, K.W., & Passos, P. (2007). Ecological validity, representative design, and correspondence between experimental task constraints and behavioural setting: Comment on Rogers, Kadar, and Costall (2005). *Ecological Psychology, 19*(1), 69-78.

17. Araujo, D., & Kirlik, A. (2008). Towards an ecological approach to visual anticipation for expert performance in sport. *International Journal of Sport Psychology, 39,* 157-165.

18. Atchison, D., Mon-Williams, M., Tresilian, J., Stark, L.R., & Strang, N.C. (1997). The value of training accommodative facility for ball sports. *Clinical and Experimental Optometry, 80*(4), 127-132.

19. Athletic Republic (2011a, April 7). Nike SPARQ Vapor Strobe Sample Drills [video file]. Retrieved May 23rd, 2014, from https://www.youtube.com/watch?v=JZEffQ4mN4Q&list=PL0C45E4A1D637DD55.

20. Athletic Republic (2011b, December 1). NFL Players SEE SPORT BETTER with the Nike SPARQ Vapor Strobe [video file]. Retrieved May 23rd, 2014, from https://www.youtube.com/watch?v=A3Wir88Zvh8.

21. Bach, M. (1996) The "Freiburg Visual Acuity Test" – Automatic measurement of visual acuity. Optometry and Vision Science 73:49–53.

22. Baker, J., Fraser-Thomas, J., Dionigi, R.A., & Horton, S. (2010). Sport participation and positive development in older persons. *European Review of Aging and Physical Activity, 7*(1), 3-12.

23. Ball, K., Edwards, J.D., Ross, L.A., & McGwin, G. (2010). Cognitive training decreases motor vehicle collision involvement in older drivers. *Journal of the American Geriatrics Society, 58*, 2107-2113.

24. Ball, K., & Owsley, C. (1992). The useful field of view test: A new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association, 63*, 71–79.

25. Banister, H., & Blackburn, J.M. (1931). An eye factor affecting proficiency at ball games. *British Journal of Psychology. General Section, 21*(4), 382-384.

26. Barlow, H.B., & Mollon, J.D. (1985). *The Senses.* Cambridge, Eng. Cambridge University Press.

27. Bartlett, Sir. F. (1951). The bearing of experimental psychology upon human skilled performance. *British Journal of Industrial Medicine, 8,* 209-217.

28. Bass, R. (1939). An analysis of the components of tests of semi-circular canal function, and of static and dynamic balance. *Research Quarterly, 10*(2), 33-52.

29. 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(4),* 442-449.

30. Berry, B.A. (1995). *The effects of crossed-dominant vision, reaction time and response time on hitting performance in baseball.* Unpublished master's thesis, Emporia State University.

31. Bialystok, E. (2006). Effect of bilingualism and computer video game experience on the Simon task. *Canadian Journal of Experimental Psychology, 60*(1), 68-79.

32. Bishop, D., Burnett, A.F., Farrow, D., Gabbett, T., & Newton, R. (2006). Sports science roundtable: Does sports science research influence practice? *International Journal of Sports Physiology and Performance, 1*(2), 161-168.

33. Blundell, N.L. (1984). Critical visual-perceptual attributes of championship level tennis players. In A.M. Williams, K. Davids, & J.G. Williams (Eds.), *Visual Perception & Action in Sport,* (p. 89). London: Routledge.

34. Boot, W.R., Kramer, A.F., Simons, D.J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychologica, 129*(3), 387-398.

35. Boyd deal a sight for sore eyes. (2013, February 1). Retrieved from http://www1.skysports.com/watch/video/8459887/boyd-deal-a-sight-for-sore-eyes.

36. Breslin, G., Schmidt, R.A., & Lee, T.D. (2012). Especial skills: Generality and specificity in motor learning. In N.J. Hodges, & A.M. Williams (Eds.), *Skill Acquisition in Sport: Research, Theory and Practice* (chapter 19). New York, NY: Routledge.

37. Bruce, L., Farrow, D., & Raynor, A. (2012). How specific is domain specificity: Does it extend across playing position? *Journal of Science and Medicine in Sport, 15*, 361-367.

38. Bruce, V., Green, P.R., & Georgeson, M.A. (1996). *Visual Perception: Physiology, Psychology, and Ecology: 3rd Edition.* Erlbaum (UK): Psychology Press.

39. Brunswik, E. (1955). Representative design and probabilistic theory in a functional psychology. *Psychological Review, 62*(3), 193-217.

40. Brunswik, E. (1956). *Perception and the representative design of psychological experiments* (2nd ed.). Berkeley: University of California Press.

41. Buckolz, E., Prapavesis, H., & Fairs, J. (1988). Advance cues and their use in predicting tennis passing shots. *Canadian Journal of Sport Sciences, 13*(1), 20-30.

42. Bulson, R.C., Ciuffreda, K.J., & Hung, G.K. (2008). The effect of retinal defocus on golf putting. *Ophthalmic & Physiological Optics, 28*(4), 334-344.

43. Burg, A. (1966). Visual acuity as measured by dynamic and static tests: A comparative evaluation. *Journal of Applied Psychology, 50*(6), 460-466.

44. Burke, E.R. (1992). *Cycling health and physiology: Using sports science to improve your riding and racing.* Brattleboro, VT. Vitesse Press.

45. Calder, S.L., & Kluka, D.A. (2009). The efficacy of the EyeThinkSport training programme on South African high school cricketers. *African Journal for Physical, Health Education, Recreation and Dance, 15*(1), 44-61.

46. Carlton, L.G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7(5),* 1019-1030.

47. Castel, A.D., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica, 119*(2), 217-230.

48. Causer, J., Holmes, P.S., & Williams, A.M. (2011). Quiet eye training in a visuomotor control task. *Medicine and Science in Sports and Exercise, 43,* 1042-1049.

49. Chase, W.G., & Simon, H.A. (1973). Perception in chess. *Cognitive Psychology, 4*(1), 55-81.

50. Cincinnati Season Statistics 2011-12. In *Cincinnati Bearcats*. Retrieved June 18th, 2014, from http://www.gobearcats.com/sports/m-basebl/stats/2011-2012/teamcume.html

51. Clark, J.F., Ellis, J.K., Bench, J., Khoury, J., & Graman, P. (2012). High-performance vision training improves batting statistics for university of Cincinnati baseball players. *PLoS ONE, 7(1),* e29109. Doi:10.1371/journal.pone.0029109.

52. Clay, O.J., Wadley, V.G., Edwards, J.D., Roth, D.L., Roenker, D.L., & Ball, K.K. (2005). Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: Current and future implications. *Optometry and Vision Science, 82,* 724-731.

53. Cockerill, I.M., & MacGillivary, W.W. (1981). *Vision and Sport,* England: Stanley Thorne Ltd.

54. Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, N.J.: Erlbaum

55. Connor, S. (2012, December 21). *IQ tests are fundamentally flawed.* Retrieved from http://www.independent.co.uk/news/science/iq-tests-are-fundamentally-flawed-and-using-them-alone-to-measure-intelligence-is-a-fallacy-study-finds-8425911.html.

56. Council, F., & Allen, J. (1974). *A study of visual fields of North Carolina drivers and their relationships to accidents.* Chapel Hill, University of North Carolina Highway Safety Research Centre, 1974.

57. Craig Kieswetter: Injury could end Somerset batsman's career. (2015, January 19). Retrieved from http://www.bbc.co.uk/sport/0/cricket/30883034.

58. Cynader, M., & Regan, D. (1982). Neurons in the cat visual cortex tuned to the direction of motion in depth: effect of positional disparity. *Vision Research, 22*, 967-982.

59. Davids, K. (2008). Designing representative task constraints for studying visual anticipation in fast ball sports: What we can learn from past and contemporary insights in neurobiology and psychology. *International Journal of Sport Psychology, 39*, 166-177.

60. DeLucia, P.R., Bleckley, M.K., Meyer, L.E., & Bush, J.M. (2003). Judgements about collision in younger and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 6,* 63-80.

61. DeLucia, P.R., & Mather, R.D. (2006). Motion extrapolation of car-following scenes in younger and older drivers. *Human Factors, 48 (4),* 666-674.

62. Deveau, J., Ozer, D.J., & Seitz, A.R. (2014). Improved vision and on-field performance in baseball through perceptual learning. *Current Biology, 24*(4), 146-147.

63. Dicks, M., Button, C., & Davids, K. (2010). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Attention, Perception, & Psychophysics, 72*(3), 706-720.

64. Digges, K., Nicholson, R.M., & Rouse, E.J. (1985). The technical basis for the center high mounted stop lamps. *SAE Technical Paper Series*. May 1985. Report number: 851240.

65. Doyne, R.W. (1910). A lecture on "eye" in sport. *The British Medical Journal, 2,* 1960-1963.

66. Driving eyesight rules. (2013, January 16). Retrieved from https://www.gov.uk/driving-eyesight-rules.

67. Dunwoody, P.T. (2006). The neglect of the environment by cognitive psychology. *Journal of Theoreticaal and Philosophical Psychology, 26*(1-2), 139-153.

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

69. Elliott, D. (1988). The influence of visual target and limb information on manual aiming. *Canadian Journal of Psychology, 42(1),* 57-68.

70. Elliott, D. (1990). Intermittent visual pickup and goal directed movement: a review. *Human Movement Science, 9(3-5),* 531-548.

71. Elliott, D., Carson, R.G., Goodman, D., & Chua, R. (1991). Discrete vs. continuous visual control of manual aiming. *Human Movement Science, 10(4),* 393-418.

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

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

74. Elliott, D., & Madalena, J. (1987). The influence of premovement visual information on manual aiming. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 39*(3), 541-559.

75. Elliott, D., Helsen, W.F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin, 127(3),* 342-357.

76. Elliott, D.B., Yang, K.C.H., & Whitaker, D. (1995). Visual acuity changes throughout adulthood in normal, healthy eyes: Seeing beyond 6/6. *Optometry and Vision Science, 72*(3), 186-191.

77. Epstein, D. (2013). *The sports gene: What makes the perfect athlete.* London: Yellow Jersey Press.

78. Erickson, G. (2007). *Sports vision: Visual care for the enhancement of sports performance.* Missouri, USA: Butterworth Heinemann, Elsevier.

79. Ericsson, K.A. (2014). Expertise. *Current Biology, 24*(11), 508-510.

80. Ericsson, K.A., & Lehmann, A.C. (1996). Expert and exceptional performance: Evidence of maximal adaptation to task constraints. *Annual Review of Psychology, 47*, 273-305.

81. Ericsson, K.A., & Smith, J. (1991). *Toward a general theory of expertise: Prospects and limits.* New York. Cambridge University Press.

82. Ericsson, K.A., & Williams, A.M. (2007). Capturing naturally occurring superior performance in the laboratory: Translational research on expert performance. *Journal of Experimental Psychology: Applied, 13*(3), 115-123.

83. Farrow, D., & Abernethy, B. (2002). Can anticipatory skills be learned through implicit video-based perceptual training? *Journal of Sports Sciences, 20,* 471-485.

84. Farrow, D., & Abernethy, B. (2003). Do expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception, 32*, 1127-1139.

85. Farrow, D., Abernethy, B., & Jackson, R.C. (2005). Probing expert anticipation with the temporal occlusion paradigm: Experimental investigations of some methodological issues. *Motor Control, 9*, 330-349.

86. Fitts, P.M., & Deininger, R.L. (1954). S-R compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology, 48*(6), 483-492.

87. Franke, R.H., & Kaul, J.D. (1978). The Hawthorne experiments: First statistical interpretation. *American Sociological Review, 43(5),* 623-643.

88. Fullerton, H.S. (1921). Why Babe Ruth is greatest home-run hitter. *Popular Science Monthly, 99*(4), 19-21.

89. Furley, P., Memmert, D., & Schmid, S. (2013). Perceptual load in sport and the heuristic value of the perceptual load paradigm in examining expertise-related perceptual-cognitive adaptations. *Cognitive Processing, 14,* 31-42.

90. Gabbett, T.J., & Abernethy, B. (2013). Expert-novice differences in the anticipatory skill of rugby league players. *Sport, Exercise, and Performance Psychology, 2*(2), 138-155.

91. Gallagher, S., Smith, S.R., & Merrotsy, P. (2011). Teachers' perceptions of the socioemotional development of intellectually gifted primary aged students and their attitudes towards ability grouping and acceleration. *Gifted and Talented International, 26*(1), 11-24.

92. Gibson, J.J. (1979). *The Ecological Approach to Visual Perception.* Boston, MA: Houghton Mifflin.

93. Ghuntla, T.P., Mehta, H.B., Gokhale, P.A., & Shah, C.J. (2012). A comparative study of visual reaction time in basketball players and healthy controls. *National Journal of Integrated Research in Medicine, 3*(1), 49-51.

94. Giaschi, D.E., Regan, D., Kothe, A., Hong, X.H., & Sharpe J.A. (1992). Motion-defined letter recognition in patients with multiple sclerosis. *Annals of Neurology, 31*, 621-628.

95. Giaschi, D.E., Regan, D., Kraft, S.P., & Hong, X.H. (1992). Defective processing of motion-defined form in the fellow eye of patients with unilateral amblyopia. *Investigative Ophthalmology & Visual Science. 33*, 2483-2489.

96. Giaschi, D.E., Trope, G.E., Kothe, A.C., & Hong, X.H. (1996). Loss of sensitivity to motion-defined form in patients with primary open-angle glaucoma and ocular hypertension. *Journal of the Optical Society of America A-Optics Image Science and Vision 13*(4): 707-716.

97. Gray, R., Allsop, J., & Williams, S. (2013). Changes in putting kinematics associated with choking and excelling under pressure. *International Journal of Sport Psychology (Performance under Pressure Special Issue), 44(4),* 387-407.

98. Gray, R., & Regan, D. (2005). Perceptual processes used by drivers during overtaking in a driving simulator. *Human Factors, 47*, 394-417.

99. Gray, R., & Regan, D. (2007). Glare susceptibility test results correlate with temporal safety margin when executing turns across approaching vehicles in simulated low–sun conditions. *Ophthalmic and Physiological Optics*, *27*, 440-450.

100. Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*, 534-537.

101. Green, C.S., & Bavelier, D. (2006). Enumeration versus multiple object tracking: The case of action video game players. *Cognition, 101,* 217-245.

102. Griffith, C.R. (1928). *Psychology and Athletics.* New York: Charles Scribner's Sons. Chapts. I, II, III, and IV.

103. Griffith, C.R. (1931). An experiment in learning to drive a golf ball. *Athletic Journal*, *11*, 10.

104. Guy's and St Thomas' NHS Foundation Trust. (2013). *Occupational therapy school-age resource pack.* Retrieved from https://www.guysandstthomas.nhs.uk/resources/patient-information/therapies/occupational-therapy-school-age-resource-pack.pdf.

105. Hagemann, N., Strauss, B., & Canal-Bruland, R. (2006). Training perceptual skill by orienting visual attention. *Journal of Sport & Exercise Psychology, 28*, 143-158.

106. Hagger, M.S., & Chatzisarantis, N.L.D. (2009). Assumptions in research in sport and exercise psychology. *Psychology of Sport and Exercise, 10,* 511-519.

107. Harle, S., & Vickers, J.N. (2001). Training quiet eye improves accuracy in the basketball free throw. *The Sport Psychologist, 15,* 289-305.

108. Harvey, M. (2013, August 5). 395 milliseconds to contact. Retrieved from http://espn.go.com/mlb/story/_/page/bodyissue2013data/hitters-use-new-vision-techniques-improve-batting-average-espn-magazine.

109. Heinrich, J., Heine, S.J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Scciences, 33*(2-3), 61-83.

110. Helsen, W.F., & Starkes, J.L. (1999). A multidimensional approach to skilled perception and performance in sport. *Applied Cognitive Psychology, 13,* 1-27.

111. Henderson, S., Gagnon, S., Belanger, A., Tabone, R., & Collin, C. (2010). Near peripheral motion detection threshold correlates with self-reported failures of attention in younger and older drivers. *Accident Analysis & Prevention, 42,* 1189-1194.

112. Henry, F.M. (1968). Specificity vs generality in learning motor skill. In R.C. Brown & G.S. Kenyon (Eds.), *Classical studies on physical activity* (p. 331-340). Englewood Cliffs, NJ: Prentice-Hall.

113. Hills, B.L., & Burg, A. (1978). A reanalysis of California driver vision data: general findings. Crowthorne, England: Transport and Road Research Laboratory; 1977: Report no LR768.

114. Holliday, J. (2013). Effect of stroboscopic vision training on dynamic visual acuity scores: Nike Vapor Strobe eyewear. *All Graduate Plan B and other Reports,* paper 262.

115. Hong, X., & Regan, D.M. (1989). Visual field defects for unidirectional and oscillatory motion in depth. *Vision Research, 29,* 809-819.

116. Hoshina, K., Tagami, Y., Mimura, O., Edagawa, H., Matsubara, M., & Nakayama, T. (2013). A study of static, kinetic, and dynamic visual acuity in 102 Japanese professional baseball players. *Clinical Ophthalmology, 7,* 627-632.

117. Hubert-Wallander, B., Green, C.S., & Bavelier, D. (2011). Stretching the limits of visual attention: the case of action video games. *Wiley Interdisciplinary Reviews: Cognitive Science, 2*(2), 222-230.

118. Hughes, P.K., Bhundell, N.L., & Waken, J.M. (1993). Visual and psychomotor performance of elite, intermediate and novice table tennis competitors. *Clinical and Experimental Optometry, 76*(2), 51-60.

119. Hull KR centre Sean Gleeson retires with eye injury. (2014, June 2). Retrieved from http://www.bbc.co.uk/sport/0/rugby-league/27665020.

120. Huttermann, S., & Memmert, D. (2014). Does the inverted-U function disappear in expert athletes? An analysis of the attentional behaviour under physical exercise of athletes and non-athletes. *Physiology & Behavior, 131,* 87-92.

121. Huttermann, S., Memmert, D., & Simons, D.J. (2014). The size and shape of the attentional "spotlight" varies with differences in sports expertise. *Journal of Experimental Psychology: Applied, 20*(2), 147-157.

122. Ikarugi, C., Hattori, Y., Awata, T., Tanifuji, C., & Ikarugi, H. (2005). The relationship between visual function and performance of the girl's junior badminton athletes. *Human Performance Measurement, 2,* 22-27.

123. Isaacs, L.D. (1981). Relationship between depth perception and basketball-shooting performance over a competitive season. *Perceptual and Motor Skills, 53,* 554.

124. Ishigaki, H., & Miyao, M. (1993). Differences in dynamic visual-acuity between athletes and nonathletes. *Perceptual and Motor Skills, 77,* 835-839.

125. Ishigaki, H., & Miyao, M. (1994). Implications for dynamic visual acuity with changes in age and sex. *Perceptual and Motor Skills, 78,* 363-369.

126. Janelle, C.M., Hillman, C.H., Apparies, R.J., Murray, N.P., Meili, L., Fallon, E.A., & Hatfield, B.D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport & Exercise Psychology, 22,* 167-182.

127. Johnson, H.M. (1946). The detection and treatment of accident-prone drivers. *Psychological Bulletin, 43*(6), 489-532.

128. Jones, C.M., & Miles, T.R. (1978). Use of advance cues in predicting the flight of a lawn tennis ball. *Journal of Human Movement Studies, 4,* 231-235.

129. Kamin, L.J., & Grant-Henry, S. (1987). Reaction time, race, and racism. *Intelligence, 11,* 299-304.

130. Kanal, S. (2015). Impact of visual skills training on sports performance: Current and future perspectives. *Advances in Ophthalmology & Visual System, 2*(1), 1-3.

131. Kato, Y., & Asami, T. (1998). Difference in stimulus-response compatibility effect in premotor and motor time between upper and lower limbs. *Perceptual and Motor Skills, 87*, 939-946.

132. Keele, S.W. (1973). *Attention and Human Performance.* Pacific Palisades, CA: Goodyear.

133. Keetch, K.M., Lee, T.D., & Schmidt, R.A. (2008). Especial skills: Specificity embedded within generality. *Journal of Sport and Exercise Psychology, 30,* 723-736.

134. Khan, M.A., & Franks, I.M. (2000). The effect of practice on component submovements is dependent on the availability of visual feedback. *Journal of Motor Behavior, 32*(3), 227–240.

135. Khan, M.A., Franks, I.M., Elliott, D., Lawrence, G.P., Chua, R., Bernier, P-M., Hansen, S., & Weeks, D.J. (2006). Inferring online and offline processing of visual feedback in target-directed movements from kinematic data. *Neuroscience and Behavioral Reviews, 30,* 1106-1121.

136. Khan, M.A., Franks, I.M., & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *Quarterly Journal of Experimental Psychology Section a – Human. Experimental Psychology, 51*(2), 425–444.

137. Khan, M.A., Sarteep, S., Mottram, T.M., Lawrence, G.P., & Adam, J.J. (2011). The dual role of vision in sequential aiming movements. *Acta Psychologica, 136,* 425-431.

138. Kingstone, A., Smilek, D., Ristic, J., Friesen, C.K., & Eastwood, J.D. (2003). Attention, researchers! It is time to take a look at the real world. *Current Directions in Psychological Science, 12*(5), 176-180.

139. Kioumourtzoglou, E., Kourtessis, T., Michalopoulou, M., & Derri, V. (1998). Differences in several perceptual abilities between experts and novices in basketball, volleyball and water-polo. *Perceptual and Motor Skills*, *86*, 899-912.

140. Klapp, S.T. (2010). Comments on the classic Henry and Rogers (1960) paper on its 50th anniversary. *Research Quarterly for Exercise and Sport, 81*(1), 108-112.

141. Knudson, D., & Kluka, D.A. (1997). The impact of vision and vision training on sport performance. *Journal of Physical Education, Recreation and Dance, 68*, 17-24.

142. Kosnik, W., Winslow, L., Kline, D., Rasinski, K., & Sekuler, R. (1988). Visual changes in daily life throughout adulthood. *The Journal of Gerontology, 43*(3), 63-70.

143. Kretchmar, R.T., Sherman, H., & Mooney, R. (1949). A survey of research in the teaching of sports. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *20*(3), 238-249.

144. Kruk, R., & Regan, D. (1983). Visual test results compared with flying performance in Telemetry tracked aircraft. *Aviation, Space and Environmental Medicine 54*, 906–911.

145. Kruk, R., Regan, D., Beverley, K.I., & Longridge, T. (1983). Flying performance on the Advanced Simulator for Pilot Training and laboratory tests of vision. *Human Factors, 25*, 457–66.

146. Kumar, M.S. (2011). Impact of sport vision training for enhancing selected visual skills and performance factors of novice hockey players. *Indian Journal of Movement Education and Exercises Sciences, 1*(1), 1-5.

147. Kuzmits, F.E., & Adams, A.J. (2008). The NFL combine: Does it predict performance in the national football league? *Journal of Strength & Conditioning Research, 22*(6), 1721-1727.

148. Laby, D.M., Rosenbaum, A.L., Kirschen, D.G., Davidson, J.L., Rosenbaum, L.J., Strasser, C., & Mellman, M.F. (1996). The visual function of professional baseball players. *American Journal of Ophthalmology, 122*(4), 476-485.

149. Lacherez, P., Au, S., & Wood, J.M. (2012). Visual motion perception predicts driving ability. *Acta Ophthalmologica.* doi: 10.1111/j.1755-3768.2012.02575.x. [Epub ahead of print]

150. Larsen, P.O., & von Ins, M. (2012). The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index, *Scientometrics, 84*(3), 575-603.

151. Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21*(3), 451-468.

152. Lawrence, G.P., Khan, M.A., Buckolz, E., & Oldham, A.R.H. (2006). The contribution of peripheral and central vision in the control of movement amplitude. *Human Movement Science, 25,* 326-338.

153. Lawrence, G.P., & Khan, M.A., & Hardy, L. (2012). The effects of anxiety on the online and offline control of fast target directed movement. *Psychological Research, 77(4), 42*2-433.

154. Lee, D.N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*, 437-59.

155. Lee, M.J.C., Tidman, S.J., Lay, B.S., Bourke, P.D., Lloyd, D.G., & Alderson, J.A. (2013). Visual search differs but not reaction time when intercepting a 3D versus 2D videoed opponent. *Journal of Motor Behavior, 45*(2), 107-115.

156. Lewis, R. (2013, December 27). Darts: Gary Anderson set on world championship title despite failing eye sight. Retrieved from http://www.dailystar.co.uk/sport/other-sports/357571/Darts-Gary-Anderson-set-on-world-championship-title-despite-failing-eye-sight.

157. Lidor, R., Côté, J., & Hackfort, D. (2009). ISSP position stand: To test or not to test? The use of physical skill tests in talent detection and in early phases of sport development. *International Journal of Sport and Exercise Psychology, 7*(2), 131-146.

158. Lorains, M., Ball, K., & MacMahon, C. (2013). Expertise differences in a video decision-making task: Speed influences on performance. *Psychology of Sport and Exercise, 14*, 293-297.

159. Ludvigh, E., & Miller, J.W. (1958). Study of visual acuity during the ocular pursuit of moving test objects. *Journal of the Optical Society of America, 48*(11), 799-802.

160. Lunsman, M., Edwards, J.D., Andel, R., Small, B.J., Ball, K.K., & Roenker, D.L. (2008). What predicts changes in useful field of view test performance? *Psychology and Ageing, 23*(4), 917-927.

161. Mack, A., & Rock, I. (1998). *Inattentional blindness.* Cambridge, MA: MIT Press.

162. Mackrous, I., & Proteau, L. (2007). Specificity of practice results from differences in movement planning strategies. *Experimental Brain Research, 183*(2), 181–193.

163. Mann, D.L., Abernethy, B., & Farrow, D. (2010). Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks. *Acta Psychologica, 135,* 17-23.

164. Mann, D.L., Abernethy, B., & Farrow, D. (2010). The resilience of natural interceptive actions to refractive blur. *Human Movement Science, 29,* 386-400.

165. Mann, D.L., Ho, N.Y., De Souza, N.J., Watson, D.R., & Taylor, S.J. (2007). Is optimal vision required for the successful execution of an interceptive task? *Human Movement Science, 26*(3), 343-356.

166. Mann, D.L., Spratford, W., & Abernethy, B. (2013). The head tracks and gaze predicts: How the world's best batters hit a ball. *PLoS ONE, 8*(3): E58289. Doi: 10.1271/journal.pone.0058289.

167. Mann, D.T., Williams, A.M., Ward, P., & Janelle, C.M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport & Exercise Psychology, 29,* 457-478.

168. Martell, S.G., & Vickers, J.N. (2004). Gaze characteristics of elite and near-elite athletes in ice hockey defensive tactics. *Human Movement Science, 22,* 689-712.

169. Masters, R.S.W. (1992). Knowledge, (k)nerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *The British Journal of Psychology, 31,* 530-541.

170. Mathias, J.L., & Lucas, L.K. (2009). Cognitive predictors of unsafe driving in older drivers: a meta-analysis. *International Psychogeriatrics, 21*(4), 637-653.

171. Mazyn, L.I.N, Lenoir, M., Montagne, G., & Savelsbergh, G.J.P. (2004). The contribution of stereo vision to one-handed catching. *Experimental Brain Research, 157(3),* 383-190.

172. McKnight, A.J., Shinar, D., & Hilburn, B. (1991). The visual and driving performance of monocular and binocular heavy-duty truck drivers. *Accident Analysis & Prevention, 23*(4), 225-237.

173. McLeod, B. (1991). Effects of eyerobics visual skills training on selected performance measures of female varsity soccer players. *Perceptual and Motor Skills, 72,* 863-866.

174. Meir, R.A., Holding, R., Hetherington, J., & Rolfe, M.I. (2013). Impact of sport specific and generic visual stimulus on a reactive agility test while carrying a rugby ball. *Journal of Australian Strength and Conditioning, 21*(1), 45-49.

175. Melvill-Jones, G., & Mandl, G. (1981). Motion sickness due to vision reversal: its absence in stroboscopic light. *Annals of the New York Academy of Sciences, 374,* 303-311.

176. Memmert, D. (2006). The effects of eye movements, age, and expertise on inattentional blindness. *Consciousness and Cognition, 15,* 620-627.

177. Memmert, D., Simons, D.J., & Grimme, T. (2009). The relationship between visual attention and expertise in sports. *Psychology of Sport & Exercise, 10,* 146-151.

178. Meser, J.H. (1938). *An Attempt to Devise a Simple Method of Measuring Potential Football Intelligence.* Unpublished master's thesis, State University of Iowa.

179. Milgram, P. (1987). A spectacle-mounted liquid-crystal tachistoscope. *Behavior Research Methods, Instruments, & Computers, 19(5),* 449-456.

180. Mills, L. (1928). Unilateral sighting. *California and Western Journal of Medicine, 28*(2), 189-195.

181. Millslagle, D.G. (2000). Dynamic visual acuity and coincidence-anticipation timing by experienced and inexperienced women players of fast pitch softball. *Perceptual and Motor Skills, 90,* 498-504.

182. Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence threshold in children with autism. *Journal of Child Psychology and Psychiatry, 43*(2), 255-263.

183. Mitroff, S.R. “Marrying theoretical and practical goals to inform psychological science and society.” 21st Annual Workshop on Object Perception, Attention, and Memory. Toronto, Ontario. 14 Nov, 2013.

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

185. Mori, S., Ohtani, Y., & Imanaka, K. (2002). Reaction times and anticipatory skills of karate athletes. *Human Movement Science, 21,* 213-230.

186. Mortality statistics and road traffic accidents in the UK: An RAC foundation briefing note for the UN decade of action for road safety. (2011, May). Retrieved from http://www.racfoundation.org/assets/rac_foundation/content/downloadables/road%20accident%20casualty%20comparisons%20-%20box%20-%20110511.pdf.

187. Mullen, R., & Hardy, L. (2000). State anxiety and motor performance: Testing the conscious processing hypothesis. *Journal of Sports Sciences*, *18(10)*, 785-799.

188. Muller, S., & Abernethy, B. (2006). Batting with occluded vision: An in situ examination of the information pick-up and interceptive skills of high- and low-skilled cricket batsmen. *Journal of Science and Medicine in Sport, 9*(6), 446-458.

189. Murgia, M., Sors, F., Muroni, A.F., Santoro, I., Prpic, V., Galmonte, A., & Agostini, T. (2014). Using perceptual home-training to improve anticipation skills of soccer goalkeepers. *Psychology of Sport and Exercise, 15*(6), 642-648.

190. Nakamoto, H., & Mori, S. (2008). Effects of stimulus-response compatibility in mediating expert performance in baseball players. *Brain Research, 1189*, 179-188.

191. NHTSA. (1998). The Long Term Effectiveness of Center High Mounted Stop Lamps in Passenger Cars and Light Trucks. *National Highway Traffic Safety Administration*. Mar 1998 Technical Report. DOT HS 808696.

192. NHTSA. (2004). Lives saved by the Federal Motor Vehicle Safety Standards and Other Vehicle Safety Technologies. 1960-2002. *National Highway Traffic Safety Administration*. Oct 2004 Technical Report. DOT HS 809833.

193. Nuri, L., Shadmehr, A., Ghotbi, N., & Moghadam, A. (2013). Reaction time and anticipatory skill of athletes in open and closed skill-dominated sport. *European Journal of Sport Science, 13*(5), 431-436.

194. Olsen, E.M., Shults, R.A., & Eaton, D.K. (2013). Texting while driving and other risky motor vehicle behaviours among US high school students. *Pediatrics, 131*(6), e1708-e1715.

195. Otto, J., & Michelson, G. (2014). Repetitive tests of visual function improved visual acuity in young subjects. *British Journal of Ophthalmology, 98*, 383-386.

196. Oudejans, R.R.D., Koedijker, J.M., Bleijendaal, I., & Bakker, F.C. (2005). The education of attention in aiming at a far target: Training visual control in basketball jump shooting. *International Journal of Sport and Exercise Psychology, 3(2),* 197-221.

197. Owsley, C., Ball, K., McGwin Jr, G., Sloane, M.E., Roenker, D.L., White, M.F., & Overley, T.E. (1998). Visual processing impairment and risk of motor vehicle crash among older adults. *The Journal of the American Medical Association, 279*(14), 1083-1088.

198. Paul, M., Biswas, S.K., & Sandhu, J.S. (2011). Role of sports vision and eye hand coordination training in performance of table tennis players. *Brazilian Journal of Biomotricity, 5*(2), 106-116.

199. Pesce-Anzeneder, C., & Bösel, R. (1998). Modulation of the spatial extent of the attentional focus in high-level volleyball players. *European Journal of Cognitive Psychology, 10*, 247-267.

200. Pinder, R.A., Davids, K., Renshaw, I., & Araujo, D. (2011). Manipulating informational constraints shapes movement reorganization in interceptive actions. *Attention, Perception, & Psychophysics, 73*(4), 1242-1254.

201. Pinder, R.A., Davids, K., Renshaw, I., & Araujo, D. (2011). Representative learning design and functionality of research and practice in sport. *Journal of Sport & Exercise Psychology, 33*, 146-155.

202. Pinkman, J., Pinkman, P., & Parlovich Jr., L. (2012, May 17). Best of show: Terrific innovations that will help all levels of the game. Retrieved April 28th, 2014, from http://nikestrobegoggles.com/uncategorized/best-of-show/

203. Poltavski, D., & Biberdorf, D. (2014). The role of visual perception measures used in sports vision programmes in predicting actual game performance in Division I collegiate hockey players. *Journal of Sports Sciences,* DOI: 10.1080/02640414.2014.951952.

204. 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 training. *Human Movement Science, 6,* 181-199.

205. Proteau, L., & Cournoyer, J. (1990). Vision of the stylus in a manual aiming task – the effects of practice. *Quarterly Journal of Experimental Psychology Section a - Human*. *Experimental Psychology, 42*(4), 811–828.

206. Proteau, L. (1992). On the specificity of learning and the role of visual information for movement control. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (p. 67–103). Amsterdam: North-Holland.

207. Quevedo-Junyent, L., Aznar-Casanova, J.A., Merindano-Encina, D., Cardona, G., & Sole-Forto, J. (2011). Comparison of dynamic visual acuity between water polo players and sedentary students. *Research Quarterly for Exercise and Sport, 82*(4), 644-651.

208. Quintana, M.S., Roman, I.R., Calvo, A.L., & Molinuevo, S. (2007). Perceptual visual skills in young highly skilled basketball players. *Perceptual and Motor Skills, 104*(2), 547-561.

209. Raghuram, A., & Lakshminarayanan, V. (2006). Motion perception tasks as potential correlates to driving difficulty in the elderly. *Journal of Modern Optics, 53*, 1343–1362.

210. Reed-Jones, J.G., Reed-Jones, R.J., & Hollands, M.A. (2014). Is the size of the useful field of view affected by postural demands associated with standing and stepping? *Neuroscience Letters, 566*, 27-31.

211. Regan, D. (1991). The Charles F. Prentice Award Lecture 1990: Specific tests and specific blindnesses: keys, locks and parallel processing. *Optometry and Vision Science, 68*, 489-512.

212. Reilly, T., Williams, A.M., Nevill, A., & Franks, A. (2000). A multidisciplinary approach to talent identification in soccer. *Journal of Sports Sciences*, *18*(9), 695-702.

213. Reis, S.M., & Renzulli, J.S. (2010). Is there still a need for gifted education? An examination of current research. *Learning and Individual Differences, 20*(4), 308-317.

214. Revien, L. (1987). *Eyerobics.* Great Neck, NY: Visual Skills Inc.

215. Revien, L., & Gabor, M. (1981). *Sports Vision: Dr Revien's Eye Exercises for Athletes*. New York: Workman Publishing.

216. Rezaee, M., Ghasemi, A., & Momeni, M. (2012). Visual and athletic skills training enhance sport performance. *European Journal of Experimental Biology, 2*(6), 243-2250.

217. Riley, P.O., Dicharry, J., Franz, J., Della-Croce, U., Wilder, R.P., & Kerrigan, D.C. (2008). A kinematics and kinetic comparison of overground and treadmill running. *Medicine & Science in Sports & Exercise, 40*(6), 1093-1100.

218. Roca, A., Williams, A.M., & Ford, P.R. (2014). Capturing and testing perceptual-cognitive expertise: A comparison of stationary and movement response methods. *Behavior Research Methods, 46*(1), 173-177.

219. Rokszin, A., Márkus, Z., Braunitzer, G., Benedek, G., & Nagy, A. (2010). Visual pathways serving motion detection in the mammalian brain. *Sensors, 10*, 3218-3242.

220. Ryu, D., Abernethy, B., Mann, D.L., Poolton, J.M., & Gorman, A.D. (2013). The role of central and peripheral vision in expert decision making. *Perception, 42*, 591-607.

221. Salmela, J.H., & Fiorito, P. (1979). Visual cues in ice hockey goaltending. *Canadian Journal of Applied Sports Sciences, 4*, 56-59.

222. Sanderson, F.H., & Whiting, H.T.A. (1978). Dynamic visual-acuity - Possible factor in catching performance. *Journal of Motor Behavior, 10*, 7-14.

223. Savelsbergh, G.J.P., Haans, S.H.A., Kooijman, M.K., & van Kampen, P.M. (2010). A method to identify talent: Visual search and locomotion in behaviour in young football players. *Human Movement Sciences, 29*, 764-776.

224. Savelsbergh, G.J.P., & Whiting, H. T. (1992). The acquisition of catching under monocular and binocular conditions. *Journal of Motor Behavior, 24*, 320-328.

225. Savelsbergh, G.J.P., Williams, A.M., Van Der Kamp, J., & Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *Journal of Sports Sciences, 20*(3), 279-287.

226. Schiff, W., Oldak, R., & Shah, V. (1992). Aging persons estimates of vehicular motion. *Psychology of Aging, 7*, 518–525.

227. Schmidt, R.A., & Lee, T.D. (2011). *Motor Control & Learning: A Behavioural Emphasis*. *Fifth Edition.* Champaign, IL: Human Kinetics.

228. Schmidt, R.A., & Young, D.E. (1987). Transfer of movement control in motor learning. In S.M. Cormier & J.D. Hagman (Eds.), *Transfer of Learning* (p. 47-79). Orlando, FL: Academic Press.

229. Schneiders, A.G., Sullivan, S.J., Rathbone, E.J., Thayer, A.L., Wallis, L.M., & Wilson, A.E. (2010). Visual acuity in young elite motorsport athletes: A preliminary report. *Physical Therapy in Sport, 11*(2), 47-49.

230. Schwab, S., & Memmert, D. (2012). The impact of a sports vision training program in youth field hockey players. *Journal of Sports Science and Medicine, 11*, 624-631.

231. Sekuler, R., & Ball, K.K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America: Optics, Image Science and Vision, 3(6),* 864-867.

232. Sherman, A. (1980). Overview of research information regarding vision and sports. *Journal of the American Optometric Association, 51*(7), 661-666.

233. Shim, J., Carlton, L.G., Chow, J.W., & Chae, W.S. (2005). The use of anticipatory visual cues by highly skilled tennis players. *Journal of Motor Behavior, 37*(2), 164-175.

234. Shinar, D., & Schieber, F. (1991). Visual requirements for safety and mobility of older drivers. *Human Factors,* 33, 507-519.

235. Simons, J.P., Wilson, J., Wilson, G., & Theall, S. (2009). Challenges to cognitive bases for an especial motor skill at the regulation baseball pitching distance. *Research Quarterly for Exercise and Sport, 80,* 469-479.

236. Smith, T.Q., & Mitroff, S.R. (2012). Stroboscopic training enhances anticipatory timing. *International Journal of Exercise Science, 5(4),* 344-353.

237. Spector, R.H. (1990). Visual fields. In H.K. Walker, W.D., Hall, & J.W. Hurst, (Eds.), *Clinical Methods: The History, Physical, and Laboratory Examinations. 3rd Edition.* Boston: Butterworths.

238. Spittle, M., Kremer, P., & Hamilton, J. (2010). The effect of screen size on video-based perceptual decision making tasks in sport. *International Journal of Sport and Exercise Psychology, 8*(4), 360-372.

239. Starkes, J.L. (1987). Skill in field hockey: The nature of the cognitive advantage. *Journal of Sport Psychology, 9,* 146-160.

240. Starkes, J.L., Edwards, P., Dissanayake, P., & Dunn, T. (1995). A new technology and field test of advance cue usage in volleyball. *Research Quarterly for Exercise and Sport, 66*(2), 162-167.

241. Steenbergen-Hu, S., & Moon, S.M. (2011). The effects of acceleration on high-ability learners: A meta-analysis. *Gifted Child Quarterly, 55*(1), 39-53.

242. Steeves, J.K.E., Gonzalez, E.G., Gallie, B.L., & Steinbach, M.J. (2002). Early unilateral enucleation disrupts motion processing. *Vision Research* 42(1): 143-150.

243. Steinhaus, A.H. (1949). Why this research? In M.G. Scott (Ed.), *Research Methods in Health, Physical Education, Recreation, 2nd Edition,* (p. 1-20). Washington, USA: American Association for Health, Physical Education, and Recreation.

244. Straughn, S., Gray, R., & Tan, H.Z. (2009). To go or not to go: Stimulus-response compatibility and pedestrian collision warnings in driving. *IEEE Transactions on Haptics, 2,* 111-117.

245. Takeuchi, H., Taki, Y., Hashizume, H., Sassa, Y., Nagase, T., Nouchi, R., & Kawashima, R. (2011). Effects of training of processing speed on neural systems. *The Journal of Neuroscience, 31*(34), 12139-12148.

246. Thomas, K.T., & Thomas, J.R. (1994). Developing expertise in sport: The relation of knowledge and performance. *International Journal of Sport Psychology, 25*(3), 295-312.

247. Travassos, B., Araujo, D., Davids, K., O'Hara, K., Leitao, J., & Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours – A meta-analysis. *Psychology of Sport and Exercise, 14*(2), 211-219.

248. Tussing, L. (1940). The effect of football and basketball on vision. *Research Quarterly. American Association for Health, Physical Education and Recreation, 11*(1), 16-18.

249. Uchida, Y., Kudoh, D., Murakami, A., Honda, M., & Kitazawa, S. (2012). Origins of superior dynamic visual acuity in baseball players: Superior eye movements or superior image processing. *PLoS ONE, 7*(2): e31530. doi: 10. 1371/journal.pone.0031530.

250. Uchida, Y., Kudoh, D., Higuchi, T., Honda, M., & Kanosue, K. (2013). Dynamic visual acuity in baseball players is due to superior tracking abilities. *Medicine and Science in Sports and Exercise, 45*(2), 319-325.

251. Vaeyens, R., Lenoir, M., Williams, A.M., Mazyn, L., & Philippaerts, R.M. (2007). The effects of task constraints on visual search behaviour and decision-making skill in youth soccer players. *Journal of Sport & Exercise Psychology, 29,* 147-169.

252. Vickers, J.N. (1992). Gaze control in putting. *Perception, 21*(1), 117-132.

253. Vickers, J.N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance, 22*(2), 342-354.

254. Vickers, J.N. (2007). *Perception, cognition and decision training: The quiet eye in action.* Champaign, Il: Human Kinetics.

255. Vignais, N., Bideau, B., Craig, C., Brault, S., Multon, F., Delamarche, P., & Kulpa, R. (2009). Does the level of graphical detail of a virtual handball thrower influence a goalkeeper's motor response? *Journal of Sports Science and Medicine, 8*(4), 501-508.

256. Vilar, L., Araújo, D., Davids, K., & Renshaw, I. (2012). The need for 'representative task design' in evaluating efficacy of skills tests in sport: A comment on Russell, Benton and Kingsley (2010). *Journal of Sports Sciences, 30*(16), 1727-1730.

257. Vine, S.J., Moore, L.J., & Wilson, M.R. (2011). Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology, 2*(8), 1-9.

258. Vine, S.J., Moore, L.J., & Wilson, M.R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. *European Journal of Sport Science, 14*(sup1), S235-S242.

259. Vine, S.J., & Wilson, M.R. (2011). The influence of quiet eye training and pressure on attention and visuo-motor control. *Acta Psychologica, 136,* 340-346.

260. Voss, M.W., Kramer, A.F., Basak, C., Prakash, R.S., & Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology, 24,* 812-826.

261. Ward, P., & Williams, A.M. (2000). Levels of cognitive control actions in sport: The example of sports collectives. *Differences in perceptual skill in soccer: Effects of*

age and expertise. Symposium conducted at the SFPS International Congress of Sport Psychology, Paris, France.

262. Weissensteiner, J., Abernethy, B., Farrow, D., & Müller, S. (2008). The development of anticipation: A cross-sectional examination of the practice experiences contributing to skill in cricket batting. *Journal of Sport & Exercise Psychology, 30*, 663-684.

263. Westlake, W. (2001). Is a one eyed racing driver safe to compete? Formula one (eye) or two? *British Journal of Ophthalmology, 85,* 619-624.

264. Wilkie, R., & Wann, J. (2003). Controlling steering and judging heading: retinal flow, visual direction and extraretinal information. *Journal of Experimental Psychology: Human Perception & Performance, 29,* 363-378.

265. Wilkins, L., Gray, R., Gaska, J., & Winterbottom, M. (2013). Motion perception and driving: Predicting performance through testing and shortening braking reaction times through training. *Investigative Ophthalmology & Visual Science, 54(13),* 8364-8374.

266. Williams, A.M. (2000). Perceptual skill in soccer: Implications for talent identification and development. *Journal of Sports Sciences, 18*(9), 737-750.

267. Williams, A.M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. *Research Quarterly for Exercise and Sport, 69*(2), 111-128.

268. Williams, A.M., Davids, K., & Williams, J.G. (1999). *Visual perception & action in sport.* London: Routledge.

269. Williams, A.M., & Ericsson, K.A. (2008). From the guest editors: How do experts learn? *Journal of Sport & Exercise Psychology, 30*(6), 653-662.

270. Williams, A.M., Janelle, C.M., & Davids, K. (2004). Constraints on the search for visual information in sport. *International Journal of Sport and Exercise Psychology, 2,* 301-308.

271. Williams, A.M., Ward, P., Smeeton, N.J., & Allen, D. (2004). Developing anticipation skills in tennis using on-court instruction: Perception versus perception and action. *Journal of Applied Sport Psychology, 16*, 350-360.

272. Williams, J.M., & Thirer, J. (1975). Vertical and horizontal peripheral vision in male and female athletes and nonathletes. *Research Quarterly. American Alliance for Health, Physical Education and Recreation, 46*(2), 200-205.

273. Wilson, M.R., Causer, J., & Vickers, J.N. (2015) Aiming for excellence. The quiet eye as a characteristic of expertise. In J. Baker & D. Farrow (Eds.), *Routledge Handbook of Sport Expertise*, (p. 22-37). New York, NY: Routledge.

274. Wimshurst, Z.L., Sowden, P.T., & Cardinale, M. (2012). Visual skills and playing positions of Olympic field hockey players. *Perceptual and Motor Skills, 114*(1), 204-216.

275. Wood, G., & Wilson, M.R. (2011). Quiet-eye training for soccer penalty kicks. *Cognitive Processing, 12,* 257-266.

276. Wood, J.M. (2002). Age and Visual Impairment Decrease Driving Performance as Measured on a closed-road circuit. *Human Factors, 44,* 482-494.

277. Wood, J.M., Anstey, K.J., Kerr, G.K., Lacherez, P.F., & Lord, S. (2008). A multidomain approach for predicting older driver safety under in-traffic road conditions. *Journal of the American Geriatrics Society, 56,* 986-993.

278. Wood, J.M., & Owsley, C. (2014). Useful field of view test. *International Journal of Experimental, Clinical, Behavioural and Technological Gerontology, 60*(4).

279. Woods, D.L. (1990). The physiological basis of selective attention: Implications of event-related potential studies. In J.W. Rohrbaugh, R. Parasurasman, & R. Johnson (Eds.), *Event-Related Brain Potentials.* New York: Oxford University Press.

280. Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Review, 3(13),* 1-114.

281. Young, W., & Farrow, D. (2013). The importance of a sport-specific stimulus for training agility. *Strength and Conditioning Journal, 35*(2), 39-43.

282. Zanker, J.M. (1999). Perceptual learning in primary and secondary motion vision. *Vision Research, 39*, 1293-1304.

283. Zelinsky, G.J., Rao, R.P.N., Hayhoe, M.M., & Ballard, D.H. (1997). Eye movements reveal the spatial temporal dynamics of visual search. *Psychological Science, 8*(6), 448-453.

284. Zinn, W.J., & Solomon, H. (1985). A comparison of static and dynamic stereoacuity. *Journal of the American Optometric Association, 56*(9), 712-715.

285. Zwierko, T. (2007). Differences in peripheral perception between athletes and nonathletes. *Journal of Human Kinetics, 19,* 53-62.

APPENDIX

Accommodation	"The ability of the eye to change its refractive power to bring objects of regard at different distances into focus" (Atchison, Mon-Williams, Tresilian, Stark, & Strang, 1997).
Acuity (dynamic)	"The ability to discriminate an object when there is relative movement between the observer and the object" (Burg, 1966).
Acuity (static)	"The ability to make fine visual discriminations among objects in the visual field" (Barlow & Mollon, 1985).
Advanced cue utilisation	"An athlete's ability to make accurate predictions based on contextual information available early in an action sequence" (Williams, Davids, & Williams, 1999, p. 105).
Anticipation	"The ability to make predictions upon partial or advance sources of information" (Williams et al., 1999, p. 105).
Bilateral (vision)	"Having or relating to two sides; affecting both sides" (Oxford Dictionary of English, 2010).
Central awareness/vision	"The inner 30 degrees of vision and central fixation" (Spector, 1990).
Coincidence-timing	"The ability to coincide a motor response with the arrival of a moving object at a target point" (Abernethy & Wood, 1999, p. 211).
Colour vision	"The ability to rapidly and accurately recognise the various

	colours in the spectrum” (Williams et al., p. 62).
Contrast sensitivity	“The visual system’s capacity to filter and process object and background information under varying conditions of illumination” (Williams et al., p. 89).
Convergence	“The coordinated turning of the eyes inward to focus on an object at close range” (The American Heritage Medical Dictionary, 2007).
Depth perception	“The ability to perceive relative changes in object distance or depth” (Abernethy, Neal, & Koning, 1994, p. 187).
Divergence	“A turning of both eyes outward from a common point or of one eye when the other is fixed” (The American Heritage Medical Dictionary, 2007).
Divided attention	The “ability to distribute attention across several concurrent tasks” (Williams et al., 1999, p. 26).
(Eye) dominance	“Any sort of physiologic pre-eminence, priority, or preference by one member of any bilateral pair of structures in the body when performing various tasks” (Erickson, 2007, p. 52).
Fixation	The pause that occurs when both eyes are focused on an object that has caught one’s attention (Knudson & Kluka, 1997)
Fusion	“The ability to rapidly and accurately fuse the two images (from the athlete’s eyes) into one image, and to have the eyes work as a team to maintain this ‘oneness’ in all areas of gaze” (Williams et al., 1999, p. 63).
Hand/Body-Eye	“The ability to make synchronized motor responses with the hands

coordination	to visual stimuli”...”The ability to make synchronized motor responses with the body to visual stimuli” (Erickson, 2007, p. 61).
Monocularity	“A condition of seeing with or using only one eye at a time” (Medical-dictionary).
Motion coherence threshold	The “ability to detect coherent motion from an array of randomly moving dots” (Milne et al., 2002, p. 257).
Motion detection/perception	“The process through which one gathers information on the dynamic visual world, in terms of the speed and movement direction of its elements” (Rokszin et al., 2010, p. 3218).
Ocular muscle balance	“The extent to which the axes of both eyes are in symmetry in viewing objects at different distances” (Abernethy & Neal, 1999, p. 4).
Peripheral vision	“A part of vision that emerges outside the very center of gaze” (Schwab & Memmert, 2012, p. 624).
Processing speed	“Individual cognitive ability measured by how fast individuals execute cognitive tasks” (Takeuchi et al., 2011).
Saccadic eye movements	“The ability to change fixation from one location to another rapidly and accurately” (Erickson, 2007, p. 57).
Selective attention	“The preferential detection, identification, and recognition of selected stimulation” (Woods, 1990, p. 178).
Stereopsis/Stereoacuity	“The ability to discriminate differences in depth through the use of binocular vision” (Abernethy, Neal, & Koning, 1994, p. 187).
Unilateral (vision)	“Relating to or affecting only one side of an organ, the body, or another structure” (Oxford Dictionary of English, 2010).

Vergence	The “disjunctive movement of the eyes in opposite directions in adjusting to near or far vision; convergence or divergence” (Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health. Seventh Edition, 2003).
Visual attention	“The set of mechanisms by which relevant visual information is selected while irrelevant information is suppressed” (Hubert-Wallander, Green, & Bavelier, 2011).
Visual correction time	“The minimal time required to initiate the first saccadic eye movement in response to a stimulus” (Helsen & Starkes, 1999, p. 5).
Visual field	“The entire extent of the external world that can be seen without a change in fixation” (Erickson, 2007, p. 65).
Visual memory	“The ability to recall visual images in the form of objects, events, or words” (McGraw-Hill Concise Dictionary of Modern Medicine, 2002).
Visual reaction time (choice)	“The comparable response latency (see simple visual reaction time below) which occurs in situations where there are a number of possible stimulus events, each with their own unique response” (Abernethy & Neal, 1999, p. 4).
Visual reaction time (simple)	“The delay between the presentation of a single unanticipated stimulus and the initiation of a pre-determined response to that stimulus” (Abernethy & Neal, 1999, p. 4).
Visual recognition/search speed	The speed of “the process by which one locates a target in a cluttered scene” (Zelinsky, Rao, Hayhoe, & Ballard, 1997, p. 448).

Visual search strategies	“The way in which the eyes are used to search the display or scene for relevant information to guide action” (Williams, Janelle, & Davids, 2004, p. 301).
Visual tracking	“The ability to quickly and accurately follow a moving object and efficiently move our eyes so we can look at objects from point to point” (Guy’s and St Thomas', 2013).