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Gaze-Contingent Training Enhances Perceptual Skill Acquisition

Donghyun Ryu

Institute of Human Performance, The University of Hong Kong, Pokfulam, Hong Kong

David L. Mann

MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU

University, Amsterdam, The Netherlands

Bruce Abernethy

School of Human Movement Studies, The University of Queensland, Brisbane, Australia

& Institute of Human Performance, The University of Hong Kong, Pokfulam, Hong Kong

Jamie M. Poolton

School of Sport, Carnegie Faculty, Leeds Beckett University, UK

& Institute of Human Performance, The University of Hong Kong, Pokfulam, Hong Kong

Address for correspondence:

Donghyun Ryu

Institute of Human Performance

The University of Hong Kong, 5 Sassoon Road, Pokfulam, Hong Kong

Email: dhryu@connect.hku.hk

Phone: +852 2831 5308

Fax: + 852 2855 1712

Abstract

The purpose of this study was to determine whether decision-making skill in perceptual-cognitive tasks could be enhanced using a training technique that impaired selective areas of the visual field. Recreational basketball players performed perceptual training over three days while viewing with a gaze-contingent manipulation that displayed either (1) a moving window (clear central and blurred peripheral vision), (2) a moving mask (blurred central and clear peripheral vision), or (3) full (unrestricted) vision. During the training participants watched video clips of basketball play and at the conclusion of each clip made a decision about which teammate the player in possession of the ball should pass to. A further control group watched unrelated videos with full vision. The effects of training were assessed using separate tests of decision-making skill conducted in a pre-test, post-test, and two-week retention test. The accuracy of decision making was greater in the post-test than in the pre-test for all three intervention groups when compared to the control group. Remarkably though, training with blurred peripheral vision resulted in a further improvement in performance from post to retention test that was not apparent for the other groups. The type of training had no measurable impact on the visual search strategies of the participants and so the training improvements appear to be grounded in changes in information pick-up. The findings show that learning with impaired peripheral vision offers a promising form of training to support improvements in perceptual skill.

Keywords: perceptual training, decision-making, gaze-contingent display, attentional control, central vision, peripheral vision

Gaze-Contingent Training Enhances Perceptual Skill Acquisition

Perceptual-cognitive skill underpins expertise in dynamic tasks (Abernethy, Thomas, & Thomas, 1993). For instance, highly-skilled basketball players possess refined perceptual-cognitive skills such as the ability to anticipate the action of others at an earlier point in time (*anticipatory skill*; Jones & Miles, 1978), a capacity to perceive and recall previously seen patterns of play (*pattern recall*; Chase & Simon, 1973), and the ability to select the most appropriate response from a variety of possible options (*decision making*¹; Allard, Graham, & Paarsalu, 1980; Allard & Starkes, 1980). In externally-paced dynamic activities common in sport (Abernethy, 1991; Williams & Davids, 1998) and other activities such as driving (Crundall, Underwood, & Chapman, 1999) and aviation (Bellenkes, Wickens, & Kramer, 1997), effectual perceptual-cognitive skill requires the performer to account for rapidly changing visual information that is located across the breadth of the visual field. As a result, peripheral vision is likely to play a significant role in perceptual-cognitive performance. For example when driving, eminent hazards are typically first detected using peripheral vision, and the driver subsequently re-directs their central vision towards the hazard to assess the risk using visual information of higher resolution (Crundall et al., 1999). Similarly, skilled athletes have been presumed to use their peripheral vision to rapidly extract information about the relative position of other players to guide decision-making and interactions with the environment (e.g., Abernethy, 1991; Williams & Davids, 1998). As a result, the development of expertise in these dynamic tasks is likely to rely on a substantial advantage in the use of peripheral vision.

¹ The term *decision making* in the field of expertise refers to the ability to choose the most appropriate response when faced with a variety of different possible options and is taken as our working definition throughout this paper.

In a series of recent experiments, we have shown that skilled athletes *are* better able to make use of their peripheral vision when performing a domain-specific task (Ryu, Abernethy, Mann, & Poolton, 2015; Ryu, Abernethy, Mann, Poolton, & Gorman, 2013). In those studies the decision-making ability of skilled and less-skilled basketball players was tested when viewing video footage of basketball game scenarios. A gaze-contingent display was used to change the visual display – in real time – depending on where the observer was looking (McConkie & Rayner, 1975; Rayner & Bertera, 1979), and at critical moments in the play the video stopped and participants were required to select which teammate was best positioned to receive a pass from the player holding the ball. Participants viewed the video clips in each of three conditions: a *moving window* condition where a clear window was centered around the point of fixation but blurred elsewhere; a *moving mask condition* where central vision was blurred so that only peripheral vision was clear; and a full-vision *control* condition where vision was unperturbed. The skilled group demonstrated superior decision-making performance irrespective of the visual condition, highlighting a better capacity to use both their central *and* peripheral vision when performing the decision-making task. In contrast, when viewing with only peripheral vision the performance of the lesser-skilled players was reduced to a level that was no better than that achievable by guessing, demonstrating their lack of capacity to use information located in their peripheral vision.

The findings of the studies by Ryu et al. (2013; 2015) are consistent with the idea that lesser-skilled performers experience *perceptual narrowing* when performing a task they are less familiar with (in that case, basketball decision making). Perceptual narrowing (Easterbrook, 1959; Weltman & Egstrom, 1966) refers to the idea that the increase in stress and/or arousal that might be expected when performing an unfamiliar task will reduce an observer's ability to attend to items located in their visual periphery. In essence, perceptual narrowing is thought to restrict attention to the central portion of the visual field, at least in

part to increase the ability to attend to central processing demands. Although it is unclear whether there is an actual narrowing of vision (akin to tunnel vision) or whether there is a more general reduction of sensitivity throughout the periphery (see Crundall, Underwood, & Chapman, 2002 for a discussion), it is clear that stress or arousal can alter the ability to attend to and perceive information located in the visual periphery. Crucially, reductions in peripheral sensitivity are known to have important practical consequences. For example, the incidence of motor vehicle accidents is higher in elderly people who score poorly on an assessment of the Useful Field of View, a test designed to assess the ability to identify and localise supra-threshold targets in the visual periphery (Clay et al., 2005; Owsley, Ball, Sloane, Roenker, & Bruni, 1991).²

Given the role played by peripheral vision in the development of competence (and expertise) in dynamic tasks, it seems reasonable to question whether the rate at which one can learn to use peripheral vision can be enhanced as a result of perceptual training. The general benefits of perceptual training programs designed to enhance perceptual-cognitive skills (such as anticipatory skill and decision-making) have been known for over 50 years (e.g., Abernethy, Wann, & Parks, 1998; Damron, 1955; Ward et al., 2008). Early studies sought to formally guide the attention of learners in a very prescriptive way (e.g., Abernethy, Wood, & Parks, 1999; Farrow, Chivers, Hardingham, & Sachse, 1998), usually incorporating explicit instructions based on expert models of how the task should be performed, in the process developing declarative knowledge about how and from where the learner should extract critical information. However, there has been a growing awareness of the limitations of these training programs and the types of outcomes they might produce. Recent approaches have

² Similarly, one might expect stress and/or arousal to alter the *perceptual span*, a measure of the breadth of information that can be extracted within a single fixation. Experts in static tasks such as chess are known to have a larger perceptual span than lesser-skilled performers do (Reingold, Charness, Pomplun, & Stampe, 2001), however it is less clear whether the perceptual span is related to expertise in *dynamic* tasks such as those experienced in sports (Cañal-Bruland, Lotz, Hagemann, Schorer, & Strauss, 2011).

relied on more ‘implicit’ means of training (e.g., Smeeton, Williams, Hodges, & Ward, 2005; Farrow & Abernethy, 2002; though see Jackson, 2003; Farrow & Abernethy, 2003) to enhance skill retention without developing explicit knowledge about the underlying information used to perform the task (Jackson & Farrow, 2005). For instance the ‘color-cueing’ training approach uses video-based tasks where a colored highlight is incorporated into the video to guide the observer’s central vision towards the critical informative cues/areas that skilled performers would use – without necessarily providing explicit rules on how to use that information (Grant & Spivey, 2003; Hagemann, Strauss, & Cañal-Bruland, 2006; Ryu, Kim, Abernethy, & Mann, 2013; Savelsbergh, van Gastel, & van Kampen, 2010; Wilson et al., 2011). However, these perceptual training approaches have focused largely on the role of central vision in the development of perceptual-cognitive skill, and as a result very little is known about whether perceptual training can be used to enhance the usefulness of peripheral vision, and if so, what might be the most effective means of doing so.

In an effort to enhance the ability to use peripheral vision when performing perceptual-cognitive tasks, one possible approach could be to use a gaze-contingent display to selectively present information to only one particular segment of the visual field during training. The most intuitive gaze-contingent approach to improve the ability to use peripheral vision would be one that removes central vision so that learners must become accustomed to using the outer (peripheral) segment of their visual field. The success of this approach though relies on the assumption that the training benefits are likely to be specific to the area of the visual field that is trained (specificity of training; Henry, 1968; Proteau, 1992). If decision-making skills *do* transfer across the different segments of the visual field, then it may be that an approach that trains decision-making skill using central vision will be just as (or more) effective than one that selectively trains peripheral vision, particularly if exposing the learner

to the central processing demands of the perceptual task from the onset of training helps moderate perceptual narrowing.

The training of central vision can of course take place when viewing with the full visual field; however, there is reason to believe that a gaze-contingent approach that *removes* peripheral vision might actually prove to be, counter intuitively, the most efficacious means of improving decision-making in the peripheral visual field. The development of perceptual-cognitive skill requires learners to attend to the most pertinent information within a given scenario while ignoring the less-relevant information (Abernethy & Russell, 1987). Given that most of the less-relevant information is likely to be located in the peripheral visual field (Ryu et al., 2015), it could be that the removal of peripheral vision draws the attention of the lesser-skilled players towards the more central cues that skilled performers would typically rely on. In support, Ryu et al.'s (2015) study of skilled and less-skilled basketball players found that lesser-skilled players *improved* their decision making when a gaze-contingent display was used to blur the visual periphery. It was hypothesized that the peripheral blur may have improved information pick-up by means of enforced perceptual narrowing, whereby the concurrent demands and distractions in peripheral vision were attenuated, permitting an increased attentional focus on the critical centrally-fixated cues (Reingold, Loschky, McConkie, & Stampe, 2003). Indeed, the peripheral blur led the less-skilled players to increase the time they spent fixating the ball-carrier, a critical cue heavily relied on by skilled performers. In that study though there was a *temporary* improvement in decision-making performance in the presence of peripheral blur, and it remains unclear whether there might be longer-term benefits of *training* with peripheral blur whereby any improvements in decision making are retained in the absence of the gaze-contingent peripheral blur.

The aim of this study was to determine whether decision-making skill in perceptual-cognitive tasks could be improved as a result of perceptual training that impaired selective

areas of the visual field. We were particularly interested in what might prove to be the best means of improving the ability to use peripheral vision when performing a perceptual-cognitive task. To this end we assigned participants to one of four training groups: a *moving-window training* group (with clear central vision and blurred peripheral vision), a *moving-mask training* group (with blurred central vision and clear peripheral vision), a *full-vision training* group (unrestricted vision), and a *control* group (who undertook unrelated training with unrestricted vision). To examine the transferability of any training improvements across the different areas of the visual field, participants performed pre, post, and retention tests of decision-making skill when viewing with each of the full visual field, central vision only (moving window), and peripheral vision only (moving mask) conditions. Based on the findings of Ryu et al. (2015), we hypothesized that the *moving-window training* group who trained with blurred peripheral vision would improve their ability to attend to the informative cues within the scenarios, and as a result that their training would lead to the best improvement in overall decision-making when the gaze-contingent manipulation was removed (allowing participants to view with full vision). Moreover, we hypothesised that the benefits accrued by *moving-window training* would be generalizable across the visual field, that is, that the *moving-window training* group would experience the best possible generalizable improvement in the ability to pick-up task-specific information, ultimately ensuring that they should perform best in the post and retention tests of decision-making even when using only their peripheral vision.

Method

Participants

Fifty participants (M age = 24.2 years, SD = 3.1; 29 male) with limited recreational basketball experience (M = 1.4 years) participated in the study. Ethical approval was obtained

from the institutional human research ethics committee prior to testing, with informed consent obtained prior to the commencement of the experiment.

Apparatus

An Eyelink II (SR Research Ltd., Mississauga, ON) was used to record eye movements (250 Hz) and to control the gaze-contingent display. Experiment Builder software (SR Research Ltd., Mississauga, ON) was used to facilitate the gaze-contingent presentation of video clips. Three different types of viewing scenarios were used for both the training and tests: (i) full vision, (ii) moving window, and (iii) moving mask (see Figure 1). The *full vision* scenario presented normal, un-manipulated video clips with no blurring in either central or peripheral vision. In the *moving window* viewing scenario a clear circular window of 5° diameter (see also Ryu et al., 2015; Ryu, Abernethy, et al., 2013) was placed about the point of fixation and this moved each time the participant altered his/her position of gaze. Visual information available elsewhere in the visual field (i.e., peripheral vision) was degraded with visual blur applied to the video footage using Adobe Premiere CS 4 (Gaussian blur with filter level 50, see Ryu et al. (2015); Adobe systems Incorporated, San Jose, CA). This level of blur equates to pixel-wise Gaussian blur with a spatial frequency cut-off of 0.5 cycles per degree, and has previously been shown to be a level of blur that suitably perturbs information pick-up in this task while allowing gaze to be directed towards the areas of interest that would usually be prioritized without any gaze-contingent manipulation (see Ryu et al., 2015). In the *moving mask* scenario the same level of blur was applied centrally rather than peripherally with a moving blur mask of 5° diameter around the line of gaze. Using this gaze-contingent system the delay between an eye movement and the repositioning of the gaze contingent display on the screen was on average 16 ms (range 12-20 ms). This display-change latency is well below the 80 ms latency shown to be necessary to detect blur in gaze contingent displays (Loschky & Wolverton, 2007).

Figure 1



Test and training materials

Decision-making tests. Purposefully filmed video clips of five-on-five basketball play (the same as those used by Gorman, Abernethy, & Farrow, 2012; Gorman, Abernethy, & Farrow, 2013; see also Ryu et al., 2015; Ryu, Abernethy, et al., 2013), each of approximately 7 s duration, were occluded at a moment when a critical decision was needed by the ball carrier as to which teammate was most appropriately positioned to receive a pass. Three expert coaches collectively rated the extent to which the clip was representative of actual game play and determined the most appropriate decision to make in each scenario. Only clips that were judged to be highly representative and that concluded with a clear best option for the ball carrier were selected for use in the experiment (for more detail see Gorman, Abernethy, & Farrow, 2011; Gorman et al., 2012). The basic principles for determining the most suitable options for the ball-carrier were based on (i) the position of the attacking teammates relative to the ball-carrier, and (ii) the proximity of the teammates to the basket (as players generally aim to pass to a player in a better position to shoot the ball) (see Experiment 2 & 3, Ryu et al., 2015).

Sixteen video clips met the criteria for inclusion in the experiment and were mirrored about the vertical axis using Adobe Premiere CS 4 to produce a total set of 32 clips for the decision-making tests (see also Ryu et al., 2015). For each participant, a set of 16 video clips

(half original, half mirrored) were selected for use in a pre-test, with the remaining 16 clips used for a post-test. The set of 16 video clips viewed by participants in the pre-test and post-test was counterbalanced across participants to avoid order effects. A random selection of 8 clips from the pre-test was matched with the 8 remaining clips from the post-test for use in a retention test. At no point was the original and mirrored version of the same video clip shown in the same test (pre, post, or retention). In each of the pre, post, and retention tests participants watched each of the 16 video clips when they were completely clear (*full vision in test*), when peripheral vision was blurred (using the gaze contingent moving window manipulation; *moving window in test*) and when central vision was blurred (using the gaze contingent moving mask manipulation; *moving mask in test*). The order of the 48 trials was randomized in each test. The inclusion of the moving window and mask conditions in the tests was designed to (i) ensure that the training groups were equated in their ability to selectively use central and peripheral vision prior to the commencement of the training phase of the study and to (ii) examine the transferability of the different training interventions to the independent usage of central and/or peripheral vision in the post-test and retention test.

At the conclusion of each test clip a static response slide was shown consisting of the same basketball court without any players, but with a ball positioned at the center of the free-throw line. The position of the ball was controlled by a computer mouse, with the participant's task being to use the mouse to click the position on the court that best represented where the player was standing who they judged to be best placed to receive the pass (i.e., the position of their feet). The participant's response was established by determining which attacking player was located closest to the position of the mouse click. This was done based on the shortest of the four distances from the screen-based x-y coordinates of the mouse click to the center of the feet of the four attacking teammates (mid-point of the stance). This mode of response has been experimentally established as the most

appropriate and neutral response mode to utilize and one in which there was no inherent advantage for more experienced participants (see Ryu et al., 2015).

Training stimuli. Video footage of National Basketball Association (NBA) games was examined and suitable clips were selected for inclusion as training stimuli if the visual angle and the structure and dynamics of the game play was similar to that seen in the video clips used in the testing sessions. As in the tests, individual video clips were occluded at a key moment when a pass decision was required. To prevent participant familiarization with the time of occlusion, the duration of the video clips used for training varied from 6 to 12 s. Following editing, an expert coach rated each clip using the same criteria employed to select the testing-session video clips (i.e., the representativeness of real game play and a clear correct response). A total of 144 video clips were selected for use in the training sessions.

Procedures

The experiment consisted of four phases: pre-test, training intervention, post-test, and retention test. The pre-test took place one day prior to the commencement of the training intervention which itself was held over three consecutive days, the post-test took place the day after the training intervention, and the retention test was scheduled 2 weeks after the post-test.

Pre, post, and retention tests. Participants sat 60 cm from the Eyelink II display monitor (60Hz). The horizontal and vertical extents of the monitor subtended $30 \times 24^\circ$ of visual angle respectively (screen size = 338×270 mm). Following fitting and calibration of the gaze-registration system, an experimenter informed the participant of their task. Specifically, participants were told that a series of video clips of 5-on-5 basketball game play would be shown that would be occluded at a critical decision-making point. Participants were asked to indicate as quickly and as accurately as possible which player was best positioned to receive a pass by clicking the ball shaped cursor on the precise screen location where the

chosen player was standing at the time the video was occluded. Prior to testing, participants were given 15 practice trials to familiarize themselves with the test procedure and with the three types of gaze-contingent manipulations. The practice clips were different from those used in the test proper. Participants then completed 48 test trials (16 trials in each type of test: full vision; moving window; moving mask), with the entire test session, including practice and calibration, taking approximately 40 min to complete. Prior to each trial participants were asked to direct their gaze towards a black fixation target at the center of the display and the gaze position was registered to correct for any drift in calibration.

Training intervention. Forty-eight unique video clips were viewed in a random order in each of the three training sessions (a total of 144 training trials). At the conclusion of each clip participants were asked to respond as they had in the decision-making test; however, unlike in testing, feedback on performance was provided after the participant responded by showing the final frame of the preceding video with the correct answer highlighted.

The fifty participants were randomly assigned to one of four training groups: (i) a *moving-window training* group ($n = 13$) who watched the training clips with clear central vision and gaze-contingent blur in the periphery; (ii) a *moving-mask training* group ($n = 12$) who watched the training clips with gaze-contingent central blur and clear peripheral vision; (iii) a *full-vision training* group ($n = 13$) who watched the training clips with no gaze-contingent display manipulation; and (iv) a *control* group ($n = 12$) who were shown video clips from the NBA ‘All-Star Slam Dunk’ competition in each of the three training sessions without any gaze-contingent display manipulations (and for the same amount of time it took the other groups to watch their video clips, ~ 25 min). None of the clips viewed by the control group during training included a decision-making component. Following each training session, feedback was provided to the participants in the three training intervention groups

regarding their performance during the session (i.e., percentage of correct responses). Each training session, including calibration and feedback, took approximately 40 min to complete.

Dependent Variables and Data Analyses

Performance data. Response accuracy (RA) and response time (RT) were calculated as measures of performance in the pre-test, post-test, retention test, and during the training intervention. Response accuracy was calculated as the percentage of trials where the response of the participant matched the response agreed upon by the expert coaches. Response time was the mean time (in ms) that elapsed from the moment the clip occluded to the time that the participant's mouse click response was registered by the computer.

Gaze behavior data. To evaluate whether the different training interventions systematically influenced gaze behavior, six dependent variables were calculated. First, to determine whether the duration of the visual fixations changed as a result of the training intervention, the *mean fixation duration* (in ms) was calculated for each trial by averaging the duration of all fixations in that trial. Second, as a proxy assessment of whether the breadth of the search changed as a result of training, the *mean saccadic amplitude* (in degrees of visual angle) was determined by calculating the average angular subtense of all saccades in each trial. Third, to assess whether the training altered *where* participants directed their fixations, the distribution of gaze across ten distinct areas of interest (AoI) was assessed for each trial by calculating the *percentage of total viewing time* spent viewing each of the ten areas. The ten areas of interest were: (i) the player in possession of the ball (the ball-carrier), (ii) the defender of the ball-carrier, (iii-vi) each of the four attacking team-mates (from closest to furthest from the ball-carrier), and (vii-x) the matching defenders of the four attacking team-mates (see also Ryu et al., 2015; Ryu, Abernethy, et al., 2013). Fourth, we calculated the *breadth of search relative to the ball-carrier* to examine how widely participants searched relative to the position of the ball-carrier (known to be the most frequently fixated AoI; Ryu

et al., 2015) by taking the average of the distance between the direction of gaze and the centroid for the ball-carrier for each frame in a trial (in degrees of visual angle). Fifth, the *difference in spatiotemporal gaze pattern* from pre-test to post-test and from post-test to retention test was calculated to compare the differences in the position of central gaze between the different tests. The x-y coordinates of gaze were taken for each clip and compared for each frame to the x-y coordinates for the same frame in the corresponding clip (coordinates flipped if the video was flipped). When averaged across frames in each clip, this provided a measure (in degrees of visual angle) of how much the pattern of gaze changed as a result of training. Finally, *gaze entropy* was calculated to assess the degree to which the gaze pattern was organized or randomly distributed across the different tests. For this variable, the number of fixation transitions between the 10 distinct areas of interest was first calculated by producing a first-order transition frequency matrix of $p(i \text{ to } j)$, where i represents the AoI before the transition and j represents the AoI after the transition. These matrices were converted to conditional transition probability matrices of $p(j|i)$, which gives a 1st order Markov process where calculations are made of the probability of fixating on the j th AoI if the previous fixation were to be towards the i th AoI (Allsop & Gray, 2014; Ellis & Stark, 1986). The entropy was calculated using Ellis and Stark's (1986) equation:

$$Entropy = -\sum_{i=1}^n p(i) \left[\sum_{j=1}^n p(j|i) \log_2 p(j|i) \right], i \neq j$$

where $p(i)$ is the zero order probability of fixating on the i th AoI (based on the percentage of total viewing time towards it), $p(j|i)$ is the conditional probability of viewing AoI j if the previous fixation was on AoI i , and n is the number of AoIs (i.e., 10 in the current study). A higher entropy value represents a greater level of randomness in the visual search.

Statistical analyses. The dependent variables measuring *response accuracy*, *response time*, *mean fixation duration*, *mean saccadic amplitude*, *breadth of search relative to the ball-carrier*, and *gaze entropy* were analyzed using separate 4 (Training group: moving-window training, moving-mask training, full-vision training, control) \times 3 (Test occasion: pre-test, post-test, retention test) \times 3 (Test type: full vision in test, moving window in test, moving mask in test) ANOVAs with repeated measures on the last two factors. Separate analyses were used to examine the *difference in spatiotemporal gaze pattern* from pre to post-test and from post-test to retention test using separate 4 (Training group) \times 3 (Test type) ANOVAs with repeated measures on the last factor. The distribution of fixations towards the ten AoIs (*percentage of total viewing time*) were subject to a 4 (Training group) \times 3 (Test occasion) \times 3 (Test type) \times 10 (AoI) ANOVA with repeated measures on the last three factors. In addition, data collected during the training interventions for performance (*response accuracy* and *response time*) and from the two conventional measures of gaze behavior (*mean fixation duration* and *mean saccadic amplitude*) were subject to a 3 (Training group: moving-window training, moving-mask training, full-vision training) \times 3 (Training session: first, second, third) ANOVA with repeated measures on the second factor to check for changes during the training intervention. For all inferential tests, effect sizes were reported as partial eta squared values and Cohen's *d* when appropriate, and a Greenhouse-Geisser correction was applied to the degrees of freedom when the assumption of sphericity was violated. The alpha level for all comparisons was set at $p = .05$.

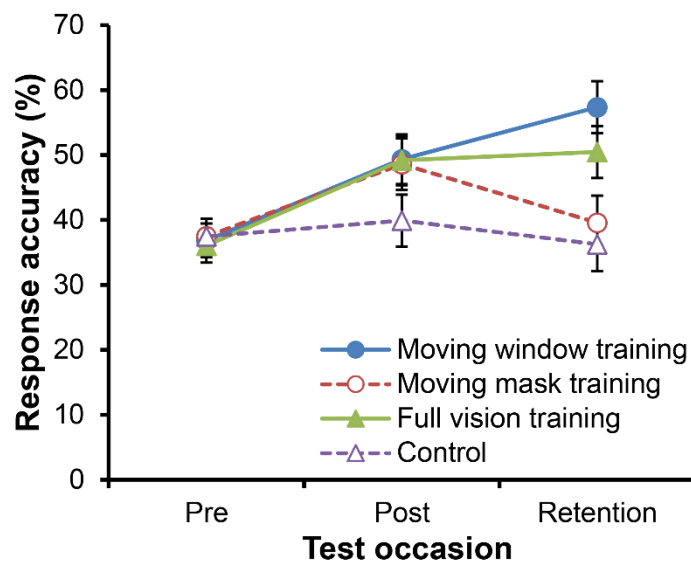
Results

Decision-making performance before and after training

Response accuracy. The *moving window training* group was the best performed of all the training groups (training group \times test occasion interaction, $F(5.28, 80.97) = 5.10, p < .001, \eta_p^2 = .25$; main effect for test occasion, $F(1.76, 80.97) = 19.82, p < .001, \eta_p^2 = .30$).

Figure 2 shows that only the performance of the *moving-window training* group improved both from pre- to post-test ($p = .016$, $d = 0.95$) and from post-test to retention test ($p = .022$, $d = 0.43$). The *full-vision training* group improved from pre-test to post-test ($p = .001$, $d = 1.10$) but not from post-test to retention test ($p = .61$, $d = 0.08$). The *moving-mask training* group improved from pre-test to post-test ($p = .022$, $d = 1.10$) but failed to retain this skill as the RA decreased from post to retention test ($p = .004$, $d = 0.97$). There were no differences in the performance of the *control* group across any of the test occasions ($ps > .24$, $ds < 0.33$). There was no difference in the RA between the groups at post-test ($F(3, 46) = 1.34$, $p = .27$, $\eta_p^2 = .081$); however clear differences were apparent in the retention test ($F(3, 46) = 5.70$, $p = .002$, $\eta_p^2 = .27$). Follow-up t-tests revealed that at retention, the RA of the *moving-window training* group was superior to that of the *control* group ($p < .001$, $d = 1.39$) and the *moving-mask training* group ($p = .004$, $d = 1.13$), whereas the performance of the *full-vision training* group was only greater than that of the *control* group ($p = .018$, $d = 1.12$). There was no difference in the RA between the *moving-window training* group and the *full-vision training* groups in the retention test ($p = .23$, $d = 0.36$).

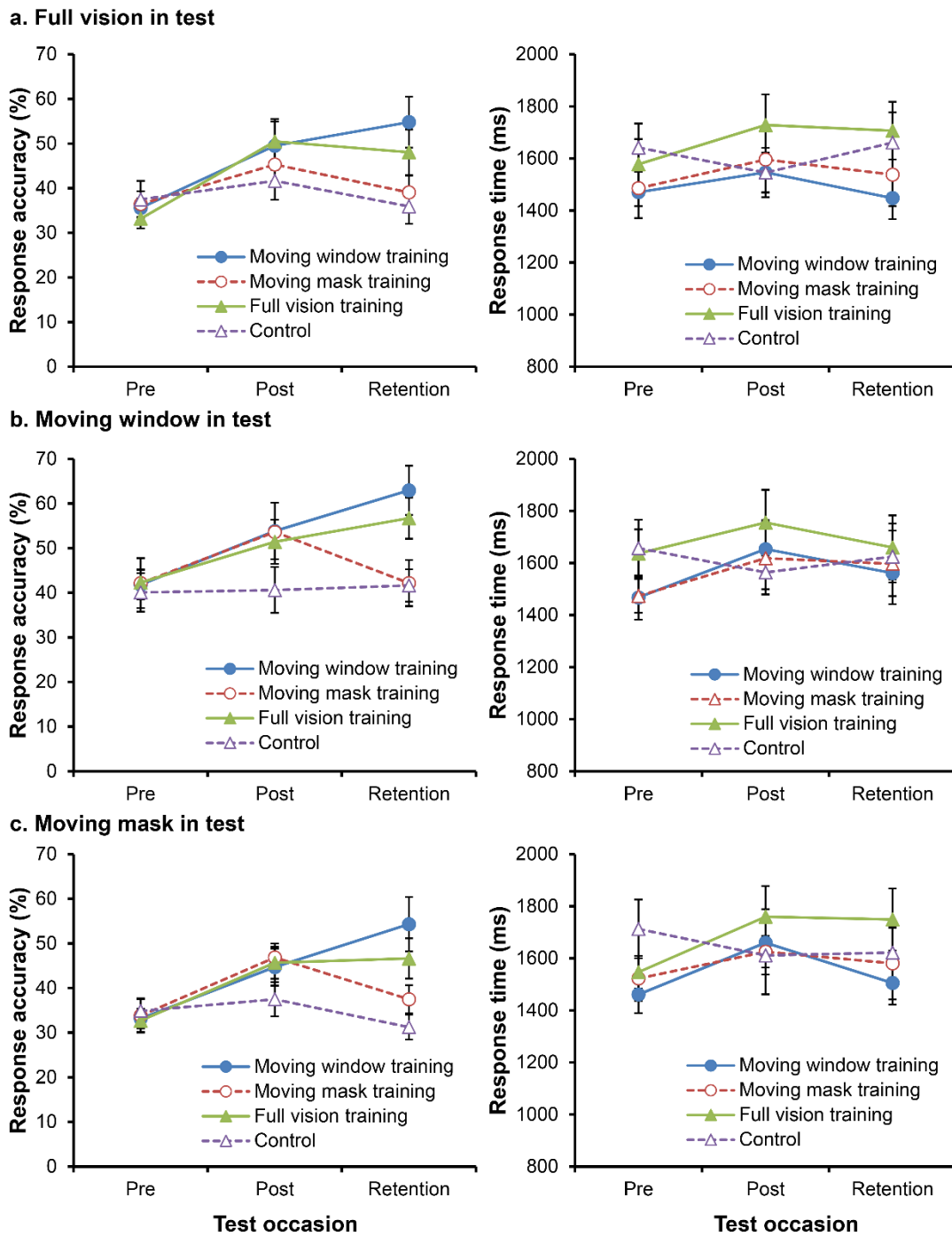
Figure 2



The advantage conferred by *moving-window training* from post to retention test was evident for each of the three different test types (no 3-way interaction, $F(12, 184) < 1$). Figure 3 (left panel) shows the changes in response accuracy for each of the three test types as a function of time of test and training group. A significant main effect for test type ($F(2, 92) = 23.69, p < .001, \eta_p^2 = .34$) highlights that performance, across all of the training groups, was best in the *moving window in test* and worst in the *moving mask in test* (moving window in test > full vision in test, $p < .001, d = 0.41$; full vision in test > moving mask in test, $p = .022, d = 0.22$), reinforcing the advantages offered by the moving window viewing scenario (see Ryu et al., 2015). All other main and interaction effects were non-significant ($ps > .12$), highlighting that the benefits of moving-window training found at retention held irrespective of whether participants were tested when viewing with central, peripheral, or full vision.

Response time. Response times did not change as a result of the training interventions (Figure 3 right panel). There were no main effects for training group ($F(3, 46) < 1$), test occasion ($F(1.55, 71.43) = 2.27, p = .12, \eta_p^2 = .05$), or test type ($F(2, 92) = 1.97, p = .15, \eta_p^2 = .04$), and no significant interactions between any of those factors ($ps > .29$).

Figure 3



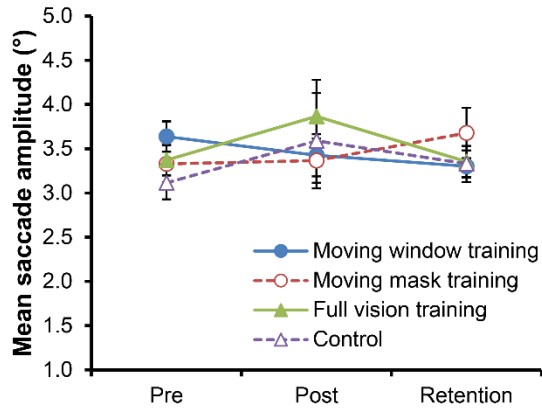
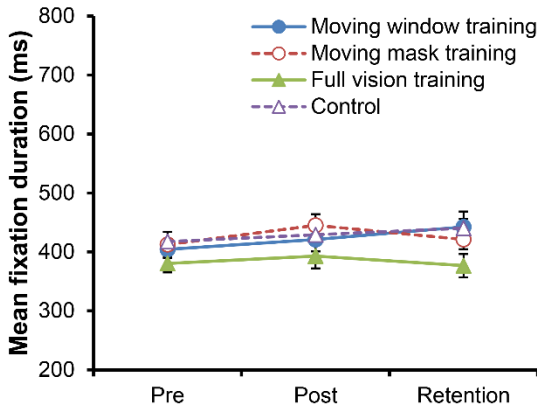
Gaze behavior before and after training

Fixation durations. The type of training performed by participants did not influence the duration of the fixations. Overall, simply taking part in training did result in significant changes in the duration of fixations (main effect of test occasion, $F(1.40, 64.22) = 37.65, p$

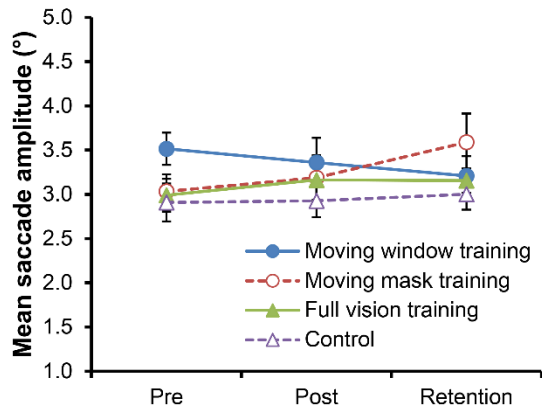
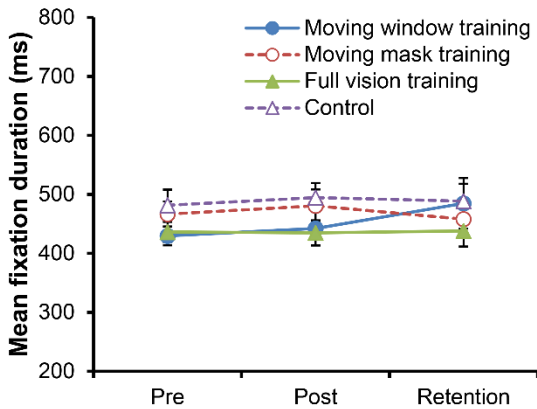
< .001, $\eta_p^2 = .45$); however these changes were not influenced by the nature of the training performed (no test occasion \times training group interaction, $F(5.27, 80.77) = 1.53, p = .19, \eta_p^2 = .091$; see Figure 4 left panel). The different test types also influenced the duration of fixations made by participants (main effect of test type, $F(1.40, 64.22) = 37.65, p < .001, \eta_p^2 = .45$), and this was affected by test occasion (test type \times test occasion interaction, $F(2.66, 122.44) = 4.89, p = .004, \eta_p^2 = .096$; no 3-way interaction, $F(7.99, 122.44) = 1.91, p = .06, \eta_p^2 = .11$; see Figure 5a). Figure 5a summarizes these findings by showing that across all test occasions the duration of fixations was longer in the *moving mask in test* than in the *moving window in test* ($p < .001, d = 0.59$), which in turn was longer than those in the *full vision in test* ($p < .001, d = 0.70$) (for similar findings when viewing static images, see Bertera & Rayner, 2000; Loschky & McConkie, 2000, 2002; Nuthmann, 2014). For the *moving mask in test*, the fixation durations increased from pre to post-test ($p = .02, d = 0.33$), but not from post-test to retention test ($p = .40, d = 0.09$). Similarly, for the *full vision in test* the durations increased from pre to post-test ($p = .04, d = 0.29$), but not from post to retention test ($p = .56, d = 0.06$). In the *moving window in test*, the fixation durations did not change across the test occasions ($ps > .41, ds < 0.12$).

Figure 4

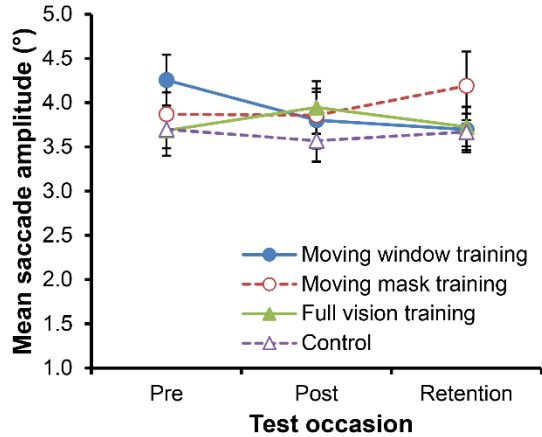
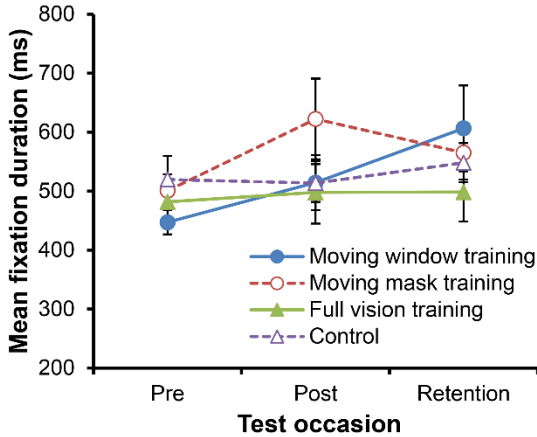
a. Full vision in test



b. Moving window in test



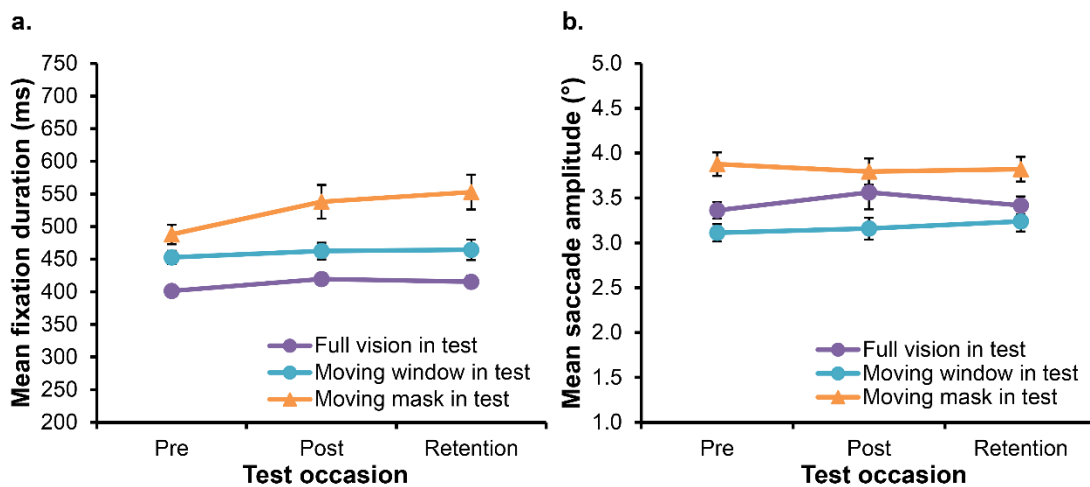
c. Moving mask in test



Mean saccadic amplitude. The mean saccadic amplitude was not influenced by the type of training performed by the participants. When compared to the *full vision in test* condition, saccadic amplitudes were larger in the *moving mask in test* and smaller in the

moving window in test (main effect for test type, $F(2, 92) = 55.08, p < .001, \eta_p^2 = .55$; see Figure 4 right panel and Figure 5b; see also for similar findings when viewing static images, Bertera & Rayner, 2000; Loschky & McConkie, 2000, 2002; Nuthmann, 2014). Further, this relationship was moderated by test occasion (test type \times test occasion interaction, $F(2.25, 103.65) = 3.12, p = .042, \eta_p^2 = .06$; see Figure 5b). The interaction seemed to be primarily the result of a rather inconsequential increase in saccadic amplitude from pre to post-test for the full vision test condition that dissipated by the time of the retention test. The type of training performed by the participants did not moderate any of the relationships (all other main and interaction effects, $ps > .24$).

Figure 5

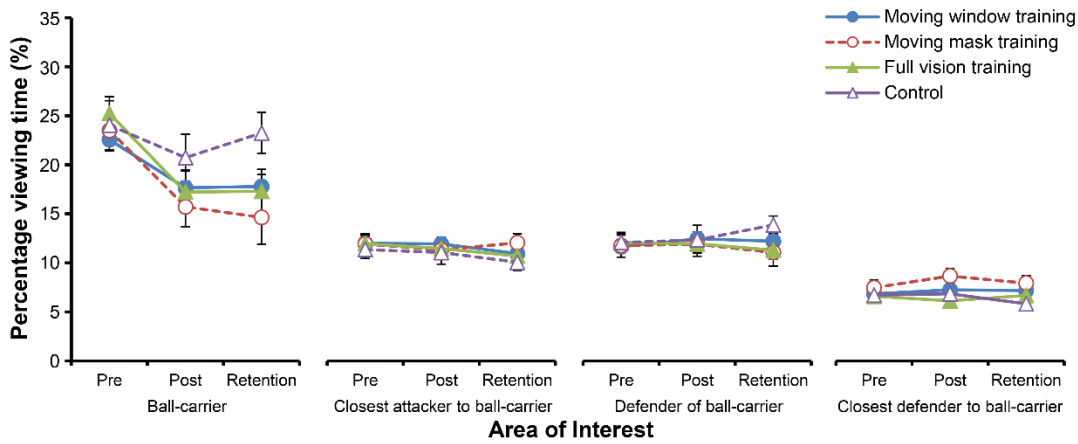


Percentage viewing time. The analysis of the percentage of total viewing time that was directed towards the ten AoIs revealed significant main effects for area of interest ($F(1.51, 69.30) = 360.97, p < .001, \eta_p^2 = .89$), and for test type ($F(2, 92) = 12.17, p < .001, \eta_p^2 = .21$), both of which though were overridden by a significant test occasion \times test type \times AoI interaction ($F(12.35, 567.86) = 2.12, p = .013, \eta_p^2 = .04$; Figure 6). Critically, there were

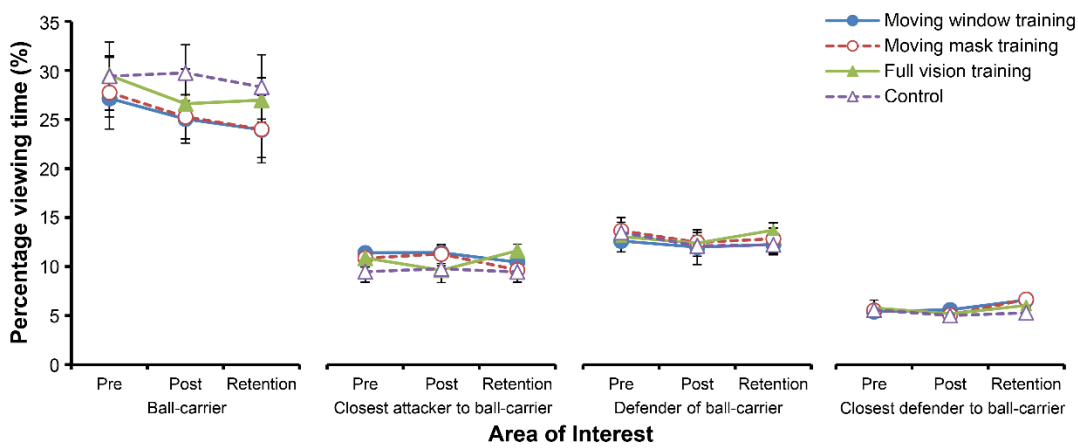
no significant main or interactive effects attributable to training group membership ($ps > .14$). While the ball carrier attracted most fixations in all test types and at all test occasions, Figure 6 shows that the participants spent proportionally more time directing central gaze towards the ball-carrier in the *moving window in test* than for the *full vision in test* ($p < .001$, $d = 1.00$) and *moving mask in test* ($p < .001$, $d = 0.59$). Participants spent proportionally less time directing gaze towards the ball-carrier in the post-test and retention test in the *full vision in test* (both $ps < .001$, $ds > 0.83$) and the *moving mask in test* ($ps < .018$, $ds > 0.47$).

Figure 6

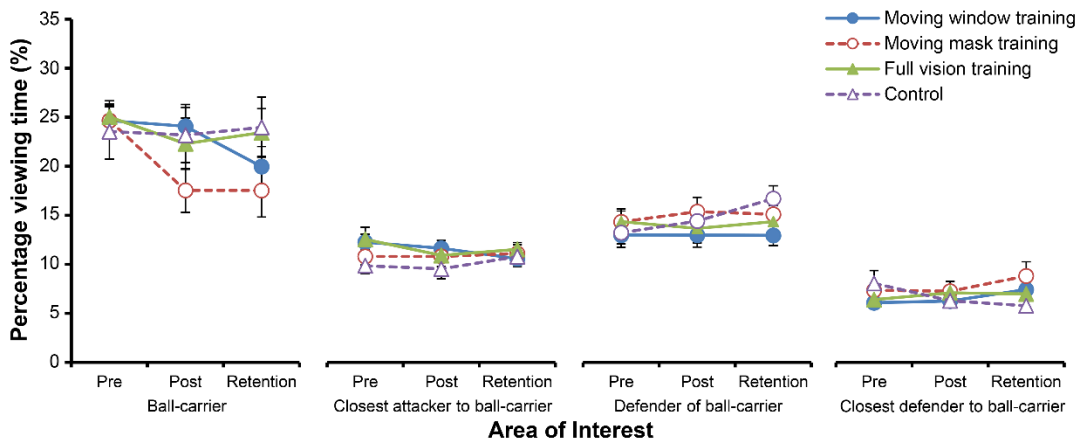
a. Full vision in test



b. Moving window in test



c. Moving mask in test



Breadth of search relative to the ball carrier. The type of training performed by participants did not alter the breadth of the search relative to the ball carrier. Training in general increased the breadth of the search from pre to post-test (pre-test: $4.0^\circ \pm 0.8$, post-

test: $4.3^\circ \pm 0.9$; $p = .008$, $d = 0.38$; main effect for test occasion, $F(2, 92) = 4.96$, $p = .009$, $\eta_p^2 = .10$), but there was no change from post-test to retention test (retention test: $4.3^\circ \pm 0.8$; $p = .71$, $d = 0.16$). In addition, the breadth of the search was significantly greater in the *full vision in test* ($4.5^\circ \pm 0.7$) than it was in the *moving mask in test* ($4.2^\circ \pm 0.8$; $p < .001$, $d = 0.41$) which, in turn, was greater than that in the *moving window in test* ($4.0^\circ \pm 0.9$; $p < .001$, $d = 0.34$; main effect for test type, $F(1.63, 75.16) = 26.63$, $p < .001$, $\eta_p^2 = .37$). All other main and interaction effects were non-significant ($ps > .09$).

Difference in spatiotemporal gaze pattern. The spatiotemporal gaze pattern did not change from pre to post-test or from post-test to retention test. There were no main or interaction effects for any of the comparisons of the spatiotemporal gaze pattern ($ps > .11$).

Gaze entropy. The gaze entropy was significantly greater (i.e. gaze was more random) in the *full vision in test* (2.5 bits \pm 0.2) than it was in the *moving mask in test* (2.3 bits \pm 0.2; $p < .001$, $d = 0.51$) which, in turn, was greater than that in the *moving window in test* (2.2 bits \pm 0.3; $p < .001$, $d = 0.46$; main effect for test type, $F(2, 92) = 61.87$, $p < .001$, $\eta_p^2 = .57$). However, again, these effects were not influenced by the type of training undertaken by the participants (all other main and interaction effects were non-significant, $ps > .07$).

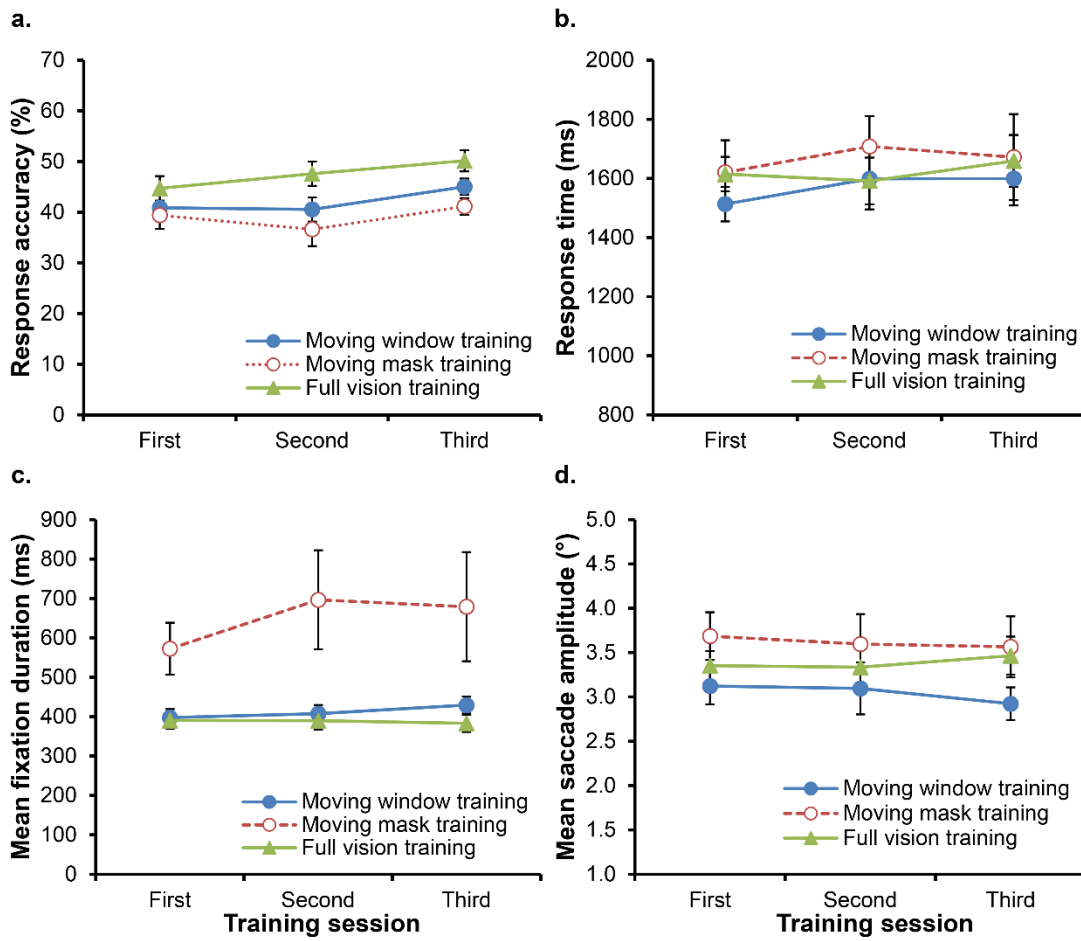
Performance and gaze behavior *during* the three-day training interventions

All results reported to this point compare performance before and after the training intervention. We now turn to a consideration of the results found *during* the three-day training interventions. Figure 7a shows that, as would be expected, the response accuracy increased as a result of training (main effect for training session, $F(2, 70) = 4.94$, $p < .01$, $\eta_p^2 = .12$) and that, consistent with the similar training group improvements observed from pre to post-test, these increases were not moderated by the type of training performed by participants (no training group \times training session interaction, $F(4, 70) < 1$). During the

training, the *full-vision training* group performed better than the *moving-mask training* group ($p = .006$, $d = 0.96$; main effect for training group, $F(2, 35) = 5.69$, $p = .007$, $\eta_p^2 = .25$), while the RA of the *full-vision training* and *moving-window training* groups were not different ($p = .12$, $d = 0.70$). The response times (Figure 7b) did not change as a result of training (no main effect of training session, $F(1.67, 58.48) = 1.63$, $p = .208$, $\eta_p^2 = .04$) and did not differ between the training groups (no main effect for training group, $F(2, 35) < 1$; no interaction between training group and training session, $F(3.34, 54.48) < 1$).

Figure 7c shows that the mean fixation duration of the *moving-mask training* group was significantly longer than that for the *full-vision training* and *moving-window training* groups ($ps < .004$, $ds > 0.85$; main effect for training group, $F(2, 35) = 7.14$, $p = .003$, $\eta_p^2 = .29$); however, these differences did not change as a result of the training (no main effect for training session and no training group \times training session interaction, both $Fs < 1$). The mean saccadic amplitude (Figure 7d) did not change during the training interventions and did not differ between the training groups (all $Fs < 1$).

Figure 7



Discussion

In this study, we sought to determine whether decision-making skill in perceptual-cognitive tasks could be enhanced by training that selectively impaired different areas of the visual field. In particular, we were interested in what might prove to be the best form of training to improve the ability to use peripheral vision when performing a dynamic decision-making task. Given the previous finding that the decision-making performance of inexperienced basketball players temporarily improved while peripheral vision was blurred (Ryu et al., 2015), we hypothesized that training with peripheral blur would be effective in improving decision-making skill even when the gaze-contingent manipulation was removed and participants viewed with full (unrestricted) vision or with only the peripheral segment of

their visual field. To examine this, novice basketball players were randomly assigned to one of four training groups: a moving window, a moving mask, a full vision, and a control group. The findings revealed that all three training groups increased their decision-making performance immediately after the training intervention. However, it was the results in the retention test held two-weeks after the post-test that revealed the decisive differences between the groups. At retention, the decision-making performance of the moving-window training group who trained with blurred peripheral vision was clearly superior to that of the moving-mask training group that trained with blurred central vision. And although the decision-making performance of the moving-window group was not superior at retention to that of the group that trained with full vision, it was only the moving-window training group that benefited from ‘offline’ gains in performance, that is, continued improvement from post-test to retention test. Despite training when viewing with only clear central vision, the improvements of the moving-window training group from pre to post-test and from post to retention test held irrespective of whether they were tested using central vision, peripheral vision, or the full visual field (i.e., benefits generalized across all viewing conditions). Moreover, their changes in performance were not underpinned by any distinctive alterations to the visual search strategy when compared to the other training groups. Taken together the findings imply that the performance gains of the moving-window training group were the result of superior information pick-up, which generalized across the whole visual field, suggesting that training with blurred peripheral vision improved the ability of less-skilled players to use both their central *and* peripheral vision.

The advantageous nature of training with peripheral blur

Consistent with other perceptual training studies (Abernethy, Schorer, Jackson, & Hagemann, 2012; Hagemann et al., 2006; Ryu, Kim, et al., 2013), evidence was accrued in this study to demonstrate that repeated practice when viewing decision-making clips is

valuable in improving decision-making skill. As Figure 3 (left panel) reveals, all three groups who trained with decision-making scenarios significantly improved their response accuracy from pre-test to post-test whereas the control group, who viewed videos but not of decision-making scenarios, showed no such improvement.

Our *a priori* prediction, extrapolated from the findings from the Ryu et al. (2015) study, was that following training the *moving-window training* group would demonstrate a greater capability for decision-making compared to any of the other training groups. In particular, we expected that moving-window training rather than moving-mask training would lead to improvements in the ability to use peripheral vision when performing the decision-making judgments. The results from the measures of decision-making accuracy collected in this study were largely consistent with these predictions. However, it was the contrast from post-test to retention test that revealed the crucial differences between the three key training groups. The performance of both the *moving-window training* and *full-vision training* groups was better than that for the *control* group in the retention test, and although there was no significant difference between the retention test performance of the *moving-window training* and *full-vision training* groups, it was only the *moving-window training* group who *improved* their performance from post to retention test. While the *moving-mask training* group was able to improve their decision-making as a result of the particular type of training they received, their retention test results suggest that any benefits accrued in the post-test were lost two weeks later by the time of the retention test. Consistent with our hypothesis, the retention test revealed that moving-window training led to an improvement in decision-making when using peripheral vision (in the *moving mask test*) that was not apparent for the *moving-mask training* group. However, it is not clear whether the peripheral restriction applied during moving-window training would lead to long-term benefits in the use of peripheral vision beyond those possible via normal full-vision training.

Are training benefits specific or transferable?

In this study decision-making performance was tested, on all three occasions, using three different test types: a *full vision test*, a *moving window test*, and a *moving mask test*. The full vision test provided the criterion condition upon which the true efficacy of the different training interventions was best judged. The other conditions were included to assess the specificity/transferability of training effects. If training benefits are highly specific, improvements in the performance of the *moving-window training* group may be expected to be restricted primarily to the moving window test (that mirrors the kind of experience accrued by that particular group in training) and, for the same reason, improvements in the performance of the *moving-mask training* group may be expected to be restricted primarily to the moving mask test. Conversely if training benefits are generalizable and transfer across the different sections of the visual field then performance improvements for each particular training group might be expected to show on all test types and not just the one that most closely mimics their training experience.

The findings from this study point very strongly to the generalizability of the training benefits accrued by all of the training groups – the training effects were transferable with respect to information pick-up from either central and/or peripheral vision. If the moving-window training intervention had instead simply taught participants to attend to information in the central visual field while ignoring peripheral information (without any underlying improvement in information pick-up), then post and retention test improvements should have been found when viewing with only central vision and with the full visual field, but not when viewing with only peripheral vision when the central information available was restricted (in fact, performance should have decreased). This was not the case. Rather, the training experienced by the *moving-window training* group provided benefits not just to their ability to use central vision, but also their capability to make decisions when information was

available across the full visual field, and even when information was available to only the peripheral field of view in the moving mask test. This shows that the attenuation of peripheral information during moving-window training led to better decision-making skill that could subsequently be utilized across the breadth of the visual field.

Do the different training methods alter gaze in unique ways?

The measures of gaze behavior provide an indication of the visual search strategy used by participants in the different training groups when making decisions. One of the most compelling features of the analyses of gaze in this study was that the type of training experienced (i.e., training group membership) had no measurable impact on any of the gaze parameters that we measured. The different test conditions that were used influenced some elements of gaze, and some measures did change from test to test, but these remained unaffected by whether participants had experienced moving-window training, moving-mask training, full-vision training, or indeed no decision-making training at all.

The impact that the *type of test* had on gaze was largely consistent with the observations described in the Ryu et al. (2015) study (using the same stimuli), and in other studies that have employed gaze-contingent displays (but used other visual stimuli). The participants narrowed their pattern of visual search (with shorter saccades) in the *moving window test* (for similar findings when viewing static images, see Bertera & Rayner, 2000; Cornelissen, Bruin, & Kooijman, 2005; Loschky & McConkie, 2000, 2002; Nuthmann, 2014), and used a more expansive search strategy (with larger saccades) in the *moving mask test* (Figure 4; see also Cornelissen et al., 2005; Loschky & McConkie, 2002; Nuthmann, 2014). This indicates that the search strategies were adapted as the participants explored ways to compensate for the restrictions specific to the different areas of the visual field. Fixation durations were higher for all participants in the *moving window in test* and *moving mask in test* (when compared to the *full vision in test*; Figure 5a), consistent with there being an

increase in processing time necessary to account for the gaze-contingent display manipulations (Bertera & Rayner, 2000; Loschky & McConkie, 2000, 2002; Nuthmann, 2014). However, again the crucial finding was that the type of training that participants had undertaken did not moderate any of these effects. The characteristics of the visual search patterns did not differ between groups even when that training provided extensive exposure to the moving window or mask manipulations.

What are the underlying mechanism(s) for improved decision making with peripheral blur?

A crucial observation from this study was that there were clear differences in decision-making as a result of the type of training experienced yet there were no associated differences in gaze behavior. If the improvements in decision-making performance seen as a result of training had been attributable to a more efficient pattern of gaze behavior then we would have expected to see clear differences between the groups in the measures of gaze behavior in the post- and retention tests. This was not the case. As a result, this suggests that the improvements in decision-making performance that were observed are likely attributable to a generalized improvement in the ability to pick-up task-specific information that could then be applied across the whole of the visual field. Training with peripheral blur may have facilitated this pick-up through the guidance of attentional focus towards the critical central cues in the scene. The capacity of inexperienced participants to contemporaneously attend to central and peripheral visual information is most probably limited, and so we propose that the success of the moving window training is most likely attributable to the attenuation of peripheral demands and distractions. In doing so, the moving window training encourages attention to be aligned with central vision (although it does not necessarily force the two to be aligned, see Ryu, Abernethy, et al., 2013), increasing the likelihood of attention being

allocated towards the more informative regions of the visual field (Lingnau, Schwarzbach, & Vorberg, 2010).

It is important to note that the effect of training with peripheral blur in this study was tested on participants who possessed only limited basketball experience and so the training benefits could be very specific to participants of this skill level. It is likely that the participants in our study possessed only a limited knowledge base to support the pick-up of the requisite information required to do well on this basketball-specific decision-making task. The imposition of peripheral blur may have expedited the ability of the less-skilled players to pick-up salient information. However, more skilled players who already possess the requisite knowledge may be less likely to benefit from such an intervention. Instead, *moving-mask* training that forces participants to rely on peripheral vision and probably requires observers to apply their existing knowledge base to an area of the visual field that they may be less accustomed to using, may well prove to be a more advantageous form of training for skilled players.

One could argue that an alternate explanation for the training effect found in this study is that the peripheral blur could have *enhanced* the pick-up of peripheral information. We used blur rather than completely opaque occlusion to obscure selective areas of the visual field in an effort to limit information pick-up while still allowing sufficient peripheral information to guide the selection of subsequent fixation location(s) (see also Loschky & McConkie, 2000, 2002; Nuthmann, 2014). However, blur has been found, in some circumstances, to *enhance* the ability of observers to perceive movement (di Lollo & Woods, 1981; Jackson, Abernethy, & Wernhart, 2009; Luria & Newacheck, 1992; Mann, Abernethy, & Farrow, 2010). For instance, Jackson et al. (2009) found that a high level of full-field blur increased the ability of skilled tennis players to anticipate the direction of an opponent's tennis serve. Similarly, Mann et al. (2010) found that full-field blur increased the capability

of inexperienced cricket batters to verbally anticipate the direction of cricket balls bowled towards them. It could be argued that, in the present study, the peripheral blur altered the pick-up of peripheral information rather than (or possibly in addition to) attenuating attention; for instance, by removing potentially distracting background information to leave only vision of the key information of relative player position. But there are at least two reasons to think that this is unlikely. First, in the studies by Jackson et al. (2009) and Mann et al. (2010), visual blur was applied to the full visual field rather than to one sector of the field. It was reasoned in those studies that the improvements in performance could have been attributable to the attenuation of high spatial frequency information, particularly in central vision. Clearly that is not the case in our study as blur was only applied to the peripheral field (which can resolve only lower spatial frequencies). Benefits in the present study (and in Ryu et al., 2015, Experiment 4) have only been observed when the central field was clear and the *periphery* was blurred. In fact, training with central blur was detrimental when compared to the control training performed with normal full vision. A second explanation is that, if peripheral blur were to enhance peripheral information pick-up, then one should expect pick-up to be possible when viewing with only blurred peripheral information (i.e., with no central vision). This is clearly not the case. In Experiment 4 in the study by Ryu et al. (2015), it was found that when viewing with only peripheral vision (i.e., when central vision was fully opaque), the decision-making performance of inexperienced participants was no better than chance, and performance did not improve irrespective of the level of peripheral blur applied. Evidently the peripheral blur appears unlikely to have aided the pick-up of peripheral information in a way that could explain the improved decision making performance found in this study.

Why were the crucial differences in performance found from post-test to retention test?

The mechanism by which the *moving-window training* group improved from post- to retention test poses a residual issue for which we see at least two possible explanations. First, it is not completely uncommon to observe offline gains in performance after a period of time without training (e.g., Stickgold, 2005; Telgen, Parvin, & Diedrichsen, 2014; Wright, Rhee, & Vaculin, 2010). These improvements are particularly observed in studies of implicit learning where skills are acquired using approaches that minimize the concurrent accumulation of verbalisable (declarative) knowledge about how the task is performed. In these studies it is reasoned that implicit forms of learning are more likely to be resistant to forgetting and as a result engender better skill retention or even skill improvement (e.g., Allen & Reber, 1980). For instance, Abernethy et al. (2012) compared the efficacy of four different methods of perceptual training (viz., explicit learning, verbal cueing, colour cueing, and implicit learning) and found that the training group that experienced implicit learning improved their performance in a retention test held *five months* after the post-test, an improvement that was not achieved by any of the other training groups. Rendell, Masters, Farrow, and Morris (2011) found similar offline gains in the performance of a *motor* task that was learned while experiencing high contextual interference (i.e., where two or more different skills were learned concurrently and sequenced in a random manner), a form of learning thought to be implicit in nature. But why would a moving window encourage an implicit form of learning whereas a moving mask or full visual field would not? One possible explanation is the way that the gaze-contingent manipulation forced gaze and attention either into or out of alignment. For participants in the *moving-window training* group, the removal of peripheral information ensured that gaze and attention were likely to be aligned. As a result, any conscious reallocation of attention towards the periphery was unnecessary and unlikely to be beneficial. Participants in the *full-vision training* group did have the opportunity to dissociate gaze and attention and in doing so may have required conscious

thought to redirect attention peripherally. Finally, participants in the *moving-mask training* group were consistently required to dissociate their attention from their direction of gaze during training. If they wanted to direct attention towards a particular area of the visual field then they were required to target their gaze towards a different area of the visual field. This may have led to a very explicit form of processing, with participants consistently required to consciously think about the direction in which their gaze needed to be directed. Taken together, the degree to which attention and gaze were dissociated are likely to have influenced the level of conscious thought engaged during the training, and as a result this may have influenced skill retention. Such a hypothesis could be verified by the inclusion of manipulation checks thought to be confirmatory for implicit learning in future experiments (e.g., stress tests, verbal reports of explicit knowledge, or long-term retention tests).

A second potential explanation for the improvement from post-test to retention test is that the post-test itself could have functioned as a re-calibration/additional learning opportunity (as it provided 16 clips of full vision with both central and peripheral vision available) but that this opportunity was only able to be used by those training groups who had already acquired the requisite ability to use central vision. For the *full-vision training* group (who have trained with full vision throughout), the availability of some further trials with full vision in the post-test probably did not assist them (the test experience provided nothing new) and therefore their performance did not change from post-test to retention test. For the *moving-window training* group, the training condition likely facilitated greater focal attention towards central cues. This underpins improvement from the pre-test to the post-test; however, there was no opportunity to calibrate the improved central pick-up with concurrent (clear) peripheral information. The availability of some full vision trials in the post-test may have provided an opportunity to do so and this then could explain the improvement from post-test to retention test. For the *moving-mask training* group, the training condition provided no

stimulus or opportunity for central vision learning. Consequently, for that particular training group, there might not have been the primed base to benefit from the availability of the full vision trials in the post-test in a way that was comparable to that enjoyed by the *moving-window training* group. The inclusion of full vision trials into a moving-window training program would help to establish whether this possible explanation holds true.

Future challenges

The somewhat counter intuitive nature of the findings from this study pose new and interesting questions for those who seek to understand and/or train perceptual-cognitive skill in dynamic tasks. The first relates to the optimal design of gaze-contingent perceptual-training interventions. In our study the intervention period was relatively short (three sessions of ≈ 25 mins) and it is likely that participants had not maximized their possible learning benefits by the end of the intervention (Figure 7a). Therefore, our results may not fully reflect the full extent of the benefit of moving-window training. Empirical work that uses longer intervention periods is required to verify this claim. As discussed in the previous section, the mechanism underlying the continued improvement of the moving-window group from post-test to retention test also warrants exploration.

From a more practical standpoint, it is imperative to test whether perceptual skill gains off-court transfer to improved decision-making in competition. Successful on-field transfer has been demonstrated in perceptual-training studies designed to enhance *anticipatory skill* in less-skilled (Farrow & Abernethy, 2002; Williams, Ward, Knowles, & Smeeton, 2002) and highly skilled athletes (Hopwood, Mann, Farrow, & Nielsen, 2011), but it remains unclear to what degree video-based decision-making training might improve on-field performance. One limiting factor is that perceptual-training studies necessarily rely on highly representative and structured scenarios that ensure there is an agreed best response to unambiguously measure decision-making proficiency. Yet scenarios in matches are not

always so highly structured and the correct decision is not always so clear-cut. It remains unclear whether the improvements evidenced in our study are restricted to structured scenarios, or would generalize to situations where the decision about who to pass the ball to (and when) might not be as obvious. Practical matters of this kind can be examined in more ecologically valid simulations where the player must couple an action to a decision (e.g., Bruce, Farrow, Raynor, & Mann, 2012), and/or by the analysis of match statistics designed to evaluate the success of decisions made in real matches (e.g., Bruce, Farrow, Raynor, & May, 2009).

Conclusions

This study used the gaze-contingent paradigm in an attempt to determine whether perceptual training when viewing with the selective impairment of different areas of the visual field would lead to a superior means of training perceptual skill. The findings highlight that training with a moving window of clear central vision and blurred peripheral vision provides a promising means of training decision-making skill in dynamic externally-paced activities, and in particular, in improving the ability to use peripheral vision when performing these tasks. The moving-window training group demonstrated advantages in information extraction that held irrespective of test type, indicating that the training effects were generalizable to when viewing with full unrestricted vision and not just restricted to when viewing with a moving window. As a result, this approach appears to offer a useful means of modifying information pick-up in a manner that is beneficial for decision-making. These results suggest that, at least for task novices, there are benefits in adopting training approaches that force attention and gaze into alignment to help effectively enhance decision-making skills.

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References

- Abernethy, B. (1991). Visual search strategies and decision-making in sport. *International Journal of Sport Psychology*, 22, 189-210.
- Abernethy, B., & Russell, D. G. (1987). The relationship between expertise and visual search strategy in a racquet sport. *Human Movement Science*, 6, 283-319. doi: 10.1016/0167-9457(87)90001-7
- 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, 143-153. doi: 10.1037/a0028452
- Abernethy, B., Thomas, K. T., & Thomas, J. R. (1993). Strategies for improving understanding of motor expertise. In J. L. Starkes & F. Allard (Eds.), *Cognitive issues in motor expertise* (pp. 317-356). Amsterdam: Elsevier.
- Abernethy, B., Wann, J. P., & Parks, S. (1998). Training perceptual-motor skills for sport. In B. C. Elliott (Ed.), *Training in sport: Applying sport science* (pp. 1-68). Chichester: Wiley.
- 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, 313-318. doi: 10.1080/02701367.1999.10608050
- Allard, F., Graham, S., & Paarsalu, M. E. (1980). Perception in sport: Basketball. *Journal of Sport Psychology*, 2, 14-21.
- Allard, F., & Starkes, J. L. (1980). Perception in sport: Volleyball. *Journal of Sport Psychology*, 2, 22-33.
- Allen, R., & Reber, A. S. (1980). Very long term memory for tacit knowledge. *Cognition*, 8, 175-185. doi: 10.1016/0010-0277(80)90011-6

- 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*, 63-71. doi: 10.1016/j.jarmac.2014.04.010
- Bellenkes, A. H., Wickens, C. D., & Kramer, A. F. (1997). Visual scanning and pilot expertise: The role of attentional flexibility and mental model development. *Aviation, Space, and Environmental Medicine, 68*, 569-579.
- Bertera, J. H., & Rayner, K. (2000). Eye movements and the span of the effective stimulus in visual search. *Perception & Psychophysics, 62*, 576-585. doi: 10.3758/bf03212109
- Bruce, L., Farrow, D., Raynor, A., & Mann, D. (2012). But I can't pass that far! The influence of motor skill on decision making. *Psychology of Sport and Exercise, 13*, 152-161. doi: 10.1016/j.psychsport.2011.10.005
- Bruce, L., Farrow, D., Raynor, A., & May, E. (2009). Notation analysis of skill expertise differences in netball. *International Journal of Performance Analysis in Sport, 9*, 245-254.
- Cañal-Bruland, R., Lotz, S., Hagemann, N., Schorer, J., & Strauss, B. (2011). Visual span and change detection in soccer: An expertise study. *Journal of Cognitive Psychology, 23*, 302-310. doi: 10.1080/20445911.2011.496723
- Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215-281). New York: Academic Press.
- 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.

- Cornelissen, F. W., Bruin, K. J., & Kooijman, A. C. (2005). The influence of artificial scotomas on eye movements during visual search. *Optometry and Vision Science*, *82*, 27-35.
- Crundall, D., Underwood, G., & Chapman, P. (1999). Driving experience and the functional field of view. *Perception*, *28*, 1075-1087. doi: 10.1068/p2894
- Crundall, D., Underwood, G., & Chapman, P. (2002). Attending to the peripheral world while driving. *Applied Cognitive Psychology*, *16*, 459-475. doi: 10.1002/acp.806
- Damron, C. F. (1955). Two and three-dimensional slide images used with tachistoscopic training techniques in instructing high school football players in defenses. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *26*, 36-43. doi: 10.1080/10671188.1955.10612797
- di Lollo, V., & Woods, E. (1981). Duration of visible persistence in relation to range of spatial frequencies. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 754-769. doi: 10.1037/0096-1523.7.4.754
- Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review*, *66*, 183-201.
- Ellis, S. R., & Stark, L. (1986). Statistical dependency in visual scanning. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *28*, 421-438. doi: 10.1177/001872088602800405
- Farrow, D., & Abernethy, B. (2002). Can anticipatory skills be learned through implicit video-based perceptual training? *Journal of Sports Sciences*, *20*, 471-485. doi: 10.1080/02640410252925143
- Farrow, D., & Abernethy, B. (2003). Implicit perceptual learning and the significance of chance comparisons: a response to Jackson. *Journal of Sports Sciences*, *21*, 511-513. doi: 10.1080/0264041031000101827

- Farrow, D., Chivers, P., Hardingham, C., & Sachse, S. (1998). The effect of video-based perceptual training on the tennis return of serve. *International Journal of Sport Psychology, 29*, 231-242.
- Gorman, A. D., Abernethy, B., & Farrow, D. (2011). Investigating the anticipatory nature of pattern perception in sport. *Memory & Cognition, 39*, 894-901. doi: 10.3758/s13421-010-0067-7
- Gorman, A. D., Abernethy, B., & Farrow, D. (2012). Classical pattern recall tests and the prospective nature of expert performance. *The Quarterly Journal of Experimental Psychology, 65*, 1151-1160. doi: 10.1080/17470218.2011.644306
- Gorman, A. D., Abernethy, B., & Farrow, D. (2013). Is the relationship between pattern recall and decision-making influenced by anticipatory recall? *The Quarterly Journal of Experimental Psychology, 66*, 2219-2236. doi: 10.1080/17470218.2013.777083
- Grant, E. R., & Spivey, M. J. (2003). Eye movements and problem solving: Guiding attention guides thought. *Psychological Science, 14*, 462-466. doi: 10.1111/1467-9280.02454
- Hagemann, N., Strauss, B., & Cañal-Bruland, R. (2006). Training perceptual skill by orienting visual attention. *Journal of Sport & Exercise Psychology, 28*, 143-158.
- Henry, F. M. (1968). Specificity vs. generality in learning motor skill. In R. C. Brown & G. S. Kenyon (Eds.), *Classical studies on physical activity* (pp. 328-331). Englewood Cliffs, NJ: Prentice-Hall.
- Hopwood, M. J., Mann, D. L., Farrow, D., & Nielsen, T. (2011). Does visual-perceptual training augment the fielding performance of skilled cricketers? *International Journal of Sports Science & Coaching, 6*, 523-535.
- Jackson, R. C. (2003). Evaluating the evidence for implicit perceptual learning: a re-analysis of Farrow and Abernethy (2002). *Journal of Sports Sciences, 21*, 503-509. doi: 10.1080/0264041031000101818

- Jackson, R. C., Abernethy, B., & Wernhart, S. (2009). Sensitivity to fine-grained and coarse visual information: The effect of blurring on anticipation skill. *International Journal of Sport Psychology, 40*, 461-475.
- Jackson, R. C., & Farrow, D. (2005). Implicit perceptual training: How, when, and why? *Human Movement Science, 24*, 308-325. doi: 10.1016/j.humov.2005.06.003
- Jones, C. M., & Miles, T. R. (1978). Use of advanced cues in predicting the flight of a lawn tennis ball. *Journal of Human Movement Studies, 4*, 231-235.
- Lingnau, A., Schwarzbach, J., & Vorberg, D. (2010). (Un-) Coupling gaze and attention outside central vision. *Journal of Vision, 10*, 13. doi: 10.1167/10.11.13
- Loschky, L. C., & McConkie, G. W. (2000). User performance with gaze contingent multiresolutional displays. In A. T. Duchowski (Ed.), *Proceedings of the 2000 Symposium on Eye Tracking Research & Applications* (pp. 97-103). Palm Beach, FL: ACM.
- Loschky, L. C., & McConkie, G. W. (2002). Investigating spatial vision and dynamic attentional selection using a gaze-contingent multiresolutional display. *Journal of Experimental Psychology: Applied, 8*, 99-117. doi: 10.1037//1076-898x.8.2.99
- Loschky, L. C., & Wolverton, G. S. (2007). How late can you update gaze-contingent multiresolutional displays without detection? *Acm Transactions on Multimedia Computing, Communications, and Applications, 3*, 1-10. doi: 10.1145/1314303.1314310
- Luria, S. M., & Newacheck, J. S. (1992). The effect of defocusing the image on the perception of the temporal order of flashing lights. *Perception, 21*, 359-363. doi: 10.1068/p210359
- Mann, D. L., Abernethy, B., & Farrow, D. (2010). Visual information underpinning skilled anticipation: The effect of blur on a coupled and uncoupled in situ anticipatory

response. *Attention, Perception, & Psychophysics*, 72, 1317-1326. doi:

10.3758/APP.72.5.1317

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, 17, 578-586. doi: 10.3758/BF03203972

Nuthmann, A. (2014). How do the regions of the visual field contribute to object search in real-world scenes? Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 40, 342-360. doi:

10.1037/a0033854

10.1037/a0033854

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, 6, 403-415.

doi: 10.1037/0882-7974.6.3.403

Proteau, L. (1992). On the specificity of learning and the role of visual information for movement control. In P. Luc & E. Digby (Eds.), *Vision and motor control* (Vol. 85, pp. 67-103). Amsterdam: North-Holland.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, 206, 468-469. doi:

10.1126/science.504987

Reingold, E. M., Charness, N., Pomplun, M., & Stampe, D. M. (2001). Visual span in expert chess players: Evidence from eye movements. *Psychological Science*, 12, 48-55. doi:

10.1111/1467-9280.00309

Reingold, E. M., Loschky, L. C., McConkie, G. W., & Stampe, D. M. (2003). Gaze-contingent multiresolutional displays: An integrative review. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 45, 307-328. doi:

10.1518/hfes.45.2.307.27235

- Rendell, M. A., Masters, R. S. W., Farrow, D., & Morris, T. (2011). An implicit basis for the retention benefits of random practice. *Journal of Motor Behavior, 43*, 1-13. doi: 10.1080/00222895.2010.530304
- Ryu, D., Abernethy, B., Mann, D. L., & Poolton, J. M. (2015). The contributions of central and peripheral vision to expertise in basketball: How blur helps to provide a clearer picture. *Journal of Experimental Psychology: Human Perception and Performance, 41*, 167-185. doi: 10.1037/a0038306
- 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. doi: 10.1068/p7487
- Ryu, D., Kim, S., Abernethy, B., & Mann, D. L. (2013). Guiding attention aids the acquisition of anticipatory skill in novice soccer goalkeepers. *Research Quarterly for Exercise and Sport, 84*, 252-262. doi: 10.1080/02701367.2013.784843
- Savelsbergh, G. J. P., van Gastel, P. J., & van Kampen, P. M. (2010). Anticipation of penalty kicking direction can be improved by directing attention through perceptual learning. *International Journal of Sport Psychology, 41*, 24-41.
- Smeeton, N. J., Williams, A. M., Hodges, N. J., & Ward, P. (2005). The relative effectiveness of various instructional approaches in developing anticipation skill. *Journal of Experimental Psychology: Applied, 11*, 98-110. doi: 10.1037/1076-898x.11.2.98
- Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature, 437*, 1272-1278. doi: 10.1038/nature04286
- Telgen, S., Parvin, D., & Diedrichsen, J. (2014). Mirror reversal and visual rotation are learned and consolidated via separate mechanisms: Recalibrating or learning De Novo? *The Journal of Neuroscience, 34*, 13768-13779. doi: 10.1523/jneurosci.5306-13.2014

- Ward, P., Farrow, D., Harris, K. R., Williams, A. M., Eccles, D. W., & Ericsson, K. A. (2008). Training perceptual-cognitive skills: Can sport psychology research inform military decision training? *Military Psychology, 20*, S71-S102. doi: 10.1080/08995600701804814
- Weltman, G., & Egstrom, G. H. (1966). Perceptual narrowing in novice drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 8*, 499-506. doi: 10.1177/001872086600800604
- Williams, A. M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. *Research Quarterly for Exercise and Sport, 69*, 111-128. doi: 10.1080/02701367.1998.10607677
- Williams, A. M., Ward, P., Knowles, J. M., & Smeeton, N. (2002). Anticipation skill in a real-world task: Measurement, training, and transfer in tennis. *Journal of Experimental Psychology: Applied, 8*, 259-270. doi: 10.1037/1076-898x.8.4.259
- Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S. W., Defriend, D., & McGrath, J. S. (2011). Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: A randomized, controlled study. *Surgical Endoscopy, 25*, 3731-3739. doi: 10.1007/s00464-011-1802-2
- Wright, D. L., Rhee, J. H., & Vaculin, A. (2010). Offline improvement during motor sequence learning is not restricted to developing motor chunks. *Journal of Motor Behavior, 42*, 317-324. doi: 10.1080/00222895.2010.510543

Figure captions

Figure 1. Static screenshot of the: (a) full vision, (b) moving window, and (c) moving mask viewing scenarios.

Figure 2. Mean response accuracy of each training group in the pre-test, post-test, and retention test. The data represent values of response accuracy collapsed across all three types of test. Error bars indicate the standard error of the mean.

Figure 3. Mean response accuracy (left) and response time (right) for (a) full vision in test; (b) moving window in test; (c) moving mask in test. Error bars indicate the standard error of the mean.

Figure 4. Mean fixation duration (left) and mean saccadic amplitude (right) for (a) full vision in test; (b) moving window in test; (c) moving mask in test. Error bars indicate the standard error of the mean.

Figure 5. Mean (a) fixation duration and (b) saccadic amplitude for each test type in the pre-test, post-test, and retention test. Error bars indicate the standard error of the mean.

Figure 6. Percentage of total viewing time towards each of four key areas of interest for the (a) full vision in test, (b) moving window in test, (c) moving mask in test for each group. To reduce complexity, only the four most frequently fixated areas of interest are shown: the ball-carrier and their defender, and the teammate closest to ball-carrier and their defender. Error bars indicate the standard error of the mean.

Figure 7. Performance and gaze behavior during training sessions. Figures show changes in (a) response accuracy, (b) response time, (c) fixation duration, and (d) saccadic amplitude for the moving-window training, moving-mask training, and full-vision training groups. Error bars indicate the standard error of the mean.