CURRENT ISSUES IN PERCEPTUAL TRAINING: FACING THE REQUIREMENT TO COUPLE PERCEPTION, COGNITION, AND ACTION IN COMPLEX MOTOR BEHAVIOR

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CURRENT ISSUES IN PERCEPTUAL TRAINING: FACING THE REQUIREMENT TO COUPLE PERCEPTION, COGNITION, AND ACTION IN COMPLEX MOTOR BEHAVIOR

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EDITORIAL
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Editorial: Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior

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Editorial on the Research Topic

Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior

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In highly competitive sports, very little often separates the winner from their opponents. Sport scientists from around the world strive to uncover what it is that characterizes superior performance in these sports and it is these outcomes that hold the potential to further our understanding of human behavior and to optimize the training of skilled and developing athletes alike. Over recent decades, research has shown that *perceptual-cognitive skills* form an integral component of elite performance. More specifically, elite athletes are characterized by superior anticipatory and decision-making skills, are better able to recall sport-specific patterns, and show unique task-specific gaze behaviors (for an overview, see Mann et al., 2007). Studies have shown that perceptual-cognitive training can be effective to improve perceptual-skill and result in improvements in on-field performance (Farrow et al., 1998; Williams et al., 2002; Hopwood et al., 2011).

Despite the early promise shown for perceptual training, the wide variety of different training approaches and experimental designs adopted when evaluating training has resulted in a somewhat haphazard and unsystematic approach that makes comparisons between different approaches difficult (though see Abernethy et al., 2012). This includes inconsistencies in the training duration, frequency, and inclusion of tests of skill retention and transfer. Moreover, there is a lack of clarity about the degree to which perception and action should be coupled during training. Research has predominantly examined simplified training (and testing protocols) that fails to replicate the tight coupling between perception and action that would typically be present in the performance environment (i.e., designs lack *representativeness*). This is important because there is reason to question whether perceptual training would result in transfer if training does not incorporate the (motor) responses, the (visual) stimuli, and the perceptual function required when performing the real-world task (Hadlow et al., 2018).

Given the uncertainty about the training approaches most suitable to improve performance, this Research Topic sought to provide an overview of the past, present, but specifically the future approaches that may be suitable for perceptual training in sport. In doing so, the Research Topic was established to showcase current theoretical and experimental investigations. Scientists investigating all forms of perceptual training were approached and invited to take part, including those who advocate sport-specific approaches through to those that support more generic forms of vision and cognitive training. In the end, 13 papers from a variety of research groups around the world contributed to the Research Topic. Here we summarize those papers, categorizing them into those that tackle questions related to *perceptual-training interventions*, *task representativeness*, and *perception-action coupling*.

PERCEPTUAL-TRAINING INTERVENTIONS

Gray in an ambitious longitudinal study tested the degree of learning possible in baseball batting following training in a virtual environment (VE). To this end, he compared four different groups who practiced either using adaptive VE batting-training (based on challenge-point theory), additional VE batting-practice, additional regular batting-practice, and regular-practice only. The adaptive VE batting-training group outperformed all other groups in the majority of outcome measures and, additionally, showed superior on-field batting performance in the season following the training. This represents one of the first studies demonstrating improvements in on-field performance following training in virtual reality.

Panchuk et al. instead trained athletes using immersive video footage but found only mixed results. They reported that immersive video training improved the decision-making of elite youth basketball players when later tested in the immersive environment, but that there was only limited transfer on-court.

North et al. took a more classic approach to compare the benefits of verbal-guidance and visual-guidance when training pattern recognition in soccer. Results showed that both training interventions improved pattern recall, but that the guidance provided no additional benefit beyond what was possible when simply viewing the same video sequences. Moreover, none of the groups improved their anticipatory ability following training, questioning the link between pattern recall and anticipatory skill.

Schorer et al. investigated the potential benefits of computerized pattern-recall training in combination with normal field-training in soccer. They found some evidence that, when tested with computerized test stimuli, in particular at retention, the experimental group outperformed the active control groups.

Two training studies investigated the potential benefit of blurring vision to enhance perceptual learning. Ryu et al. showed that participants who trained watching video footage containing low-spatial frequencies were less susceptible to deceptive actions when anticipating shuttle shot directions in badminton. Similarly, van Biemen et al. demonstrated a superior capability to distinguish dives from fouls after highly skilled football referees trained while watching blurred video footage of similar scenarios.

Finally, Harris et al. performed a systematic review to investigate the usefulness of commercial generalized cognitive training devices. In summary, they revealed good evidence only for the near transfer of these training devices, with limited evidence of far transfer largely as a result of very few studies that examined athletes, and only one study that investigated transfer to sport tasks.

TASK REPRESENTATIVENESS

When it comes to the representativeness of perceptual training interventions, Renshaw et al. provide a commentary that highlights the necessity to couple perception, cognition and action during training, and critically reviews studies of brain training and perceptual-cognitive training. In sum, they propose a theoretical framework to address these issues by emphasizing the inter-relation between motor processes, cognitive and perceptual functions as well as the constraints of the sport task to be learned.

In a field study, Maloney et al. used a mixed-methods approach to compare the affective and cognitive demands of training and competition in elite Taekwando athletes. They found that the demands of training failed to replicate those of competition, questioning the usefulness of existing training paradigms.

Finally, van Maarseveen and Oudejans studied kinematics and gaze behavior in contested and uncontested basketball jump shots and found significant differences across the two, highlighting the need to include contested shots during jump-shot training. Moreover, *post-hoc* splits of the sample indicated that the better athletes showed more stable gaze behavior than the athletes with worse performance.

PERCEPTION-ACTION COUPLING

The final three studies examined how the degree of coupling between perception and action influenced anticipatory performance and motor learning. Unenaka et al. investigated the effect of concurrent movement during an action-prediction task in basketball free throws. The results showed that only less-skilled athletes exhibited enhanced prediction accuracy, but skilled athletes did not, in an imitative-motion condition which required synchronous right-wrist flexion.

Fukuhara et al. investigated whether the slow-motion presentation of tennis forehand strokes would improve anticipatory judgements of shot direction and position recognition in skilled and novice tennis players. In contrast to expectations, only minor effects were revealed with the highest recognition performance for the experts in the slowest replay speed which, however, was not related to anticipation performance.

Finally, Klostermann and Hossner attempted to tackle the strong but also paradox finding of longer final fixation durations (i.e., Quiet Eye, QE) in experts. To this end, a motor learning study was conducted with the prediction that a large degree of variation in the task during learning would require longer QE durations in post- and retention tests. However, this was not the case, suggesting that rather a small but very dense amount of movement experience required descriptively longer QE durations.

Taken together, this Research Topic demonstrates the impressive breadth of research currently being undertaken but also provides a reminder of the work to be done to develop and test more representative training methods and a more common methodological design to improve our understanding of the optimal means by which to facilitate the acquisition of perceptual-cognitive skills in sports.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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ORIGINAL RESEARCH
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The Role of Verbal Instruction and Visual Guidance in Training Pattern Recognition

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We used a novel approach to examine whether it is possible to improve the perceptual–cognitive skill of pattern recognition using a video-based training intervention. Moreover, we investigated whether any improvements in pattern recognition transfer to an improved ability to make anticipation judgments. Finally, we compared the relative effectiveness of verbal and visual guidance interventions compared to a group that merely viewed the same sequences without any intervention and a control group that only completed pre- and post-tests. We found a significant effect for time of testing. Participants were more sensitive in their ability to perceive patterns and distinguish between novel and familiar sequences at post- compared to pre-test. However, this improvement was not influenced by the nature of the intervention, despite some trends in the data. An analysis of anticipation accuracy showed no change from pre- to post-test following the pattern recognition training intervention, suggesting that the link between pattern perception and anticipation may not be strong. We present a series of recommendations for scientists and practitioners when employing training methods to improve pattern recognition and anticipation.

Keywords: familiarity detection, anticipation, perceptual training, expertise

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INTRODUCTION

The ability to think ahead and anticipate future events consistently distinguishes expert performers from their less-expert counterparts (Triolet et al., 2013). In domains such as the military, aviation, and invasion sports, the importance of anticipation is magnified given the dynamic nature and strict time constraints under which performers must make decisions before executing complex motor skills. The ability to utilize perceptual–cognitive processes to inform decision-making and motor actions has been proposed to be a key factor that distinguishes expert performers from those less-expert across domains (Williams et al., 2011).

At a conceptual level, following extended domain-specific practice, experts develop highly specialized and refined knowledge structures which enable them to disregard non-relevant information and attend to only the most critical cues within the display (cf., Ericsson and Kintsch, 1995). These differences are believed to underpin the expert's ability to identify advance cues in the environment (Savelsbergh et al., 2002), as well as the localized relative motion information between these cues (Diaz et al., 2012), to assess the likelihood of situational probabilities (Farrow and Reid, 2012), and to perceive patterns in displays comprising multiple discrete features

(North et al., 2011). Experts encode information more efficiently and effectively, resulting in quicker and more accurate decisions and superior motor execution when compared with novice or less-expert individuals who have accrued less practice.

Perception and knowledge of patterns is typically assessed using recall and recognition paradigms. In the former, participants must recall the positions of display features after a brief exposure, whereas in the latter familiarity judgments are made as to whether or not stimuli have been previously viewed. The typical finding is that experts show a memory advantage for structured stimuli (representing typical formations that one would expect to see), but that this advantage is lost when attempting to recall or recognize unstructured stimuli (where information is randomly organized). These results were originally reported in the domain of chess (De Groot, 1965; Chase and Simon, 1973; Goldin, 1978, 1979), but subsequently the findings have been replicated across multiple domains including diagnostic imaging (Nodine and Kundel, 1987), business (McKelvie and Wiklund, 2004), and in numerous sports such as basketball (Allard et al., 1980), field hockey (Starkes, 1987), Australian Rules Football (Berry et al., 2004), and soccer (Williams and Davids, 1995). It is believed that the ability to quickly recall or recognize previously encountered situations "buys time" and facilitates more accurate anticipation judgments. In dynamic sports like soccer it is likely that participants will never truly encounter the *exact* same situation more than once; however, it is proposed that the critical features of patterns will remain consistent with some room for variability (see Gobet and Simon, 1996). Expert performers are proposed to perceive and encode these key features and relations in displays when recognizing patterns (North et al., 2017). In other words, judging the current situation against those instances previously encountered allows the observer to assess the most likely courses of action and anticipate effectively in a timely manner.

Practice history data from expert performers reveal that vast amounts of deliberate practice are required over numerous years to attain high levels of perceptual–cognitive–motor expertise (see Ericsson et al., 1993; Williams et al., 2012b). Consequently, researchers have started to consider whether training interventions may be developed that facilitate the more rapid acquisition of perceptual–cognitive skills. The majority of researchers have focused on training advance cue utilization using relatively closed skills such as goalkeepers saving penalty kicks in soccer (Savelsbergh et al., 2010) or players attempting to return serve in tennis (Farrow and Abernethy, 2002). These interventions seek to direct attention toward the most critical cues (as determined from process measures such as gaze behavior and verbal reports) and the effectiveness of this training is assessed by comparing performance post-intervention to an earlier pre-test. In general, these training programs have reported positive findings across sports (e.g., Scott et al., 1998; Williams et al., 2003; Murgia et al., 2014).

Although researchers have highlighted the potential benefit of training perceptual–cognitive skills, at least in micro-situations (i.e., one vs. one), there have been relatively few attempts to train perception of patterns in macro-situations (i.e., full-sided games). The later observation is surprising given the fairly substantive literature base focusing on identifying the processes and mechanisms underpinning this skill (Smeeton et al., 2004; North et al., 2009, 2011). Moreover, the ability to recall and recognize patterns is considered one of the key attributes of expert performers (Abernethy et al., 2005).

In one rare exception, Gorman and Farrow (2009) attempted to train the perception of patterns in basketball. However, these authors failed to report any advantage for their experimental groups over a control group and there was no positive transfer to on-court performance. A potential limitation to their approach was the mode of presentation since the viewing perspective employed during the intervention was different to that experienced in the on-court transfer task, potentially explaining the lack of on-court improvement. Another potential limitation was the use of highly skilled participants only. The majority of researchers who have reported the benefits of perceptual–cognitive training programs have used novice or intermediate performers. The benefits of such training programs may be restricted to, or are optimized in, more novice or intermediate populations.

A challenge when devising perceptual–cognitive training interventions is how to direct attention toward the critical cues. Typically, explicit verbal instructions have been used to focus the learner's attention on the desired display features. A series of "if-then" statements are employed to highlight how these cues related to the eventual event outcome (e.g., see Smeeton et al., 2005). Although these explicit instructional methods have produced positive training effects, it has been argued that the use of such methods can be detrimental in the long term and especially when performing under anxiety (Abernethy et al., 2012). Learning under explicit instruction is thought to result in the development of declarative knowledge, making performers prone to reinvest in this consciously controlled information when under pressure. In contrast, implicit modes of instruction seek to facilitate learning without accruing declarative knowledge, with published reports suggesting that performance is more robust when subsequently performing under pressure given the relative absence of declarative knowledge in which to reinvest (for a review, see Masters, 1992; Jackson and Farrow, 2005; Masters and Maxwell, 2008; Hill et al., 2010). In this paper, our focus was to compare different modes of implicit instruction that guided attention to relevant cues without explicitly stating how these were to be used.

It appears that methods which guide the learner's attention, as opposed to being told explicitly, and permit performers to self-discover and learn independently are the most effective strategies to train perceptual–cognitive skills as they show both short- and long-term advantages. However, there are various means by which the attention of learners can be directed. Although Smeeton et al. (2005) used simple verbal instructions to guide attention, technology allows video footage to be edited so that additional information can be overlaid on top of the footage to direct attention to the pertinent cues. Hagemann et al. (2006) and Abernethy et al. (2012) have used transparent colored masks to highlight critical cues when anticipating shots in badminton and handball, respectively. Moreover, prompts such as arrows may be overlaid on the screen to direct attention (see Ryu et al., 2013). However, the empirical evidence supporting the effectiveness of such methods is equivocal and there is no consensus as to whether one of these strategies is better than the others or if they offer any advantages at all over simply directing attention using verbal instructions (as per Smeeton et al., 2005).

The most effective method of conveying information remains unclear and conflicting results mean there is a need to further investigate the value of perceptual-training programs. In addition, there remains a paucity of research examining whether pattern recognition skill can be trained. Also, while experts may be differentiated from less-expert counterparts on their ability to recognize patterns, it has been argued such a task is only an indirect measure of expertise and not a skill that is explicitly employed in performance contexts. A debate exists as to whether recognition simply represents a by-product of exposure to the domain and does not directly contribute to the expertise they demonstrate in the performance environment (see Ericsson and Lehmann, 1996; North et al., 2009, 2011). In light of this debate, we have participants complete an anticipation test before and after the pattern recognition training intervention to assess if any benefits of training pattern recognition transferred to what may be considered a more representative measure of expertise (cf., Mann et al., 2007).

In sum, we investigate whether it is possible to train the perceptual–cognitive skill of pattern recognition between display features (i.e., players) using soccer as the vehicle. In light of the absence of any significant effects in the study by Gorman and Farrow (2009), which used elite basketball players, we examined whether this skill was amenable to training using a more novice population group. Also, we compared the relative effectiveness of four different instructional methods. Participants were assigned to either a verbal cueing, visual cueing, video only with no cueing, or a control condition. Finally, given recent findings which have suggested recognition skill may not be as closely related to anticipation as previously thought (North et al., 2009, 2011), we examined whether the benefits of training pattern recognition transfers to improvements in anticipation accuracy. Since previously researchers have shown a variety of instructional approaches to be effective in training perceptual–cognitive skill in micro-contexts, we hypothesized that all three experimental conditions would improve recognition performance from pre- to post-test in comparison to a control group. Also, we expected the verbal cueing and visual cueing groups to improve more than the video only group given that their attention was being directed to those features identified as most important in successful recognition judgments (see North et al., 2009, 2011; Williams et al., 2012a). Since only a few researchers have directly tested different instructional methods, producing contradictory results, we had no *a priori* hypothesis as to whether visual or verbal cueing would be more effective in training recognition. As knowledge and awareness of patterns of play has consistently been identified as a characteristic of expert performers (Abernethy et al., 2005; Williams et al., 2006), and even published reports suggesting the skill may not be central to anticipation performance (North et al., 2009, 2011) report positive correlations between the two, our final hypothesis was that successfully training the ability to recognize patterns of play would result in improvements in anticipation accuracy.

MATERIALS AND METHODS

Participants

Altogether, 64 amateur soccer players volunteered to participate. The performance of participants was rank-ordered based on their pre-test recognition accuracy scores, following which participants were then assigned to one of four equally matched groups of $N = 16$: control (*M* age = 19.5 years, *SD* = 2.07); visual attention guided (*M* age = 20.2 years, *SD* = 3.24); verbal instruction guided (*M* age = 19.8 years, *SD* = 3.67); and video only (*M* age = 20.9 years, *SD* = 2.47). Participants were considered as amateurs if they had only played soccer at recreational or school level. Participants reported having played soccer at this level for an average of 9.24 years (*SD* = 2.55). All reported normal or corrected to normal visual function and none reported color blindness. The research was conducted according to the ethical guidelines and approval of the second author's institution. Participants provided written informed consent and were free to withdraw at any stage.

Test Films

We used three different test films. An anticipation test film, a perceptual training test film, and a recognition test film. All test films used video footage which was recorded using a fixed, tripod-mounted video camera (Canon XM-2, Tokyo, Japan) in a raised position (approximate height 9 m) set back behind the goal (approximate distance 15 m). The camera position ensured that all players were visible at all times and that information was not excluded from wide areas. Although the raised viewing perspective is different to that which players would typically experience during game situations, construct-validity has previously been established for the approach. When using the same viewing perspective, expert–novice differences have been reported using recognition (North et al., 2011), recall (Abernethy et al., 2005), situational probability (Ward and Williams, 2003), and anticipation (North et al., 2016) paradigms. All test films comprised of a number of separate clips, each showing a developing pattern of play which culminated in a penetrative attacking pass to a teammate. All the action sequences used showed patterns of play developing in the direction of the camera (i.e., coming toward the participant) and were all "structured" in nature. Clips were classified as being structured on the basis of three expert coaches independently rating a battery of clips as being either low or high in structure using a Likert-type scale (0 = very low in structure, 10 = very high in structure). The clips rated most highly for structure were those judged to be most representative of tactics, strategies, and plans that would typically be observed in attacking play. Only clips with a mean rating above 7 were used.

Recognition Test Films

The action sequences used for the recognition test films were sampled from three English Premier League reserve team matches. The recognition test was comprised of a viewing phase and a recognition phase. Each individual clip in both viewing and recognition phases was 7 s in duration. The initial 2 s showed a static image of the first frame in the sequence, during which participants were cued to the location of the ball by a red circle. The clip then played normally for 5 s, showing a developing pattern of play before it occluded to black. There was then a 3 s inter-trial interval after which the next 7 s clip played in the same fashion. Both viewing and recognition test films contained 40 clips, however, for the recognition test film 20 of these were also present in the initial viewing test film and 20 were novel.

Anticipation Test Film

At the start of each clip in the anticipation phase, participants were shown a freeze-frame of the clip's opening frame for 2 s. During this time, a red circle was shown on the screen to cue participants as to the ball's location. The red circle then disappeared and the clip played normally, showing 6 s of action in which possession started in the defensive half (that furthest away from the participant) and ended in the attacking half (that nearest the participant). Each clip stopped when the player in possession was about to make a penetrative pass to a teammate in an attacking position. The final frame when the clip ended was paused and presented to participants for 2-s, during which time possible passing options were highlighted using red, blue, black, and yellow squares. The clip then occluded to a black screen and the next clip commenced after a 5 s inter-trial interval. In total, there were 24 clips in the anticipation test film with each being presented for a total of 10 s. An example of the first and final frames of a clip used in the anticipation test film is presented in **Figures 1**, **2**.

Perceptual Training Film

The match footage used in the perceptual training films was taken from a sample of two Football Association under 18 years Youth Cup matches. In total, there were 120 clips spread over four perceptual training sessions. Participants were assigned to one of four different perceptual training groups. The precise nature of footage in the perceptual training film was dependent on which group participants were assigned to following the pre-test.

Apparatus

Film clips were presented using a DVD player (Panasonic, DMR-E50, Osaka, Japan) and projector (Sharp, XG-NV2E, Manchester, United Kingdom) to project images onto a 9′ × 12′ screen (Cinefold, Spiceland, IN, United States) at a rate of 25 frames/s with XGA resolution. Verbal instructions were recorded onto a dictaphone and transferred onto test films using video editing software (Adobe Premiere, Adobe Systems Incorporated, San Jose, CA, United States). The same video editing software was used to create the test films and insert freeze-frames in sequences. To highlight the ball and players of interest, the Microsoft Paint Program (Microsoft Corporation 2010, Redmond, WA, United States) was used.

Procedure and Tasks

Participants completed pre- and post-tests to assess anticipation and recognition performance which were separated by 2 weeks. During the intervening 2 weeks, participants completed the perceptual training program spread over four separate sessions, with approximately 2.5 days between each perceptual training session.

Pre-tests

Participants initially completed the recognition test. This involved participants being presented with the viewing test film which comprised of 40 individual clips. Participants were informed that the ball's starting location would be highlighted by a red circle, after which the clip would play normally and show a developing attacking sequence that culminated in a player being about to make a forward attacking pass, but that the clip would occlude before this pass was played. Participants were instructed to watch the clip as if they were playing in the match as a central defensive player, but that no specific response was required. After the viewing film had been presented there was a 10 min comfort break. Participants were then presented with the recognition film which comprised of 40 clips. The participants were told that some of the clips in the recognition film had been included in the viewing phase and that others were novel; their task was to make a recognition decision for each clip as to whether they had seen it in the viewing film or not. Participants were instructed to watch each clip for its full duration before making a recognition response (yes or no) by writing down their answer using pen and paper. When each clip was occluded in the recognition phase, participants were presented with a "Respond Now" image on the screen and were instructed to respond quickly and accurately. The recognition test took approximately 20 min to complete.

After completing the recognition test, participants were provided with another 10 min break during which they completed a short questionnaire that requested demographic information as well as information about their practice history and involvement in soccer. Participants then completed an anticipation test. Participants were informed they would be presented with a further 24 clips showing developing patterns of play, which culminated in a player about to make an attacking pass and that they should watch the clips as if they were a central defensive player. The participants were told that a red circle would highlight the ball's position at the start of the clip before playing and then pausing on the final frame of the sequence. Participants were told that four different passing options would be highlighted using colored circles and that their task was to select the player they thought was most likely to receive the ball by writing down the respective colored circle on a pen and paper response sheet. The final frame was paused for 2 s, after which the message "Respond Now" was presented on the screen. Participants were instructed to respond quickly and accurately. The anticipation test took approximately 10 min to complete.

Perceptual Training

Participants were allocated to one of four equally matched perceptual-training groups based on their pre-test recognition scores. There were four training sessions, each comprising of 30

FIGURE 1 | An example of a freeze-frame shown prior to the onset of a clip with the starting position of the ball indicated by a red circle.

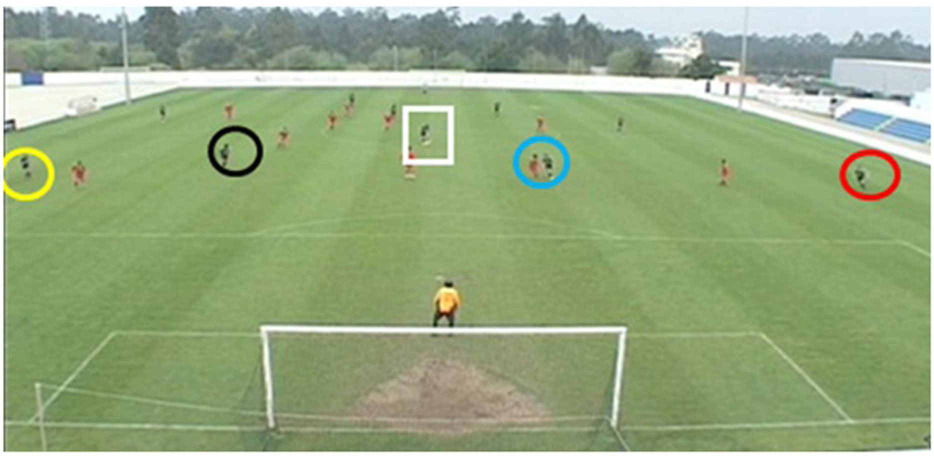

FIGURE 2 | An example of a freeze-frame shown at the end of each clip in the anticipation paradigm with the passing options highlighted by yellow, black, blue, and red circles. Note: White square shown here is for illustrative purposes to highlight ball location and was not used in the actual test film.

clips with an inter-trial interval of 5 s, with each training session taking approximately 20 min to complete. Participants were not required to make any responses during the training sessions, but they were informed to watch the clips and pay attention to any instructions or guidance provided within these session.

Verbal instruction group

When the first frame was presented and "frozen" for 2 s to cue participants to the location of the ball, participants in this group were provided with verbal instructions about where they should direct their attention during the clip. The instruction provided was based on findings reported by Williams et al. (2006) and North et al. (2009), with participants being told to focus their attention on the positions and movements of central attacking players without explicitly stating the purpose of the movements that were to be made or exactly what information this might convey. Generic verbal instructions were provided at the onset of the sequence to focus on these specific players with subsequent verbal instructions individually tailored for each clip. For example, a clip in which two strikers would move in order to create space for another teammate would play as normal after the initial 2 s freeze-frame, before a second freeze-frame would be inserted at an appropriate point in order for verbal instructions to be provided to highlight the specific movements and runs of interest. Once the verbal instructions had been provided the clip resumed and played as normal. Each clip contained 6 s of dynamic activity although the total presentation time varied due to each clip being individually tailored with freeze-frames and additional verbal instructions inserted as appropriate.

Visual guidance group

The clips used, and their order of presentation, were the same as in the verbal instruction training group. During the initial 2 s freeze-frame in which ball location was identified using a

FIGURE 3 | An example of a freeze-frame from the visual attention intervention which highlights ball location and the position and subsequent movement of the two central attacking players.

black circle, participants in this group were cued as to the most important players and where they should direct their attention using red circles (to highlight the players) and red arrows (to highlight their movements). The visual cues to guide attention were all presented during the freeze-frame only so as to avoid potentially obstructing information once clips played normally. To ensure consistency, the same players were highlighted as in the verbal instruction group and each clip was played for the same length of time with the same number of freeze-frames inserted for the same length of time. An example of a freeze-frame from the visual guidance group is shown in **Figure 3**.

Video only group

In this group, participants were presented with the same clips, in the same order, as in the verbal instruction and video guidance groups. As with these groups, participants were initially presented with a 2 s freeze-frame during which the position of the ball was highlighted using a red circle. Participants in this group though received no further information and after the initial 2 s freeze-frame the clip played normally for 6 s before the screen was occluded.

Control group

Participants in this group were not exposed to any training and only completed pre- and post-recognition and anticipation tests.

Post-tests

Participants completed recognition and anticipation post-tests 2 days after the final perceptual training session. The post-test recognition and anticipation tests were conducted following the same procedures used for the pre-tests. To prevent familiarity bias and expectancy effects, the order of presentation for clips was changed from the pre-test and the clips that were repeated in the recognition test film were different to those in the pre-test. Also, the order of clips was changed for the anticipation paradigm.

Dependent Measures and Data Analysis

The data were analyzed based on signal detection theory. This analysis method is used to measure the effectiveness of participants in distinguishing meaningful signals that may be present in displays from non-meaningful noise. Signal detection theory provides two dependent measures which were used to analyze recognition performance; a parametric measure of sensitivity (d') and criterion (c) which is a measure of response bias (Green and Swets, 1966). The measure of sensitivity (d') assesses discriminability: how well two conditions can be distinguished from one another (signal present or absent). The larger the d' value the more sensitive a person is in discriminating between signal present and signal absent stimuli, while a value of 0 indicates chance (i.e., guessing) performance. Criterion (c) measures bias and refers to the extent to which one response (i.e., responding yes or no) is more probable than the other. If the c value is negative it indicates a bias toward "yes" responses (resulting in more "hits," but also more "false alarms"), whereas if c is a positive value then it indicates the participants favor a bias to "no" responses, with fewer hits and fewer false alarms (MacMillan, 2002).

Anticipation performance was measured by dividing the total number of correct judgments by the total number of trials ($n = 24$) and then multiplying by 100 to create a percentage accuracy score. The data for d', c, and anticipation accuracy were analyzed using separate two-way mixed-design ANOVAs in which the between participant factor was Group (verbal instruction vs. visual guidance vs. video only vs. control) and the within participants factor was Time of Test (pre-test vs. post-test).

Prior to conducting the analyses, all data were tested for normality using the Shapiro–Wilks test. Partial eta squared (η_p^2) values are provided as a measure of effect size for all main effects and interactions and, where appropriate, Cohen's *d* measures are reported for comparisons between two means. For repeated measures, violations of sphericity were corrected by adjusting the degrees of freedom using the Greenhouse–Geisser correction when the sphericity estimate was less than 0.75 and the Huynh–Feldt correction when greater than 0.75 (Girden, 1992). The alpha level for significance was set at $p < 0.05$.

RESULTS

Recognition Performance

An analysis of d' revealed a significant main effect of Time of Test on recognition sensitivity, $F(1,60) = 16.53$, $p < 0.05$, $\eta_p^2 = 0.216$. Participants were more sensitive in their recognition decisions at post-test ($M = 0.55$, $SD = 0.5$) than pre-test ($M = 0.37$, $SD = 0.52$), $d = 0.34$. However, the effect of Group, $F(3,60) = 0.49$, $p > 0.05$, $\eta_p^2 = 0.02$, and the Group × Time of Test interaction, $F(3,60) = 1.53$, $p > 0.05$, $\eta_p^2 = 0.07$, was not significant. The mean recognition sensitivity scores for each experimental group at pre- and post-tests are shown in **Figure 4**.

For *c*, ANOVA showed that the effects of Time of Test, $F(1,60) = 0.39$, $p > 0.05$, $\eta_p^2 = 0.01$, Group, $F(3,60) = 0.31$, $p > 0.05$, $\eta_p^2 = 0.02$, and the Group × Time of Test interaction, $F(3,60) = 1.41$, $p > 0.05$, $\eta_p^2 = 0.07$, were all non-significant. These data demonstrate that neither the experimental group or time of test made participants more biased to responding : "yes" or "no" when making recognition decisions.

Anticipation Accuracy

The ANOVA revealed no main effect of Time of Test, $F(1,60) = 3.61$, $p > 0.05$, $\eta_p^2 = 0.06$, or Group, $F(3,60) = 0.22$, $p > 0.05$, $\eta_p^2 = 0.01$. The Group × Time of Test interaction was non-significant, $F(3,60), = 0.41$, $p > 0.05$, $\eta_p^2 = 0.02$.

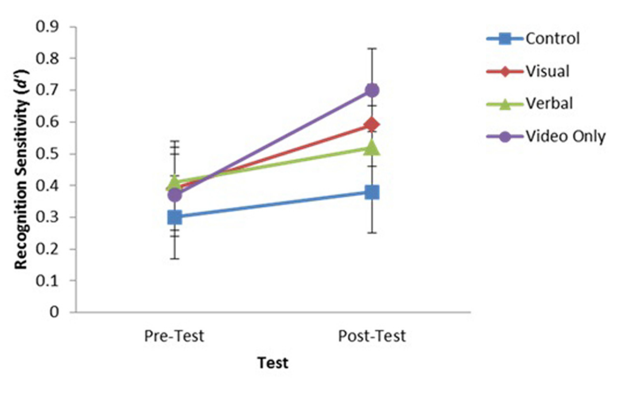

FIGURE 4 | Mean recognition sensitivity (d') with error bars for each experimental group at pre and post recognition tests.

DISCUSSION

In this paper, we had three aims. First, we examined whether participants were able to improve the perceptual–cognitive skill of recognizing patterns between features following a perceptual–cognitive training intervention. Also, we tested the relative effectiveness of different instructional approaches to train this skill. Finally, given debate as to the importance of recognition in anticipation, we examined whether our training interventions, which focused on enhancing pattern recognition would transfer to improvements in anticipation accuracy.

We hypothesized that recognition performance would improve from pre- to post-test (cf., Farrow and Abernethy, 2002; Williams et al., 2003; Smeeton et al., 2005). This hypothesis was supported. Participants became more sensitive in distinguishing previously seen from novel patterns on the post- relative to the pre-test. However, contrary to our second hypothesis, there was no main effect of group and no Group × Time of Test interaction, indicating that the mode of instruction did not affect how well participants learned to recognize patterns. This pattern of findings closely mirrors that reported by Gorman and Farrow (2009) who showed significant improvements from pre- to post-test but reported that the improvements observed in the training groups did not differ when compared with the placebo and control groups. It is often suggested that the absence of significant effects is due to the small sample size and relatively short intervention period. However, in the current study, we present one of the most extensive perceptual training interventions conducted in the literature. The intervention period (2 weeks) was longer than, or comparable to, other studies which have trained perceptual skills and reported significant effects (e.g., 3 days, Abernethy et al., 2012; 7 days, Hagemann et al., 2006; 7 days, Ryu et al., 2013; 3 weeks, Serpell et al., 2011; and 45 min, Williams et al., 2002). Over the course of the intervention period, participants were exposed to 120 training trials which is a higher number than employed in other similar perceptual training studies (e.g., 64 trials, Ryu et al., 2013; 40 trials, Serpell et al., 2011; 8 trials; Williams et al., 2002; and 30 trials, Smeeton et al., 2005).

Our intervention failed to replicate the benefits evident using perceptual–cognitive training programs designed to improve the ability to use advance postural cues. However, perceiving patterns between independent display features (i.e., players) and perceiving advance postural cues (and potentially relations between these interrelated features) are two distinct perceptual–cognitive skills. Perceiving global patterns between features may represent a higher order and more strategic skill, whereas perceiving postural cues could represent a lower-order process. As a consequence, the higher-order, more strategic skills may require an extended training program with more prolonged exposure to stimuli and game patterns in order to see the same extent of performance improvements that are observed when training the ability to perceive more localized cues. In both Gorman and Farrow's (2009) study and the current paper, there are trends in the data (albeit non-significant) for training intervention groups to improve in spite of relatively short-term interventions. Although the duration of our intervention was comparable (or longer) to that reported in other published reports where attempts have been made to train the pick-up of advance postural cues, researchers should seek to undertake more longitudinal interventions to investigate whether the trends observed lead to significant differences over time.

The information we highlighted using our training interventions was driven by research which had identified the central attacking players, and specifically the relative motion between these features, as being the critical information to convey structure and meaning in order to perceive patterns in dynamic, interactive displays (see Williams et al., 2006, 2012a; North and Williams, 2008; North et al., 2009, 2011). However, in seeking to ensure participants were attending to these critical features we provided a lot of detail (either through verbal instruction or visual highlighting) that was tailored to each individual sequence. It is possible we were overly prescriptive with the information provided and unintentionally we may have promoted an explicit style of learning. More pronounced benefits of the intervention may have been seen had participants only had their attention oriented to these features at the outset and then subsequently been allowed to discover the movement patterns and relations for themselves. Such an intervention would have likely promoted a more implicit style of learning, which is considered preferable and more advantageous than learning explicitly (Magill, 1998; Smeeton et al., 2005). Orienting attention toward the most critical features at the outset before subsequently allowing the sequence to play would have the advantage of allowing relative motion information to emerge more clearly. The level of detail we sought to present necessitated that "freeze-frames" be inserted in video sequences, which in itself is likely to have disturbed or distorted the relative motion information emerging. Williams et al. (2012a) have demonstrated that although the relationships between display features are important, specifically it is the relative motion information emerging through dynamic interactions between these features that are critical. The use of "freeze-frames" to highlight features may have served to prevent participants from extracting this critical source of information, in turn impairing their ability to perceive patterns within the displays. An intervention which simply directed attention before allowing sequences to play uninterrupted would both encourage a more implicit style of learning and enhance the potential for the critical relative motion information to emerge.

The highly prescriptive approach used to orientate attention may have resulted in participants adopting a narrow focus of attention (cf., Nideffer, 1976). While a narrow focus of attention can be advantageous in situations where the visual information is largely invariant (Nougier et al., 1991), in dynamic contexts, such as soccer, where visual information is highly variable in nature, a broader focus of attention is considered preferable (Ripoll, 1988). Although the relative motions between central attacking players have been demonstrated as critical information sources, it is likely that participants need an awareness of how these more localized relations fit within the broader and more global pattern.

Our final aim was to examine whether any improvements in pattern recognition would transfer to improvements in anticipation. We did not observe any change in anticipation accuracy from pre- to post-test. Gorman and Farrow (2009) similarly did not report any main effects or interactions. It may be that perception of patterns does not contribute to anticipation, but rather that it is merely a by-product of task experience (cf., Ericsson and Lehmann, 1996), or at the very least its contribution to anticipation is less than has been previously argued. A number of distinct perceptual–cognitive skills contribute to anticipation and decision-making (see Vaeyens et al., 2007; Williams and Ward, 2007; Roca et al., 2013). The relative importance of these perceptual–cognitive skills varies as a function of the task constraints under which one is performing. In soccer, Roca et al. (2013) and North et al. (2016) have demonstrated that when the ball is far away from the performer, they seek to perceive patterns between features to inform their decision-making. In contrast, as the ball moves closer to the performer, attention switches to utilizing postural cues, with perception of patterns between players becoming less important. The stimuli used in the anticipation paradigm in the present study all showed action sequences where the final pass was about to be made in relatively close proximity to the participant. Therefore, the task constraints used in this study may have dictated that participants seek to process postural cues rather than perceive patterns. The nature of the clips (i.e., a raised viewing perspective) is likely to have made it difficult to extract fine postural cues, meaning that while participants may have looked to use this source of information, their ability to do so will have been impaired and so this may explain why anticipation accuracy did not improve. Alternatively, the skill of perceiving patterns between features may not have been required to inform anticipation judgments in this study and may be one explanation for the lack of transfer to anticipation accuracy following the perceptual training intervention. It may also be that the methods employed to examine transfer lack sufficient sensitivity to capture any benefits that may emerge. In future, researchers may wish to consider supplementing the anticipation paradigm used here with some more direct field-based measures of performance using match analysis data or the ratings of expert coaches on *in situ* assessment of anticipation and decision-making using behavioral assessment scales (e.g., see French and Thomas, 1987; Oslin et al., 1998).

When assessing transfer effects, an important factor to consider is viewing perspective. While the raised viewing perspective used in this study has distinguished skilled and less-skilled performers in recall (Abernethy et al., 2005), recognition (Williams et al., 2006), situational probability (Ward and Williams, 2003), and anticipation tasks (North et al., 2016) it nevertheless provides a very different perspective to that which players would encounter on the field. The encoding specificity principle (Tulving and Thompson, 1973) gives reason to be skeptical that any training benefits using such third person perspectives might transfer to field environments given the clear differences in perceptual information during encoding and retrieval processes across these two contexts. A potentially fruitful area for researcher and practitioners is the use of immersive technologies (such as virtual and augmented reality), which can more faithfully represent the perceptual variables experienced in performance environments.

A final potential issue is that all of the conditions employed a perception-only mode of response (i.e., pen and paper). Some researchers argue for the need to ensure perception and action are tightly coupled when studying perceptual–cognitive–motor skills (see Mann et al., 2010) to ensure both ventral and dorsal streams are engaged and that tasks more faithfully represent those undertaken in performance environments. However, there are numerous previous examples whereby perceptual–cognitive skills have been improved using uncoupled training methods (e.g., see Farrow and Abernethy, 2002; Williams et al., 2002) and there is evidence that the motor system remains engaged during perception-only tests (e.g., see Urgesi et al., 2006). Furthermore, in applied contexts, some elite sporting organizations are opposed to athletes engaging in overt physical practice beyond formally scheduled training and competition situations due to increasing concern over overuse injuries through excessive physical exertion (see Pimenta et al., 2017; van Mechelen et al., 2017). Also, perception-only interventions have practical utility since they can be employed when players are injured or in transit to and from training and matches.

CONCLUSION

Wu attempted to train the perceptual–cognitive skill of recognizing patterns between display features. Although our analyses revealed non-significant effects, we have employed novel and innovative methods and presented a foundation for follow-up research. We have raised a number of important points that should be valuable and informative for scientists and practitioners when designing interventions to improve perception of patterns in future. A body of research now exists which identifies critical information sources for pattern perception (see North and Williams, 2008; North et al., 2009, 2011; Williams et al., 2012a). When seeking to enhance pattern perception by improving awareness of these critical information sources, we suggest that in future, researchers need to employ more longitudinal interventions. Finally, any interventions should not disturb relative motion information and any attempts to examine transfer should ensure the task constraints encourage the perception of patterns between features over and above any other perceptual–cognitive skills that performers may have available.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of Liverpool John Moores University ethics committee (ethics approval number: 09/SPS/010) with written informed consent from all participants. All participants gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Liverpool John Moores University ethics committee (ethics approval number: 09/SPS/010).

AUTHOR CONTRIBUTIONS

JN, EH, and AW study design and development; EH data collection; JN, EH, and AW data analysis and interpretation; and JN, EH, and AW writing of manuscript.

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Transfer of Training from Virtual to Real Baseball Batting

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The use of virtual environments (VE) for training perceptual-motors skills in sports continues to be a rapidly growing area. However, there is a dearth of research that has examined whether training in sports simulation transfers to the real task. In this study, the transfer of perceptual-motor skills trained in an adaptive baseball batting VE to real baseball performance was investigated. Eighty participants were assigned equally to groups undertaking adaptive hitting training in the VE, extra sessions of batting practice in the VE, extra sessions of real batting practice, and a control condition involving no additional training to the players' regular practice. Training involved two 45 min sessions per week for 6 weeks. Performance on a batting test in the VE, in an on-field test of batting, and on a pitch recognition test was measured pre- and post-training. League batting statistics in the season following training and the highest level of competition reached in the following 5 years were also analyzed. For the majority of performance measures, the adaptive VE training group showed a significantly greater improvement from pre-post training as compared to the other groups. In addition, players in this group had superior batting statistics in league play and reached higher levels of competition. Training in a VE can be used to improve real, on-field performance especially when designers take advantage of simulation to provide training methods (e.g., adaptive training) that do not simply recreate the real training situation.

Keywords: virtual environments, transfer of training, baseball, perception-action, practice design

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INTRODUCTION

In recent years there has been a renewed interest in using virtual environments (VEs)[1] as a tool for training perceptual–cognitive skills in sports (Miles et al., 2012). This has been motivated by two potential benefits that have been identified. First, using a sports VE creates the opportunity to train under conditions that are impossible in the real world. For example, attempting to catch a virtual

[1]A VE is defined as a system which includes the following elements: (i) a projection/display system which can present an image with a relatively large field view (FOV) such as a Head Mounted Display (HMD) or a Cave Automatic Virtual Environment (CAVE), (ii) some means of tracking the user's movements to allow for interaction with objects in the virtual world such as a motion capture system that tracks markers placed on the user's body, a cyber glove which tracks hand movements, or a motion-tracked effector like a bat or racquet, (iii) some means for providing feedback to the user about their actions such visual (e.g., ball flying on the field), auditory (e.g., sound of bat-ball contact) and/or haptic (e.g., vibration of force feedback from contact), and (iv) software used to render a 3D computer generated model of a sports-specific environment. Research on transfer for sports training systems which include some but not all of this elements, although potentially still valuable, is not considered here. Examples include video occlusion training of anticipation/decision-making skills (e.g., Abernethy, 1991) which is typically non-interactive due to the use of video and the Neurotracker system (Romeas et al., 2015) which involves passive user responses, is not interactive, and does not use sports-specific stimuli. For more discussion of this issue please see Gray (in press).

ball that does not obey the laws of gravity (Zaal and Bootsma, 2011) or one for which there is a conflict between perceptual information sources (Gray and Sieffert, 2005). Second, using a sports VE allows some of the key evidence-based principles of practice design (Hendry et al., 2015) to be more easily and effectively incorporated into training. These include adding a high degree of variability to practice conditions and systematically adjusting the level of challenge based on the athlete's performance. The goal of the present study was to evaluate the effectiveness of a type of VE training designed to take advantage of potential practice design benefits.

As discussed in Gray (in press), the primary criterion for any training VE should always be positive transfer of training to the real environment. Transfer of training can be defined as the gain (or loss) in the capability for performance of one task as a result of practice on some other task (Schmidt and Lee, 1982). Secondary criteria for VE evaluation (including fidelity, immersion, and technical specifications such as the size of the field of view) should only be considered important to the extent to which they aid in creating positive transfer of training. While it has been shown that sports VEs have many of the characteristics necessary (but not sufficient) for effective training outcomes (reviewed in Gray, in press), there have been relatively few studies that have directly assessed transfer for VEs designed for sports training.

In evaluating transfer from any sports training there are several important research design factors that must be taken into account (Abernethy and Wood, 2001). First, does the study include appropriate controls to rule out placebo and basic practice effects? Second, does the study include some assessment of the underlying mechanism(s) the training is purported to improve? For example, if a new training program is designed to improve sports performance by improving the clarity of vision, is visual acuity assessed pre- and post-training using a test that is validated and is preferably different than the task used during training? This helps to assess to what extent any improvements in sports performance are directly related to the training. Finally, does the study include some assessment of far transfer? "Far" in this context refers to the distance between the task performed in training (the transfer task) and the actual sport (the criterion task) (Abernethy and Wood, 2001). Solely assessing near transfer of training (e.g., quantifying to what extent athletes improve on the task used during training) is insufficient for assessing the value of a sports VE because near transfer is almost always positive and large in magnitude while producing positive, far transfer is much more difficult (Schmidt and Young, 1987). Therefore, it is critical that transfer studies include some measurement of far transfer involving a task that is close to what is performed during actual competition. The small number of transfer studies that have been published are examined next using these criteria.

Todorov et al. (1997) investigated transfer of training for a virtual table tennis trainer. In this study, a group that was trained by a coach was compared to a group training in a VE which contained an image of the table, ball, and the user's paddle (which was linked to their actual paddle movements using a motion tracker). A second paddle was also displayed in the simulation which showed the movements of an expert player (the coach) when hitting a shot. In a first experiment, a control group that received traditional coaching was compared to a VE training group. Pre- and post-training tests involved hitting a ball at a target on a real table. In terms of target hits, the group that trained in the VE showed a significantly greater improvement than the traditional training group.

In a second experiment, a more difficult shot task was used in which a barrier was placed on the table that participants could either attempt to hit over or under. Again, the increase in the number of targets hit from pre–post-training was significantly greater for the group that trained in the VE as compared to a traditional training group. An analysis of stroke kinematics revealed the differences between the paddle movement between each participant and the expert coach were significantly smaller for players in the VE training group. However, for the VE group, this difference increased throughout training and segments of the stroke (e.g., the backswing) were often completely different from the pattern of the coach by the end of training. This suggests participants were not simply copying the movements of the coach's racquet in the VE but were rather using them as a guide to find their own individual perceptual-motor solution to the task. Overall, this study includes most elements of a good transfer study and provides evidence of the potential value of VE training in sports. The only element that is missing is a measure of far transfer in which performance during a table tennis match is assessed in some way.

Lammfromm and Gopher (2011) examined transfer for a juggling VE. The VE was a very low fidelity simulation in which participants controlled simulated representations of their hands to juggle balls in a 2D wall display. So essentially the simulation could be used to learn some of the perceptual–cognitive aspects of juggling, but did not accurately recreate the motor component. The VE had the advantage that it allowed participants to practice juggling at lower speeds than are possible in real juggling and gradually increase speed as they improve. A group that performed both real and virtual juggling training was compared with a control group that was trained in real juggling alone. In terms of the number of consecutive juggling cycles that could be performed, both training groups improved by the same amount pre–post-training when tested at typical juggling speeds. However, when forced to juggle at higher speeds, the group that received the additional VE training performed significantly better than the real training only group. While this study again provides some evidence for the benefits of VE training, it would have been useful to include a VE training only group and some assessment of the performance changes (e.g., kinematics, eye movements) to determine exactly what value VE training was adding.

Rauter et al. (2013) investigated transfer of training for a very high fidelity rowing simulation. This VE included a large CAVE display of the water, realistic sounds of the boat moving through the water, and oars that were attached to a series of ropes that delivered highly realistic haptic feedback to the rower. In the training study, four participants trained in the simulation and four did real training on the water where they received verbal feedback from a coach. Pre- and post-training tests (which involved participants attempting to produce their best rowing technique) were conducted in both the simulator and on water. Performance was evaluated primarily using biomechanical measures specific to rowing technique. The results provided evidence for transfer in both directions. That is, participants that trained in the VE showed significant improvement (pre–post-training) for several of the biomechanical measures when tested on open water while participants trained on open water show significant improvements when tested in the VE. Although this pilot study provides interesting results, it is limited by its low sample size and lack of a measure of far transfer (e.g., time to complete a rowing race).

Finally, Tirp et al. (2015) examined transfer of training from the darts game in the Microsoft Kinect VE to real darts. In this study three groups were compared: a group that practiced real darts, one that practiced in the VE, and a control group that did not practice. Pre- and post-tests involved executing 15 shots at the bullseye on a real dartboard. A unique aspect of this study was that the quiet eye duration (i.e., the amount of time the thrower fixated on the target before releasing the dart, Vickers, 1992) was measured. Both the real and virtual training groups showed improvements (from pre–post-training) in throwing accuracy that were significantly greater than for the control group. However, performance improvements were significantly greater for the real training group than the VE training group. The quiet eye duration increased significantly for both groups after training with the increase being significantly larger for the VE group. In sum, this study provides somewhat equivocal results with regards to the benefits of VE training. While the gaze behavior change seems to indicate the VE training was comparable or even superior to real training, this was not borne out in actual throwing performance.

From this review of existing research on the topic, it is abundantly clear that more work is needed to determine whether training in a sports VE will produce positive transfer of training to real sport. Without effective evaluation of transfer it will continue to be difficult for sports teams to determine whether a VE is worth the investment and to determine which technological components are required for training success. While existing studies are generally well designed they are small in number and none involve tests of far transfer (i.e., performance in actual competition or competition-like conditions). Furthermore, from existing research it is unclear whether a sports training VE's value will come from just giving an athlete more repetitions or "reps" of the skill (i.e., recreating real training) or whether it will come from taking advantage of VEs to design types of practice that are difficult or impossible to do in real life (as suggested by the table tennis and juggling results described above) or both.

The goal of the present study was to address these limitations by examining the transfer of perceptual-motor skills trained in an adaptive baseball batting VE to real baseball performance. Eighty participants who were taking part in regular training were assigned equally to groups undertaking adaptive hitting training in the batting VE, extra sessions of batting practice in the VE, extra sessions of real batting practice, and a control condition involving no additional training to the players' regular practice. The adaptive training involved performance-based adjustments of pitch speed, pitch type, and location using staircase methods. The batting practice training (both real and VE) involved blocked practice of different pitch types with speed and location held constant, as is typical in baseball (e.g., American Baseball Coaches Association, 2009). Performance on a batting test in the VE, in an on-field test of batting, and on a pitch recognition test was measured pre- and post-training. The league batting statistics for the season following training and the highest level of competition reached in a 5-year period following the training were also analyzed. The experiment was designed to test the following specific hypotheses:

(i) For all performance measures, the change from pre–post-training would be significantly greater for the VE adaptive training group than for all other groups. This was predicted because (as described in detail below) the adaptive training involved taking advantage of the VE to incorporate evidence-based training elements that are not typically used in real training.
(ii) Batting performance in the season following training would be significantly greater for the VE adaptive training group than for all other groups.
(iii) A significantly greater proportion of batters in the VE adaptive training group would reach a level of competition higher than high school baseball than for all other groups.

MATERIALS AND METHODS

Participants

The participants in the study were 80 male baseball players who played competitive high school baseball in the United States at the time of training. The sample size of 20 per group was determined based on power analysis (power = 0.8) using the mean effect size ($f = 0.75$) from previous studies comparing batters of different skill levels using the same batting VE (Gray, 2002, 2004; Castaneda and Gray, 2007) with the goal of having sufficient power to detect group × phase (i.e., pre–post-training) interactions. All players were in their senior year and were either 17 or 18 years of age. Players were recruited, trained, and tested over a 3-year period from 2008 to 2010. They were recruited from 18 different teams and all players started the majority of the games at their position the previous season. This study was carried out in accordance with the recommendations of and was approved by the Arizona State University Institutional Review Board with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

The 80 participants were randomly assigned to one of four training groups (described in detail below): (i) Adaptive training in a batting VE, (ii) extra sessions of batting practice in the VE, (iii) extra on-field sessions of real batting practice, and (iv) a control condition involving no additional training to the players' regular practice. The mean number of years of competitive playing experience for the four groups was, respectively, 8.6 ($SD = 1.2$), 8.3 ($SD = 0.9$), 8.8 ($SD = 1.4$), and 8.5 ($SD = 1.1$). A one-way ANOVA revealed that there was no significant difference in the number of year of competitive playing experience, $p > 0.5$, $\eta^2_p < 0.1$.

Apparatus

The baseball batting VE used in the present study has been used in several previous experiments (e.g., Gray, 2002, 2004, 2009a,b; Castaneda and Gray, 2007). Briefly, participants swung a baseball bat at a simulated approaching baseball. The image of the ball, a pitcher, and the playing field was projected on a single 6.9′ (2.11 m) (h) × 4.8′ (1.47 m) (v) screen positioned in front of the batter using a Proxima 6850+ LCD projector updated at a rate of 60 Hz. The flight of the ball was simulated until it was approximately 5 feet (1.7 m) from the front of the plate so batters could not see the virtual ball as it crossed the plate. The bat was not simulated in the visual display so participants could not see the point of bat–ball contact. Research on gaze behavior in baseball suggests that the ball will be well outside foveal vision at a distance of 5 feet for most batters (Bahill and LaRitz, 1984). The importance of the fidelity of the VE used in the present study is considered below.

Mounted on the end of the bat [Rawlings Big Stick Professional Model; 33″ (84 cm)] was a sensor from a Fastrak (Polhemus) position tracker. The sensor was not wireless so the position of the cord was adjusted after each trial so as not to interfere with the batter's swing. All of the batters in the study reported that they could swing freely and naturally. The x, y, z position of the end of the bat was recorded at a rate of 120 Hz. The position of the ball in the simulation was compared with the recording of bat position in real-time in order to detect collisions between the bat and ball. Batters received visual, auditory, and tactile feedback about the success of their swing [see Gray (2009b) for details]. Three pitch types were used: (i) a "four seam" fastball with an average speed of 85 mph (38 m/s), thrown with backspin, and with a spin rate of 1900 rpm, (ii) a "12–6" curveball with an average speed of 65 mph (29.0 m/s), thrown with topspin, and with a spin rates of 1700 rpm, and (iii) a "straight change" with an average speed of 70 mph (31.2 m/s), thrown with backspin, and with a spin rate of 1800 rpm. As described in detail below, both right-handed and left-handed pitchers were simulated with the ratio of their usage in training and testing (75% right-handed) roughly reflecting the typical ratio found in baseball.

For real batting practice training and on-field tests, batters hit balls projected by a Rawlings Spin Ball Pro 3 Spin Wheel™ pitching machine. The same three pitch types were used and the pitching machine was moved to different sides of the pitching rubber to simulate left- and right-handed deliveries.

Procedure

Pre-tests

Prior to training, all batters completed three pre-test performance assessments: VE batting, real batting, and pitch recognition in the VE. For practical reasons, the two VE tests were always performed in the same session while the real batting test was performed in a separate session. The order of the VE and real tests was fully counterbalanced across participants ($n = 10$ per order) as was the order of the hitting and pitch recognition tests within the VE session ($n = 5$ per order). The details of the three tests were as follows:

VE batting test

In this test, batters faced a series of pitches until the sum of the number of strikes plus the number of hits was equal to 20. A strike occurred when the batter swung and missed the ball, the batter did not swing at a ball that crossed the plate in the strike zone, the batter hit a ball that did not make it to the outfield, or the batter hit the ball into foul territory. Hits included homeruns (balls hit further than 320 feet) and balls that landed in fair play beyond the infield. If the batter did not swing and the ball crossed the plate outside the strike zone, the pitch was not added to their total, i.e., the batter could "take" pitches. All definitions of a "hit" and how their performance would be scored was explained to each batter before they were tested. The motion tracker was used to determine whether or not the bat crossed the front of the plate for swinging strike calls.

The lateral location and height of each pitch when it crossed the plate was varied to simulate pitches that were "strikes" (i.e., crossed the plate in the strike zone) and pitches that were "balls" (i.e., did not cross in the strike zone). The Major League Baseball (MLB) definition of the strike zone (Triumph Books, 2004) was used to determine balls and strikes: "the strike zone is that area over home plate the upper limit of which is a horizontal line at the midpoint between the top of the shoulders and the top of the uniform pants, and the lower level is a line at the top of the knees." "Strikes" and "balls" were selected randomly for each pitch with a "strike" probability of 0.65. Pitch type (fastball, curveball, or changeup) was also chosen randomly on each trial. For each pitch type, there were 10 different combinations of pitch parameters (horizontal and vertical launch angle and speed) that resulted in strikes and 9 different combinations of pitch parameters that resulted in balls. The range of pitch speeds was ±5 mph (2.2 m/s) around the average speed for each pitch type described above. Strikes were spread equally throughout the strike zone while pitches that were not strikes crossed the plate either above or below the strike zone or were outside (i.e., on the side of the plate opposite to where the batter was standing). All balls missed the strike zone by 4″ (10 cm). Pitches that were off the plate inside were not used because this condition was not included in the real batting test for safety reasons.

The simulated pitcher was right-handed for the first 15 strikes + hits then was switched to left-handed for the remainder of the test. Batters hit from their preferred side of the plate and were allowed to switch-hit (i.e., switch sides when the simulated pitcher handedness was changed) if they wished. Batters were given 10 min breaks after every 20 pitches to reduce fatigue. Batters were told the definition of hit, how many pitches they would receive, that taking pitches outside the strike zone would not count to their total, and to "try and get as many hits as possible."

Real batting test

In this test, batters attempted to hit regulation baseballs thrown by a pitching machine. The procedure was identical to that described for the VE test except for balls and strikes were called by umpires with a minimum 5 years of experience. Pitching machine settings for the different pitch outcomes were determined in pilot testing.

Pitch recognition test

In this test, batters passively viewed pitches in the batting VE that were occluded (and replaced with a blank screen) 150 ms after release. This viewing duration was chosen based on previous research suggesting that this is roughly the point at which a batter must make a decision about whether or not to complete a full swing (Gray, 2009a). There were a total of 20 pitches in the test. The pitch parameters were identical to that described for the VE batting test. Batters were given the following instruction: "for each pitch your task is judge the pitch type (fastball, curveball, or changeup) and whether the pitch was a strike or a ball as accurately and as quickly as possible. You should make your response verbally and indicate the pitch type first." The experimenter recorded the responses for each pitch and response time was not calculated. Batters were not given feedback about the accuracy of their judgments.

Training

All three training groups completed two 45 min sessions per week for 6 weeks. All training was completed in the year prior to players' final season of high school baseball. Details of the training sessions were as follows:

Batting practice in the VE

In each session, batters attempted to hit 30 pitches with the instructed goal of "attempting to hit the ball hard over the infield." All pitches were strikes and traveled down the center of the strike zone. The three pitch types were blocked with 10 pitches per type and the order randomized in each session. The initial pitch speeds for each type were 80 mph (38 m/s) fastball, 65 mph (29 m/s) curveball, and 70 mph (31.2 m/s) changeup. In each session, the pitcher had a constant handedness with the first nine training sessions using a right-handed pitcher and the final three using a left-hander. After every three sessions, the speed of each pitch was increased by 1 mph (0.45 m/s). The design of this training was based on what is typically done in real baseball. For example, pitch type and pitcher handedness were blocked and speeds were not varied within pitch type because it is impractical to vary these parameters from pitch to pitch in a real training session.

Real batting practice

This training was identical to the VE batting practice group except that, of course, batters attempted to hit real balls thrown by a pitching machine.

Adaptive VE training

As was the case in the other two training groups, batters attempted to hit 30 pitches per training session with the first nine training sessions using a right-handed pitcher and the final three using a left-hander. However, the design of this training was based on previous research demonstrating that training outcomes are improved when practice is designed so that the task difficulty is appropriately matched to the performer's skill level (i.e., the challenge point hypothesis, Guadagnoli and Lee, 2004) and includes variability in practice conditions (Schmidt, 1975).

To manipulate challenge, the pitch parameters in the batting VE were determined by three one-up-one-down staircases (Levitt, 1971), with one staircase corresponding to each pitch type. An example staircase for the fastball is shown in **Figure 1**. At the start of training, the pitch speed (i.e., the initial value in the staircase) was the mean for that particular pitch type. All pitches were initially strikes that traveled down the center of the strike zone. If the batter successfully achieved a hit for this pitch, the speed was increased by 2 mph (0.9 m/s) for the next pitch in that staircase. If the result of the pitch was a strike (denoted by 'K' in **Figure 1**), the speed was decreased by 2 mph (0.9 m/s). After three reversals (i.e., trails for which the outcome was opposite to what occurred on the previous trial), the "challenge speed" was determined by calculating average speed for the last two trials of that staircase. The pitch speed was then held constant at this value. Another way of thinking of this manipulation is the following. The simulation program altered the pitch speed until a "threshold" value was found for which an increase in speed would typically cause the batter to not get a hit while a decrease would lead to hits for most pitches. See Gray and Allsop (2013) for a similar procedure.

After this challenge speed value was found, the variability in the pitch crossing height was next varied. Specifically, instead of always traveling down the center of the strike zone, pitch crossing height varied randomly between $\pm y$ cm around the center. The initial value of y was 2″ (5 cm). The value of y was increased by 2″ (5 cm) after each hit and was decreased by 2″ (5 cm) after each strike. After three reversals or if the batter achieved three consecutive hits for the maximum y value (9.8″, 25 cm), the "challenge crossing height variability" was set. The final manipulation involved an analogous adjustment of the variability of the lateral crossing location.

At the start of each new training session, the initial pitch parameters were equal to the final settings from the previous session. Once the three challenge points (speed, crossing height, and lateral location) were determined these values were used for the next full training session. After this, the entire procedure started over (i.e., a new speed challenge point was determined, etc.). The entire procedure was also started over for the final

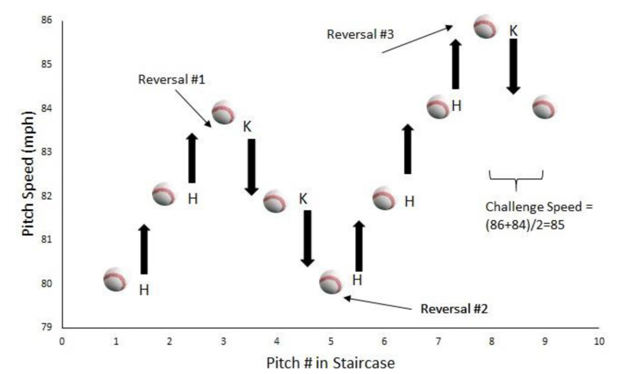

FIGURE 1 | Example of the staircase procedure used for the adaptive VE training group. After each successful hit (H) the pitch speed was increased by 2 mph while after each strike (K) it was decreased by the same amount. After three reversals, the challenge speed was determined by averaging the pitch speed on the final two trials.

three sessions in which the batter faced the left-hander pitcher. To manipulate the variability of practice conditions the three staircases (each corresponding to one pitch type) were randomly interleaved during each session.

Post-tests

Post-tests were identical to the pre-tests and were conducted roughly 2 weeks after the final training session for all participants.

Retention Tests

Retention tests were identical to the pre- and post-tests and were completed roughly 1 month after the post-test. The retention tests were included to determine to what extent any training benefits were maintained after training ended.

Data Analysis

Batting Performance Assessments

For the VE and on-field batting tests the following dependent variables were analyzed: total number of hits, % of swings at pitches inside the strike zone (Z-Swing %), and % of swings at pitches outside of the strike zone (O-Swing %).[2] These variables were chosen because they reflect both a player's hitting ability and their knowledge of the strike zone. For the pitch recognition test, the total number of pitch types and balls/strikes correctly identified were used as dependent variables. These variables were first analyzed using a 3 (testing phase: pre, post, retention) × 4 (group: adaptive VE, VE batting practice, real batting practice, control) MANOVA with significant effects further analyzed using ANOVAs and *t*-tests.

Five-Year Follow Up

For all participants, we calculated the on-base percentage (OBP) for their senior high school season following the training. OBP is a measure of how often a player reaches base with the exact formula, OBP = Hits + Walks + Hit by Pitch)/(At Bats + Walks + Hit by Pitch + Sacrifice Flies). This variable was chosen because it captures both a player's ability to hit and their knowledge of the strike zone, both of which were targeted in training. OBP data for the four training groups were first analyzed using a one-way ANOVA. Next, we sought to determine which of the dependent variables in the batting assessments were significantly related to OBP. To achieve this end, a linear multiple regression was performed with OBP as the dependent variable and change scores (from pre- to post-training) for batting assessments as independent variables.

For the four training groups, the highest level of competition for which each player competed at least one full season within the 5 years following training was determined. This included NCJAA junior college, NCAA college, or any level of MLB (e.g., A, AA, AAA). The proportion of players reaching a level above high school baseball was compared for the groups using a Chi-square test of proportions.

[2]Note, Z-Swing which is used to indicate a pitch inside the strike "Z"one and O-Swing which is used to indicate a pitch "O"utside the strike are used here to be consistent with the terminology currently used in baseball analytics (https://www.fangraphs.com/library/offense/plate-discipline/).

RESULTS

Batting Performance Assessments

Figures 2–4 show the mean values for the performance assessment variables in three phases of the study, respectively. The MANOVA performed on the eight batting assessment

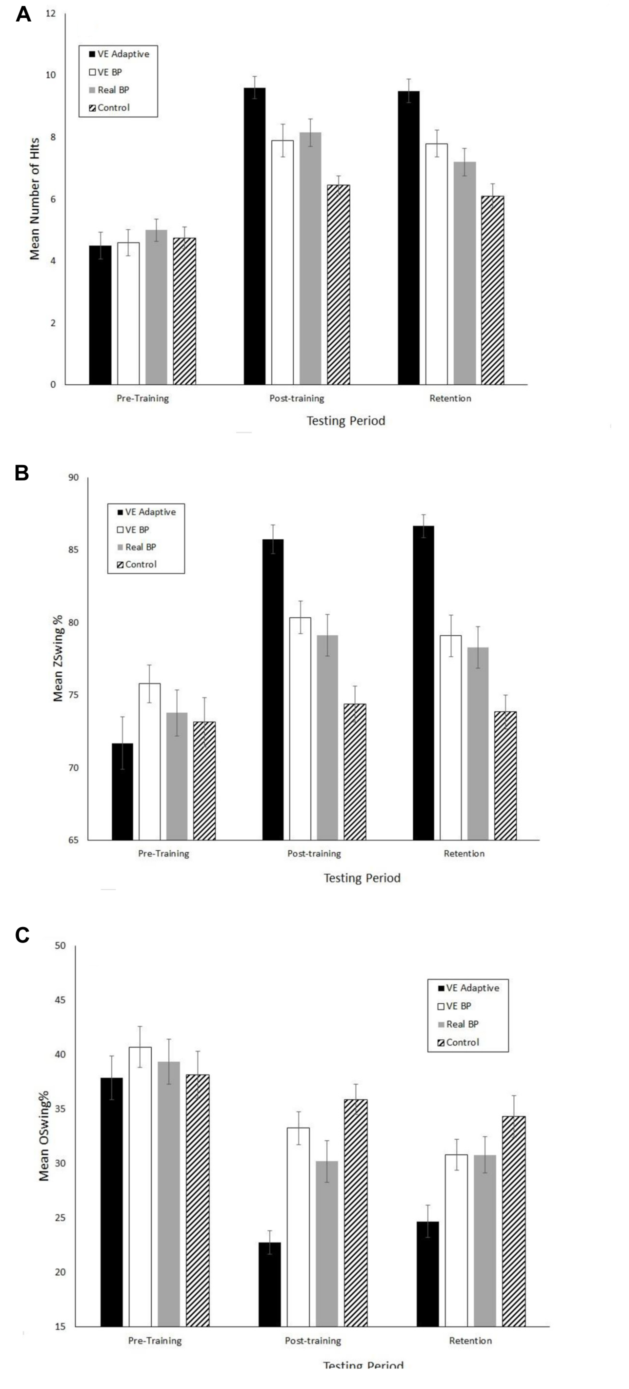

FIGURE 2 | Mean performance scores for the VE batting tests. **(A)** Number of hits. **(B)** Z-Swing %. **(C)** O-Swing %. Error bars are standard errors.

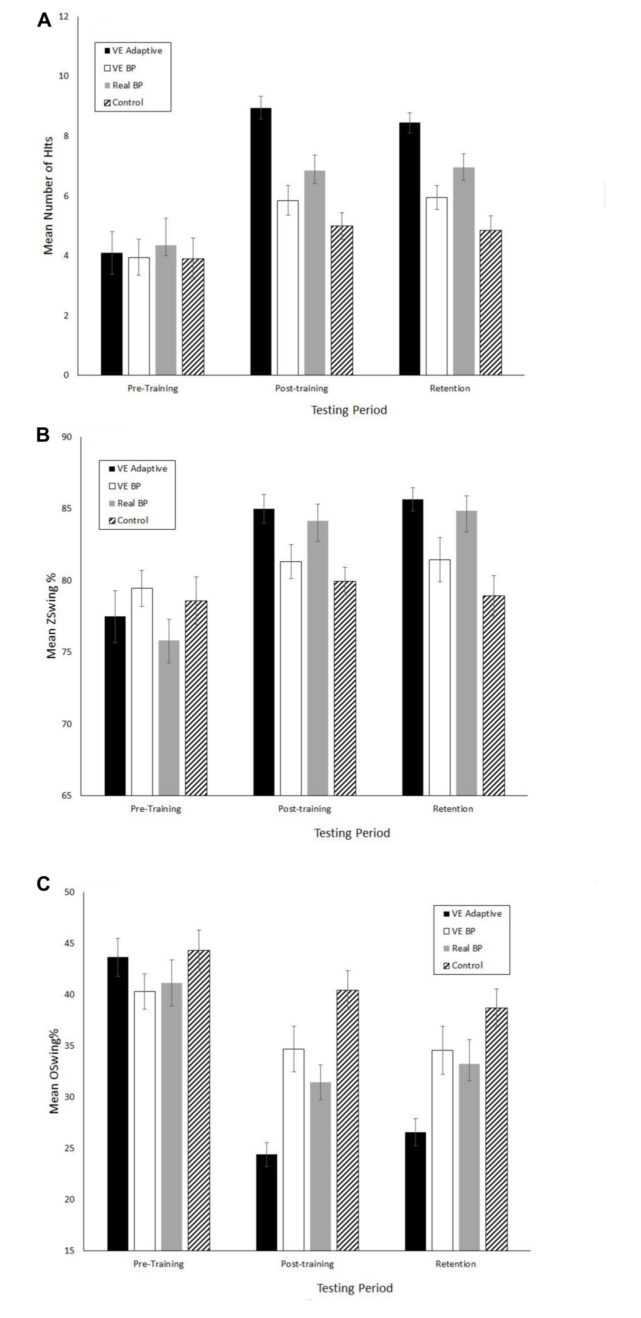

FIGURE 3 | Mean performance scores for the real batting tests. **(A)** Number of hits. **(B)** Z-Swing %. **(C)** O-Swing %. Error bars are standard errors.

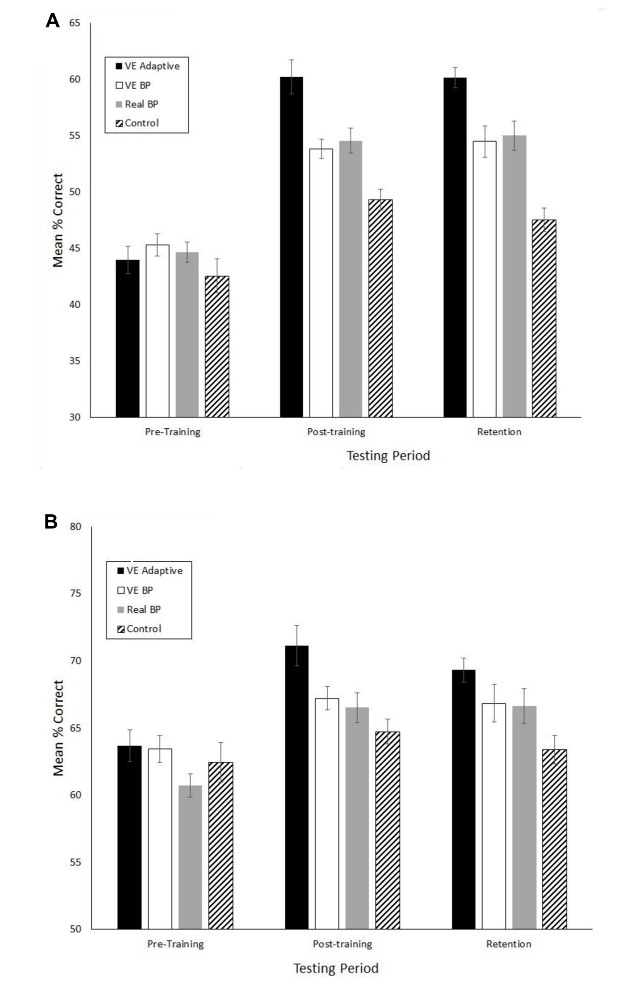

FIGURE 4 | Mean accuracy for the pitch type **(A)** and strike/ball **(B)** judgments in the pitch recognition test. Error bars are standard errors.

variables revealed significant main effects of group, $F(8,69) = 4.3$, Wilks $\lambda = 0.17$, $p < 0.001$, $\eta_p^2 = 0.33$, phase, $F(16,61) = 49.3$, Wilks $\lambda = 0.07$, $p < 0.001$, $\eta_p^2 = 0.93$, and a significant group × phase interaction, $F(48,189) = 2.0$, Wilks $\lambda = 0.19$, $p = 0.001$, $\eta_p^2 = 0.34$.

The results of the 3 × 4 ANOVAs performed on each of the dependent variables are shown in **Table 1**. For all variables there were significant main effects of group and phase. With the exception of the total number of balls/strikes correctly identified, these effects were qualified by significant group × phase interactions for all dependent variables. In the following sections, these effects are further broken down by the phases of the experiment.

Pre-test

To determine whether there were any pre-test group differences for any of the dependent variables, scores were compared using independent samples *t*-tests with Bonferroni correction (critical $p = 0.008$). These analyses revealed no significant group differences for any of the dependent variables, *p*s all > 0.05, *d*s all < 0.5.

Post-test

To break down the significant group × phase interactions, pre- and post-test scores were compared separately for each of the training groups using pairwise *t*-tests with Bonferroni correction (critical $p = 0.006$). The results of these analyses are shown in **Table 2**. The VE adaptive training group had significant pre–post improvements for all dependent variables. For the real batting practice group, there were significant improvements for 7/8 of dependent variables, with no significant effect for Z-Swing % in the VE batting test. For the VE batting practice group, there were significant improvements for 3/8 of the variables (number of hits in the VE batting test, O-Swing% in the VE batting test, and number of correct pitch identified in the recognition test). Finally, for the control group, there were significant improvements for 2/8 of the variables (number of hits in the VE test and number of pitch types correctly identified in the recognition test).

To test hypotheses (i), pre- to post-test change scores were calculated for each group and each dependent variable. The change score for the VE adaptive group was compared to each of the other groups using independent samples *t*-tests with Bonferroni correction (critical p value = 0.006). The results of these analyses are shown in **Table 3**. In comparison to the VE batting practice group, the VE adaptive training group had significantly greater change scores for 5/8 of the dependent measures (Z-Swing % in the VE batting test; number of hits, Z-Swing % and O-Swing% in the real batting tests; number of correct pitch types identified). In comparison to the real batting practice group, the VE adaptive training group had significantly greater change scores for 5/8 of the dependent measures (number of hits in the VE batting test; number of hits and Z-Swing % in the real batting tests; number of correct pitch types identified). Finally, as compared to the control group, the VE adaptive training group had significantly greater change scores for 7/8 of the dependent measures with the only non-significant difference occurring for the number of strikes correctly identified.

Retention

To evaluate the degree to which post-training performance was retained, post-test and retention scores were compared for dependent variables using pairwise *t*-tests with Bonferroni correction (critical $p = 0.008$). This analysis revealed no significant differences for any of the training groups, *p*s all > 0.05, *d*s all < 0.5.

Five-Year Follow Up

Figure 5 shows the mean season OBP for each player's high school season following the training. For these data, two participants (one from the VE batting practice and one from the control group) were removed because they played in fewer than five games due to injury. The one-way ANOVA performed on these data revealed a significant main effect of training group, $F(3,74) = 10.8$, $p < 0.001$, $\eta_p^2 = 0.30$. Independent samples *t*-tests with Bonferroni correction (critical $p = 0.017$) revealed that OBP was significantly higher for the VE adaptive as compared to the VE batting practice, $t(37) = 3.7$, $p = 0.001$, $d = 1.2$, and the control group, $t(37) = 4.8$, $p < 0.001$, $d = 1.8$. There was a marginally significant difference (with a medium-large effect size) between the VE adaptive and real batting practice group, $t(38) = 2.5$, $p = 0.025$, $d = 0.7$.

The multiple linear regression performed on OBP indicated that four predictors explained 68% of the variance ($R^2 = 0.47$, $F(8,69) = 9.7$, $p < 0.001$). The significant predictors were ΔVE hits ($\beta = 0.013$, $p = 0.01$), Δreal hits ($\beta = 0.0.07$, $p = 0.045$), Δreal O-Swing % ($\beta = -0.08$, $p = 0.041$), and Δpitch type accuracy ($\beta = 0.02$, $p = 0.021$). ΔVE hits explained the highest amount of variance followed by Δpitch type accuracy.

TABLE 1 | Results of the 3 × 4 ANOVAS performed on the Batting Assessment Variables.

Dependent variable	Group $F(3,76)$	Phase $F(2,152)$	Group × Phase $F(6,152)$
VE_Hits	12.3*, $\eta_p^2 = 0.33$	82.6*, $\eta_p^2 = 0.52$	4.8*, $\eta_p^2 = 0.16$
VE_ZSwing	13.3*, $\eta_p^2 = 0.34$	29.6*, $\eta_p^2 = 0.28$	7.0*, $\eta_p^2 = 0.22$
VE_OSwing	10.0*, $\eta_p^2 = 0.29$	35.5*, $\eta_p^2 = 0.32$	2.8[b], $\eta_p^2 = 0.10$
Real_Hits	15.1*, $\eta_p^2 = 0.37$	51.5*, $\eta_p^2 = 0.40$	4.7*, $\eta_p^2 = 0.16$
Real_ZSwing	2.9[a], $\eta_p^2 = 0.11$	21.5*, $\eta_p^2 = 0.22$	3.8*, $\eta_p^2 = 0.13$
Real_OSwing	11.4*, $\eta_p^2 = 0.31$	37.2*, $\eta_p^2 = 0.33$	4.3*, $\eta_p^2 = 0.14$
PR_Type	40.7*, $\eta_p^2 = 0.62$	152.0*, $\eta_p^2 = 0.67$	7.2*, $\eta_p^2 = 0.22$
PR_Strike	8.5*, $\eta_p^2 = 0.25$	21.6*, $\eta_p^2 = 0.22$	1.5[c], $\eta_p^2 = 0.06$

*$p < 0.001$, [a]$p = 0.037$, [b]$p = 0.013$, [c]$p = 0.18$.

TABLE 2 | Results of pairwise *t*-tests comparing pre- and post-test scores.

Group	Dependent variable	$t(19)$	p	d
VE_Adaptive	VE_Hits	9.4*	<0.001	2.8
	VE_ZSwing	7.5*	<0.001	2.1
	VE_OSwing	−7.1*	<0.001	1.9
	Real_Hits	13.9*	<0.001	1.9
	Real_ZSwing	8.5*	<0.001	1.2
	Real_OSwing	−10.6*	<0.001	2.8
	PR_Type	9.2*	<0.001	2.7
	PR_Strike	6.0*	<0.001	1.4
VE_BP	VE_Hits	4.8*	<0.001	1.5
	VE_ZSwing	2.4	0.027	0.6
	VE_OSwing	−3.2*	0.005	0.9
	Real_Hits	2.5	0.018	0.8
	Real_ZSwing	1.2	0.23	0.3
	Real_OSwing	−1.7	0.10	0.6
	PR_Type	7.0*	<0.001	2.1
	PR_Strike	2.8	0.01	0.7
Real_BP	VE_Hits	6.0*	<0.001	1.7
	VE_ZSwing	2.6	0.018	0.7
	VE_OSwing	−3.4*	0.003	1.0
	Real_Hits	4.3*	<0.001	0.8
	Real_ZSwing	5.1*	<0.001	1.4
	Real_OSwing	−3.3*	0.004	1.1
	PR_Type	7.5*	<0.001	2.2
	PR_Strike	3.5*	0.003	1.1
Control	VE_Hits	3.9*	<0.001	1.1
	VE_ZSwing	0.83	0.42	0.2
	VE_OSwing	−1.09	0.29	0.3
	Real_Hits	2.2	0.043	0.4
	Real_ZSwing	0.66	0.52	0.2
	Real_OSwing	−1.8	0.087	0.4
	PR_Type	5.0*	<0.001	1.2
	PR_Strike	1.6	0.13	0.5

**Significant at corrected p = 0.006.*

The number of participants that played at least one full season at a level higher than high school baseball in the 5 years following the study was as follows: VE adaptive, 8 (1 AA, 1 A, 4 NCAA, 2 NCJAA); VE batting practice, 1(NCAA); Real batting practice, 3(1 A, 1 NCAA, 1 NCJAA); and Control, 1 (NCAA). A Chi-square test of proportions revealed that this distribution is significantly different from equality, $\chi^2 = 7.9$, $p = 0.047$.

TABLE 3 | Results of *t*-tests comparing the VE adaptive group to other training groups.

Dependent variable	Group	*t*(38)	*p*	*d*
VE_Hits	VE_BP	2.05	0.05	0.7
	Real_BP	3.5*	0.001	0.8
	Control	4.9*	<0.001	1.5
VE_ZSwing	VE_BP	3.6*	0.001	1.1
	Real_BP	2.7	0.009	0.8
	Control	5.3*	<0.001	1.7
VE_OSwing	VE_BP	−2.4	0.019	0.7
	Real_BP	−1.8	0.09	0.5
	Control	−4.4*	<0.001	1.4
Real_Hits	VE_BP	3.6*	0.001	1.0
	Real_BP	3.4*	0.001	0.7
	Control	6.1*	<0.001	1.2
Real_ZSwing	VE_BP	3.2*	0.002	1.0
	Real_BP	0.43	0.667	0.1
	Control	2.8	0.009	0.9
Real_OSwing	VE_BP	−3.7*	0.001	1.2
	Real_BP	−3.1*	0.005	0.8
	Control	−5.5*	<0.001	1.7
PR_Type	VE_BP	3.6*	0.001	1.4
	Real_BP	3.1*	0.005	1.1
	Control	4.3*	<0.001	1.6
PR_Strike	VE_BP	−1.9	0.056	0.6
	Real_BP	0.80	0.43	0.3
	Control	2.7	0.01	0.8

*Significant at corrected $p = 0.006$.

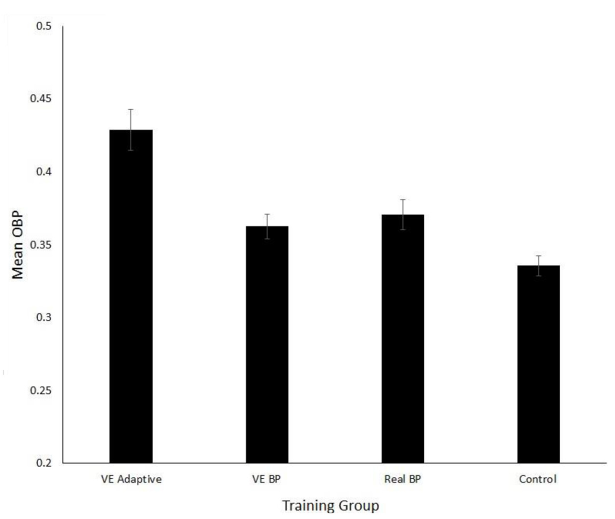

FIGURE 5 | Mean on-base percentage (OBP) for the four training groups. Error bars are standard errors.

DISCUSSION

The goal of the present study was to evaluate the transfer of perceptual-motor skills trained in an adaptive baseball batting VE to real baseball performance. The VE adaptive training used in the present study was superior to the other types of training investigated in many ways. Players in the VE adaptive group showed significant improvements for 7/8 of the batting performance assessments and these improvements were maintained in a 1-month retention test. Consistent with hypothesis (i), for the majority of the assessments, the magnitude of improvement was significantly greater than what was found for the other three groups in the study. Finally, consistent with hypotheses (ii) and (iii), the batting performance in the full season following the training (as assessed by OBP) was significantly higher for VE adaptive group as compared to the other groups and a significantly higher proportion of players in the VE adaptive group reached levels of competition above high school. Therefore, the results of the present study provide evidence for both near and far transfer of training for a baseball batting VE.

In looking at the level of play reached by the participants in the study it is interesting to compare to general trends for US high school players[3]. It has been estimated that about 6% of high school players go on to play NCAA college baseball and only about 0.5% are drafted by a MLB team. Comparable numbers for players in the VE adaptive training group of the present study were 20 and 10%. Although these values cannot be compared statistically, this result does again suggest good transfer of training to real baseball.

When examining transfer of training effects it is important to consider the underlying perceptual-motor and cognitive mechanisms. This can be done in a few different ways using the data from the present study. First, consider the differences in results between the VE adaptive and VE batting practice groups. The significant differences in the magnitude of performance improvements, OBP, and the results of the 5-year follow up suggest that the benefits of the VE adaptive training in the present study were not simply due to the fact that it provided more repetition of hitting practice relative to the control group. Looking more closely, both types of VE training lead to increases in the number of hits in the VE test that were not statistically different in magnitude. However, there were two primary differences between these groups. First, as shown in **Figure 4**, the VE adaptive training resulted in significant improvements in performance on the real batting tests while the VE batting practice training did not. In other words, the results of the present study suggest that simply performing multiple hitting repeats in a VE has poor transfer to real batting. Second, batters in the VE Adaptive group exhibited greater knowledge of the strike zone

[3]http://www.hsbaseballweb.com/probability.htm

(as shown by a greater increase in Z-Swing %) and superior pitch type recognition as compared to the VE batting practice group.

For the VE adaptive and real batting practice training, the group differences were smaller than what was found for the two VE training groups. Similar to the VE adaptive training, real batting practice lead to significant improvements in 7/8 of the batting performance assessments. Notably, real batting practice lead to significant changes in the number of hits and O-Swing % in the VE batting tests. Therefore, there was an asymmetry in the results of the present study with real batting practice leading to improvements in some aspects of virtual batting but not vice versa. Turning to a comparison of the magnitude of improvements from pre–post training, not surprisingly VE adaptive training did result in significantly more hits in the VE batting test than real batting training. But it also resulted in significantly greater improvements in the number of hits and O-Swing % in the real batting test, and significantly better pitch-type recognition.

A final way of examining the perceptual-motor mechanisms underlying the transfer effects found in the present study is via the multiple regression analysis quantifying the relationship between OBP and the performance assessment variables. When the data for all groups were used, there were two types of significant effects that were observed. First, perhaps not surprisingly, batters that showed the greatest improvements in the number of hits achieved (both in the VE and real tests) had better batting performance in league play. Taken on its own this effect could be explained in multiple different ways. For example, perhaps those participants that showed the greatest improvements on the hitting tests were also those players that put more effort into the regular team practice or were more motivated.

The second type of effect seen in the multiple regression analysis suggests there were also some improvements related to the mechanisms underlying batting skill, however. Specifically, improvements in pitch-type recognition and O-Swing % as a result of training were also significantly related to OBP. The change in O-Swing % (i.e., the likelihood the batter swings at a pitch that is outside of the strike zone) is particularly notable because it was not directly targeted in the tests or training, e.g., batters were not explicitly told that they should swing only at strikes. Instead, this improvement seemed to be a positive side effect of the training manipulations. These findings are consistent with recent research that has shown significant correlations between batting performance, plate discipline, and pitch recognition in professional baseball batters (Morris-Binelli et al., in press).

Taken together, the results of the present study suggest that the VE adaptive training lead to some key perceptual-motor changes which underlie the improvements. First, the changes in pitch recognition ability, O-Swing %, and Z-Swing % described above all suggest that the training resulted in greater sensitivity to visual information provided by the ball in flight. Specifically, these findings suggest that the VE adaptive training resulted in an improved ability to use the pattern of lace rotation to recognize the pitch type (Hyllegard, 1991; Gray, 2002) and an improved ability to use monocular cues to direction of motion in depth to determine whether or not a pitch would cross the plate in the strike zone (Gray, 2002). It is further proposed that these improvements were facilitated by the use of the staircase procedure in training. Overall, batters in the VE adaptive group were exposed to combinations of pitch types and trajectories that are more representative of the range of conditions they face in game play. However, rather than facing the full range of conditions right away, the staircase procedure presumably facilitated better learning by keeping challenge at an appropriate level (Guadagnoli and Lee, 2004). Finally, it is possible that the conditions in the VE adaptive training promoted a greater degree of exploration of the perceptual-motor space leading to a better calibration between the motor responses involved in producing a swing to a particular location and the visual information about the ball flight (Davids et al., 2008).

There are some important limitations of the present study that will need to be addressed in future research. First, the definition of a successful "hit" in present study (homerun or ball that travels to the outfield) does, of course, not match with what is used in games. The choice to use this definition was primarily a practical one (i.e., the difficulty of recruiting/simulating the other seven fielders). For the real batting test, this would have also added a further complication in that the performance on the batting tests would depend partially on the skill of the fielders. A more effective solution in future research might be to use ball tracking technology to calculate quality of contact variables (e.g., launch angle and exit velocity) as metrics of hitting performance.

A second limitation is that the present study did not include a real batting training group in which challenge and variability were manipulated in a similar manner to what was done with the VE adaptive group. On a theoretical level, it would be interesting to determine if these practice principles have similar effects in real and virtual training. However, this condition was not included in the present study because, while not impossible to recreate on the field, using the staircase procedure and randomly interleaving pitch types is highly impractical and is, therefore, very unlikely to be adopted in real practice.

A third limitation was the variation of pitcher "handedness" in the real batting training and testing. Obviously, there are more differences between a left-handed vs. right-handed pitcher than the horizontal release point varied by moving a pitching machine. Therefore, it is possible that one of the reasons for the difference in results for the VE adaptive and real batting practice groups was that the former group received opportunities to view the (simulated) delivery of a left-handed pitcher in training while the latter group did not. However, it is argued that this effect cannot explain all of the differences between these groups or the VE batting practice group (which also faced the simulated left-handed pitcher) would have also had superior results to the real batting practice group. As can be seen in **Figures 2–4**, this was clearly not the case.

A final point to consider is the fidelity of the simulation used in the present study. The physical fidelity of the VE used to collect the data presented here was clearly much lower than VR technology currently in use (e.g., CAVE and HMD systems). Specifically, the field of view was considerably smaller, the bat was not simulated, binocular information about ball flight was not included, and the flight of the ball was not simulated all the way to the plate. Although it was not measured, it is also likely that the degree of immersion was considerably lower. This raises the possibility that different (even greater) training benefits might be found using VE training systems that have a higher degree of physical fidelity and immersion. However, to date, there is little if any evidence to support the assumption that higher physical fidelity and greater immersion leads to more effective training (reviewed in Gray, in press). Furthermore, along with the present results, effective transfer of training has been found for relative low fidelity simulations (e.g., Todorov et al., 1997; Lammfromm and Gopher, 2011). Clearly, more research is needed to determine the specific characteristics of sports training VEs that are important for achieving effective transfer of training.

The present study adds to the (slowly) growing body of evidence on the effectiveness of VE training for sports (reviewed in Gray, in press). It provides evidence of positive, near (performance on tests similar to the training procedures), and far (performance in league play and competition level reached) transfer of training. As has been discussed in the context of research (e.g., Zaal and Bootsma, 2011), the present findings also suggest that the real value of using VE as a training tool for sports is not the ability to create more repetitions of the same types of practice that area used in real training. Instead, the real return on investment for developing a sports VE is likely to come from the ability to create unique, evidence-based training conditions that are impossible or highly impractical to use in real training.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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Taekwondo Fighting in Training Does Not Simulate the Affective and Cognitive Demands of Competition: Implications for Behavior and Transfer

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Enhancing practice design is critical to facilitate transfer of learning. Considerable research has focused on the role of perceptual information in practice simulation, yet has neglected how affect and cognition are shaped by practice environments and whether this influences the fidelity of behavior (Headrick et al., 2015). This study filled this gap by examining the fidelity of individual (cognition, affect, and actions) and interpersonal behavior of 10 highly skilled Australian Taekwondo athletes fighting in training compared to competition. Interpersonal behavior was assessed by tracking location coordinates to analyze distance-time coordination tendencies of the fighter–fighter system. Individual actions were assessed through notational analysis and approximate entropy calculations of coordinate data to quantify the (un)predictability of movement displacement. Affect and cognition were assessed with mixed-methods that included perceptual scales measuring anxiety, arousal, and mental effort, and post-fight video-facilitated confrontational interviews to explore how affect and cognitions might differ. Quantitative differences were assessed with mixed models and dependent *t*-tests. Results reveal that individual and interpersonal behavior differed between training and competition. In training, individuals attacked less ($d = 0.81$, $p < 0.05$), initiated attacks from further away ($d = -0.20$, $p < 0.05$) and displayed more predictable movement trajectories ($d = 0.84$, $p < 0.05$). In training, fighters had lower anxiety ($d = -1.26$, $p < 0.05$), arousal ($d = -1.07$, $p < 0.05$), and mental effort ($d = -0.77$, $p < 0.05$). These results were accompanied by changes in interpersonal behavior, with larger interpersonal distances generated by the fighter–fighter system in training ($d = 0.80$, $p < 0.05$). Qualitative data revealed the emergence of cognitions and affect specific to the training environment, such as reductions in pressure, arousal, and mental challenge. Findings highlight the specificity of performer–environment interactions. Fighting in training affords reduced affective and cognitive demands and a decrease in action fidelity compared to competition. In addition to sampling information, representative practice needs to consider modeling the cognitions and affect of competition to enhance transfer.

Keywords: affective learning design, ecological dynamics, representative learning design, representative design, transfer, Taekwondo

INTRODUCTION

A key issue for practitioners working in competitive sport is enhancing the design of practice to facilitate the transfer of skills from training to competition. One way to enhance practice is through simulating key aspects of competition through the design of representative learning tasks (Araujo et al., 2007; Pinder et al., 2011b; Barris et al., 2014). However, recent theorizing has highlighted that designing adequate simulations of competitive performance environments in practice is not simple and requires consideration of factors other than information and action (Oudejans and Pijpers, 2010; Headrick et al., 2015). For example, in competition performers must adapt to unique constraints such as consequences, prizes, referees, crowds, and unfamiliar opponents, given the complexity of performance environments and an acknowledgment of the impact that affect[1] and cognitions may have on perceptions and actions in high stakes competition, representative practice tasks need to also model the cognitive, affective, and behavioral demands of competition (Pijpers et al., 2006; Headrick et al., 2015). However, currently there is little understanding of the extent to which typical training environments adequately simulate the affective and/or cognitive demands of competition and whether this impacts on the fidelity of training behavior and subsequent transfer. Therefore, the paper aims to explore this issue in a combat sport setting and assess whether Taekwondo fighting in training adequately simulates the affective and cognitive demands of competition, and subsequently, whether the affective-cognitive demands observed in training impact on the representativeness of individual and interpersonal behavior relative to competition. A growing body of work has explored how improving training task design can potentially enhance the learning and transfer of skills to competition environments (Araujo and Davids, 2015). One way to describe the usefulness of different training tasks in sport is through the lens of ecological dynamics (Davids and Araújo, 2010). Ecological dynamics integrates concepts from dynamical systems theory and ecological psychology to understand how athletes coordinate their actions with the surrounding environment (Brunswik, 1956; Gibson, 1979; Kelso, 1995). An underpinning principle of this approach is the need for learners to form functional relationships with their environment (Fajen and Warren, 2003; Fajen et al., 2009).

In sport specific environments, social and physical information supports athletic behavior and provide opportunities for action (Fajen et al., 2009; Rietveld and Kiverstein, 2014). As behavior is regulated prospectively by a continuous process of perceiving and moving, invitations for action emerge in the form of affordances as an athlete moves around the environment picking up information (Gibson, 1979). For instance, in the combat sports, picking up certain postural or kinematic information from an opponent might invite an opportunity to attack. As an athlete learns, they attune to environmental features and the different actions they afford (Gibson, 1979; Bruineberg and Rietveld, 2014). Attunement 'educates' the attention of performers toward the most useful information, improving their 'fit' within the environment (Michaels and Jacobs, 2007; Bruineberg and Rietveld, 2014). The implications for training design in sport are that the coupling between the performer and environment present in competition needs to be preserved so that athlete learnings can transfer between environments.

These implications were captured by marrying concepts from Gibson's ecological psychology and Brunswik's representative design to develop a framework to guide the design of practice environments in sport (Brunswik, 1956; Gibson, 1979; Pinder et al., 2011b). Representative learning design emphasizes the need for the practice task constraints to represent the task constraints of the competition task (Pinder et al., 2011a). Therefore, any practice needs to satisfy this principle if transfer from practice to competition is to be optimized. A way to evaluate the potential for practice to transfer is through the specificity of relationship between performer and environment. The specific nature of this relationship – our actions are tightly coupled to specific information – provides a principled approach for scientists to evaluate the representativeness of different training tasks through comparing the fidelity of action responses (Stoffregen et al., 2003; Pinder et al., 2011b; Davids et al., 2012; Araujo and Davids, 2015).

Action fidelity refers to the correlation between a performance in a reference situation (real world environment) and a performance in a simulated situation (e.g., training) (Stoffregen et al., 2003; Stoffregen, 2007; Pinder et al., 2011b). The concept of fidelity specifically deals with transfer and is assessed in terms of task performance. Fidelity is achieved when behavior in a simulated (e.g., training) task represents the behavior observed in the performance task (Stoffregen, 2007). The fidelity of athlete behavior in learning tasks is known to be impacted when practitioners omit key ecological constraints to create *non-representative* practice conditions (Shim et al., 2005; Pinder et al., 2009; Dicks et al., 2010; Barris et al., 2013; Greenwood et al., 2016). For example, when cricket batters practiced with a ball projection machine as opposed to a human bowler it resulted in re-organized low fidelity action responses (Pinder et al., 2011a). In contrast, fidelity is maintained when practitioners sample key informational constraints from performance environments to design *representative* practice tasks (Dicks et al., 2010; Pinder et al., 2011a; Barris et al., 2013; Greenwood et al., 2016). Designing representative practice tasks that maintain fidelity will theoretically have positive implications for transfer (Brunswik, 1956; Araujo et al., 2007; Pinder et al., 2011b; Araujo and Davids, 2015). However, much of this research has focused on the utility of different external information sources on action fidelity, neglecting to consider how other factors such as affect and cognitions constrain perception and action behavior in sports practice (Pinder et al., 2015).

Researchers in psychology have demonstrated how task and environmental constraints shape the emergence of affective and cognitive responses (Pijpers et al., 2006; Oudejans and Nieuwenhuys, 2009). For example, Nieuwenhuys and Oudejans (2010) compared the behavior of police officers between two different practice tasks: a non-representative task where officers were required to shoot a 'dummy' target that could not move

[1]The term 'affect' will be used to refer to a range of phenomena such as feelings, emotions and mood. The terms affect and emotion will be used interchangeably to follow previous work in the area (Lewis and Granic, 2000; Headrick et al., 2015).

or shoot back versus a more representative task where the target could 'shoot back.' Practicing in the more representative task resulted in higher levels of anxiety and mental effort which were accompanied by poorer performance, quicker movement responses, increased blinking, and changes in postural orientation. Perception and action behaviors declined in the high anxiety task, raising questions about how to best train for tasks and environments that induce high amounts of affect.

An expanding body of work has demonstrated that enhancing the representativeness of practice tasks through the consideration of affective and cognitive demands will improve skill transfer to demanding environments (Oudejans and Pijpers, 2009, 2010; Nieuwenhuys and Oudejans, 2011; Alder et al., 2016). For instance, expert dart players who practiced under anxiety and high amounts of mental effort were able to maintain performance outcomes despite still experiencing high anxiety, arousal, and mental demands in a high anxiety transfer test (Oudejans and Pijpers, 2009). These findings suggest that training in conditions that simulate the affective and cognitive demands of performance environments may provide performers with opportunities to adapt to these performance constraints (Fajen, 2005; Oudejans and Nieuwenhuys, 2009; Rietveld and Kiverstein, 2014).

The importance of ensuring training environments simulate the affective-cognitive demands of performance environments has been captured in recent theoretical work. Affective learning design (ALD) builds on representative learning designs' framework to consider affective and cognitive constraints in conjunction with environmental information (Headrick et al., 2015). Headrick et al. (2015, p. 85) advocate for practice tasks that afford "emotion-laden learning experiences that effectively simulate the constraints and demands of performance environments in sport." The practical application of ALD promotes the design of practice tasks that afford rich competition-like experiences so that athletes are cognitively and affectively engaged so that they *think* and *feel* like they would in competition (Headrick et al., 2015; Pinder et al., 2015). Whilst work has examined affect and cognition in competition settings no studies have looked at whether typical sport training tasks simulate the affective and cognitive demands of competition and what the implications for skill transfer may be (Sève and Poizat, 2006; Hauw and Durand, 2007; Ria et al., 2011; Bridge et al., 2013).

At the elite level, fighting fellow squad members is a key training activity to prepare for combat competitions (Hodges and Starkes, 1996). Using the principle of fidelity, assessment of Taekwondo performance provides an opportunity to gain insight as to whether changes in affective and cognitive demands impact on performance behaviors in competition and training. One candidate performance variable that might be impacted is the interpersonal distance (IPD) of fighters (Dietrich et al., 2010). IPD is a global variable representative of the fighter–fighter system (Okumura et al., 2017). The distance between fighters' provides different affordances for action and different striking techniques emerge and decay depending on this IPD (Hristovski et al., 2006; Okumura et al., 2017). Practically, IPD constrains the respective *attackability* of each fighter (i.e., specific critical IPDs invite an attack or being attacked). Given the influence of cognitive-affective subsystems on perception and action, any changes in affect should manifest in measures of IPD.

The aims of this study were twofold. First, we aimed to assess whether Taekwondo fighting in training adequately simulated the affective and cognitive demands of competition. Second, we wished to use the concept of fidelity to assess whether changes in these demands impacted the representativeness of fighting actions compared to competition. For our first aim it was hypothesized that the training environment would not adequately simulate the affective and cognitive demands of competition due to factors such as familiar opponents and lack of consequences. This would be evident in a reduction in affect (arousal, anxiety, and frequency of reported emotions) and less demanding cognition (mental effort and reported thoughts). In line with ALD, it was reasoned that this would lead to athletes being less emotionally and cognitively engaged in the task, creating intra and interpersonal fighting actions of lower fidelity. These reductions in engagement would manifest through a greater amount of time spent at larger IPD, larger attack initiation IPD, more predictable movement behavior, and fewer attacks.

MATERIALS AND METHODS

The university Human Research Ethics Committee of the first author approved the protocol for this study. All participants provided written informed consent prior to the commencement of the study in accordance with the Declaration of Helsinki.

Participants

Ten international level senior Taekwondo athletes (seven male, three female) participated in the study. The average age of participants was 23 years ($SD = 5$ years). Participants were members of a national team and their demographics can be found in **Table 1**.

Experimental Task

Data were collected during a national training camp. Participants were filmed and participated in mixed methods data collection as

TABLE 1 | Highest level of competition and world ranking range for each participant.

Participant	Highest level of competition	World ranking at testing
1	Olympics*	5–10
2	Olympics*	5–10
3	Olympics	11–20
4	World Championships*	5–10
5	World Championships*	11–20
6	World Championships*	20–50
7	World Championships	100–150
8	G4 International competition*	20–50
9	G2 International competition*	100–150
10	G2 International competition*	50–100

**Denotes multiple times competing at the highest level of competition.*

they fought in two distinct conditions – a typical training fight and a simulated competition fight. Training condition data was collected first during one of the national teams' training sessions. The training condition consisted of the typical training activity of sparring against a fellow national team member. From practice observations, this is one of the teams most common practice tasks and would generally be prescribed multiple times per week. As per usual training custom, the coach acted as the referee and allocated fighters into pairs of similar ability. The composition of these pairs was determined according to the judgment of the national coach, who based the match ups on skill level, sex and weight category. Much like the competition task, the coach would usually provide instructional feedback to the athletes during the fight; however, he did so at his own discretion.

Competition condition data was subsequently collected during a 'friendly' competition against a visiting international team. This condition included competition-specific task constraints of an international opponent, crowd, professional referees, professional judges, and competition for an individual prize for highest score, and a team prize for most collective wins. In order to control for athletes intentions, in both conditions they were given the aim of winning the fight. Players received feedback from their coach at the coaches discretion just as they usually would in competition.

Quantitative Measures

Perceived Anxiety and Arousal

Perceptions of cognitive and somatic anxiety were assessed using the Competitive State Anxiety Inventory-2 (Martens et al., 1990). Autonomic arousal was assessed by collecting the pre-fight average heart rate of participants in the 1 min epoch before the fight started. This approach has been used successfully before in similar studies to infer anxiety and arousal (Nieuwenhuys et al., 2012).

Perceived Mental Effort

Participants perception of mental effort has proved an insightful measure of task demands (e.g., Oudejans and Pijpers, 2009). Consequently, perceived mental effort was determined using the Rating Scale of Mental Effort (Zijlstra, 1993). This scale consists of a vertical axis scale with a range of 0–150 and descriptive anchors from not effortful to awfully effortful and has shown to be reliable across a range of real life settings (Zijlstra, 1993).

Movement Trajectories

To understand the emergent time-distance coordination strategies of fighters the evolution of system behavior was plotted over time for the entire fight. The movement trajectories of the players were manually tracked at 25 frames per second using digitizing software (Kinovea, version 0.8.25). This processes provided x and y coordinates for each participant across the duration of their fight. The court was calibrated using the known distances provided by the 1.00 m × 1.00 m mats that made up the 8.00 m × 8.00 m octagon fighting space. Digitizing consisted of tracking the center of mass, the mid-point between fighters' feet. This was chosen due to past research that had used a similar technique in tracking individual movement trajectories (Headrick et al., 2012). Measurement accuracy was assessed by digitizing eight known distances within the calibrated space. The error of the measurement was found to be 0.02 m. The reliability of the digitizing methods was determined by re-digitizing the first round (2 min, or 33%) of a fight. This provided 3000 x and y coordinates for reliability analysis. The reliability between the two sets of x and y coordinates was assessed using an absolute agreement 2-way mixed effects intra class correlation coefficient (ICC) (Headrick et al., 2012). An acceptable degree of reliability was found: the average ICC for x coordinates was 0.994, 95% CI [0.994,0.995], and the average ICC for y coordinates was 0.997, 95% CI [0.994,0.998].

Interpersonal Distance

Interpersonal distance was determined using Pythagorean Theorem and the x and y coordinates for two fighters with the following calculation:

$$\mathrm{IPD} = \sqrt{(x2 - x1)^2 + (y2 - y1)^2}$$

Attack Initiation Interpersonal Distance

Attack initiation IPD was analyzed using both the video and IPD data following previously published methods (Okumura et al., 2017). Attack initiation was determined using the video and defined as either the first forward movement of an attack, or if the athlete did not move forward, the time at which the foot first left the ground. Attack initiation IPD was defined as the IPD at the onset of attack initiation.

Number of Kicks

The number of attacks was assessed from the video data by counting the number of times participants performed a kicking action.

Qualitative Measures

Self-confrontational Interview

Verbalisation data was collected from individual self-confrontational interviews with each participant using a course-of-action methodology (Theureau, 2003). Self-confrontational interviews are a tool used to 'confront' actors about their context specific behavior soon after that behavior took place and capture their in-performance cognitions and feelings (von Cranach and Harre, 1982). While watching a video replay of the fight, participants were asked to relive their experience and comment and/or answer questions based on what they did, thought, and felt during the fight (Theureau, 2003). These techniques reconstruct meaning actors give to their *in situ* activity through the recall and explanation of experiences (Ria et al., 2011). A number of previous studies have demonstrated how this approach is useful in understanding task demands and complementing quantitative approaches to increase understanding (Sève et al., 2005; Hauw and Durand, 2007; Seifert et al., 2017).

The interviews averaged 46 min in length (SD = 9 min) and were completed by the lead author who was familiar to the participants. To ensure trustworthiness of the data, leading questions that might have influenced the responses were avoided

(Patton, 2002). During the interview both viewers could stop and rewind the video at any point. Generally, the video was stopped by either player or interviewer after an interaction between the two fighters. At this point the player would make a comment or the interviewer would ask a prompting question.

In-fight Emotions

Previous work has used the course-of-action methodology to determine in-competition emotions experienced by participants (Ria et al., 2011). During the confrontation interview participants were asked how they felt throughout the fight (Ria et al., 2011). Previous studies have shown that athletes are able to reliably recall their emotions in retrospect within 7 days (Martinent et al., 2012). To facilitate accurate recall of emotions, participants were provided with a list of emotions based on those reported in the Sports Emotion Questionnaire (SEQ), a 22 item tool developed to measure Emotions in sport (Jones et al., 2005). The list of emotions in the SEQ was developed from two sources: a list of emotions gathered from the literature, and completion of an open-ended questionnaire to identify emotions experienced by athletes in sport. The 22 items of the SEQ collapse into five basic emotions: happiness, anger, dejection, excitement, and anxiety. For the purposes of this study, collected emotions were collapsed into one of those five basic emotions.

Procedure

A repeated measures design was adopted and the procedure for both conditions was identical. **Table 2** details the measures and their timing of collection. Upon arrival participants were fitted with heart-rate monitors (Firstbeat Technologies, Finland). Participants were then instructed to go about their usual warm-up routine before presenting to marshaling 10 min before the fight. At this point participants completed the Competitive State Anxiety Inventory-2. Participants then sat for 1 min before entering the ring to begin their fight. During this period pre-fight heart rate was collected. Fights consisted of three 2-min rounds, separated by a 1 min break. Official World Taekwondo Federation rules were adhered to and scoring was undertaken via the standard electronic protector and scoring system (Daedo TK-Strike, South Korea). Video data was collected using a digital video camera (Sony HXR-NX30P) positioned approximately 4.00 m above ground level, orientated at approximately 45 degrees to the central point of the court (Bartlett, 2007). This data was to be used to digitize player movement trajectories and as a stimulus for the confrontational interview. Following the fight, participants returned to the marshaling area to fill out the Rating Scale of Mental Effort. Within 24 h of the fight finishing participants completed the confrontational interview. None of the participants participated in another fight between data collection and their confrontational interview and were asked to avoid analyzing their fight.

TABLE 2 | Table of measures and their timing of collection.

Measure	Pre-fight	Fight	Post-fight	24 h post-fight
Competitive State Anxiety Inventory-2	X			
Heart rate	X			
Video		X		
Rating Scale of Mental Effort			X	
Interview and in-fight emotions				X

Quantitative Analysis

The predictability of participants' movement trajectories was assessed by running the x and y coordinates of each participant in each condition through a sample entropy equation. The analysis for sample entropy was carried out using the R package RACMA (Borchers, 2017; R Core Team, 2017).

Interpersonal distance frequency and attack initiation IPD were analyzed descriptively by calculating the relative percentage of total observations that occurred in each 0.20 m IPD region between 0.00 m and 4.00 m in each condition (Okumura et al., 2017). The first zone was 0.00–0.20 m, the next zone 0.21–0.40 m, and so forth. For both variables (IPD frequency and attack initiation IPD) the 0.20 m IPD regions with the largest relative percentage of observations were selected for statistical comparison between conditions. These were called peak IPD frequency and peak attack initiation IPD.

Differences between competition and training conditions in perceived cognitive and somatic anxiety, mental effort, pre-fight heart rate, peak IPD frequency, peak attack initiation IPD and the number of kicks were analyzed using paired t-tests and Cohen's d effect size calculations (Cohen, 1988). These were analyzed using SPSS computer software (version 19.0).

Differences between conditions for the entropy scores, attack initiation IPD, and in-fight emotion frequency were analyzed using linear mixed models, also performed in SPSS. The entropy mixed model had two fixed factors and one random factor; fixed factors: condition (training or competition) and coordinates (x or y), random factor: participant. The attack initiation IPD model had one fixed factor and one random factor; fixed factor: condition (training or competition), random factor: participant. The in-fight emotion frequency mixed model had two fixed factors and one random factor; fixed factors: condition (training or competition) and emotion (anger, anxiety, dejection, excitement, or happiness); random factor: participant. Significant effects were further investigated with pairwise comparisons using Bonferroni corrected alphas. Assumption testing of the residual values was carried out for all models and no violations were observed.

Qualitative Analysis

The verbal data were analyzed using a four step methodology (Theureau, 2003; Gernigon and Arripe-longueville, 2004): (1) Producing a summary table of time-matched actions and verbal data, (2) Establishing the elementary units of meaning (EUM) for an individual, (3) Reconstructing the course of action for each EUM and labeling the EUM with a name representative of its content, (4) Grouping EUMs into like categories exclusive to either training or competition conditions (d'Arripe-Longueville et al., 2001; Theureau, 2003).

For the first step, two types of data were collated and paired chronologically: the verbatim transcripts from the confrontational interviews and match logs of the participants' observed behavior during their fights. The second step consisted of identifying the smallest courses of action that were meaningful for each individual. For Taekwondo fighters this was generally confined to an interaction (attack or defense) with their opponent. The third step required identifying the underlying components of each elementary unit of meaning: the object, representment and interpretant (Hauw and Durand, 2007). This was achieved by asking a set of specific questions about the data: what is the participants' intention (object)? What part of the situation is the athlete perceiving or making judgment of (representment)? And what prior knowledge is the athlete using to interpret the situation (interpretant)? An object is linked to a representment through an interpretant. When these components are linked together, an EUM emerges. The third step also included naming the EUM with a label representative of the contents (d'Arripe-Longueville et al., 2001; Gernigon and Arripe-longueville, 2004). EUMs were grouped into categories corresponding to higher order themes, which were then grouped into broader categories termed dimensions (d'Arripe-Longueville et al., 2001; Gernigon and Arripe-longueville, 2004). Summary labels were used for each grouping variable (d'Arripe-Longueville et al., 2001; Gernigon and Arripe-longueville, 2004). Finally we characterized the experience of the participants in competition and in training, specifically we were interested in the dimensions that lead to divergent experiences related to the affective and cognitive demands of each environments (Kiouak et al., 2016).

RESULTS

A summary of quantitative results can be found in **Table 3**.

Perceived Anxiety and Arousal

Perceived anxiety and arousal graphed results can be found in **Figure 1**. Greater levels of cognitive anxiety were reported in the competition condition ($M = 17.3$, $SD = 4.35$) compared to the training condition ($M = 15.2$, $SD = 3.73$); $t(9) = 3.99$, $p < 0.05$, $d = 1.26$.

Greater levels of somatic anxiety were reported in the competition condition ($M = 17.8$, $SD = 4.85$) than the training condition ($M = 15.0$, $SD = 3.83$); $t(9) = 3.38$, $p < 0.05$, $d = 1.07$.

Confidence levels were lower in competition ($M = 21.6$, $SD = 4.60$) compared to training ($M = 24.70$, $SD = 4.67$); $t(9) = -2.99$, $p < 0.05$, $d = -0.95$.

One minute pre-fight average heart rate was higher in competition ($M = 129.0$, $SD = 8.93$) compared to training ($M = 116.1$, $SD = 7.10$); $t(9) = 3.44$, $p < 0.05$, $d = 1.09$.

Perceived Mental Effort

Fighters reported greater levels of mental effort (**Figure 2**) in the competition ($M = 102.5$, $SD = 26.79$) compared to the training condition ($M = 77.5$, $SD = 27.87$); $t(9) = 2.43$, $p < 0.05$, $d = 0.77$.

Movement Trajectories

The linear mixed model revealed a significant fixed effect for condition, $F(1,28) = 12.408$, $p = 0.001$ (**Figure 3**). *Post hoc* pairwise comparisons revealed that the movement trajectories of participants were more unpredictable in competition ($M = 0.15$, $SD = 0.06$) compared to training ($M = 0.11$, $SD = 0.03$), $p = 0.001$, 95% CI [0.01, 0.07], $d = 0.84$. There was no significant effect for coordinates $F(1,28) = 3.18$, $p = 0.085$.

Interpersonal Distance Frequency

The percentage scores for time spent at each IPD (**Figure 4**) reveal that the peak region of IPD frequency was closer in competition ($M = 177.0$ cm, $SD = 8.23$) compared to training ($M = 187.0$ cm, $SD = 11.6$); $t(9) = -2.45$, $p < 0.05$, $d = -0.80$.

Attack Initiation Interpersonal Distance

The linear mixed model revealed a significant fixed effect for condition $F(1,981.77) = 10.631$, $p = 0.001$. *Post hoc* pairwise comparisons revealed that attack initiation IPD was closer in competition ($M = 156.87$, $SD = 47.25$) compared to training ($M = 166.62$, $SD = 48.70$), $p = 0.001$, 95% CI [−16.088, −3.999], $d = -0.203$. These results can be found graphed in **Figure 5**.

Analysis of the peak IPD zone of attack (**Figure 6**) was closer in competition ($M = 188.0$ cm, $SD = 13.98$) compared to training ($M = 206.0$ cm, $SD = 18.97$); $t(9) = -3.86$, $p < 0.05$, $d = -1.22$.

Number of Kicks

The number of kicks was greater in competition ($M = 67.4$, $SD = 13.23$) compared to training ($M = 55.8$, $SD = 12.14$); $t(9) = 2.57$, $p < 0.05$, $d = 0.81$.

Self-Confrontational Interview

Self-confrontational interview data can be seen summarized in **Tables 4**, **5**.

In-fight Emotions

In-fight emotion frequency results are summarized in **Figure 7**, while exemplar data is provided in **Figure 8**. Results of the linear mixed model revealed no significant interaction between emotion and condition. There was, however, a significant fixed effect of emotion, $F(4,81) = 7.141$, $p = 0.000$, and a significant fixed effect for condition, $F(1,81) = 16.363$, $p = 0.000$. *Post hoc* pairwise comparisons revealed that the mean frequency of each emotion was greater in competition ($M = 3.20$, $SD = 2.39$) compared to training ($M = 1.70$, $SD = 1.71$), $p = 0.000$, 95% CI [0.76, 2.24], $d = 0.63$.

DISCUSSION

Research has focused on the role of physical information when designing representative learning environments, yet has neglected the role of affect and cognition and how they might influence the representativeness of behavior (Pinder et al., 2011a; Headrick et al., 2015). The aims of the study were to assess whether Taekwondo fighting in training adequately simulates the

TABLE 3 | Results summary of perceived anxiety, arousal and perceived mental effort.

Variable	Training average	Competition average	*t* statistic	*p*	Mean difference	*SE* difference	Cohen's *d*	95% Confidence Interval	
								Lower	Upper
CSAI-2 cognitive anxiety	15.2 ± 3.74	17.3 ± 4.35	3.99	0.003*	2.1	0.53	1.26	0.91	3.29
CSAI-2 somatic anxiety	15.0 ± 3.83	17.8 ± 4.85	3.38	0.008*	2.8	0.83	1.07	0.93	4.67
CSAI-2 confidence	24.7 ± 4.67	21.6 ± 4.60	−2.99	0.015*	−3.1	1.04	−0.95	−5.45	−0.75
Rating Scale of Mental Effort	77.5 ± 27.87	102.5 ± 26.79	2.43	0.038*	25	10.27	0.77	1.77	48.23
Ave pre-fight heart rate (BPM)	116.1 ± 7.06	129.0 ± 8.93	3.44	0.007*	12.98	3.77	1.09	4.45	21.51
Number of kicks	55.8 ± 12.14	67.4 ± 13.23	2.57	0.03*	11.6	4.51	0.81	1.40	21.80
Peak IPD frequency (cm)	187.0 ± 11.6	177.0 ± 8.23	−2.54	0.032*	−10	3.94	−0.80	−18.92	−1.08
Peak attack initiation IPD (cm)	206.0 ± 18.97	188.0 ± 13.98	−3.86	0.004*	−18	4.67	−1.22	−28.56	−7.44

**Denotes statistical significance ($p < 0.05$).*

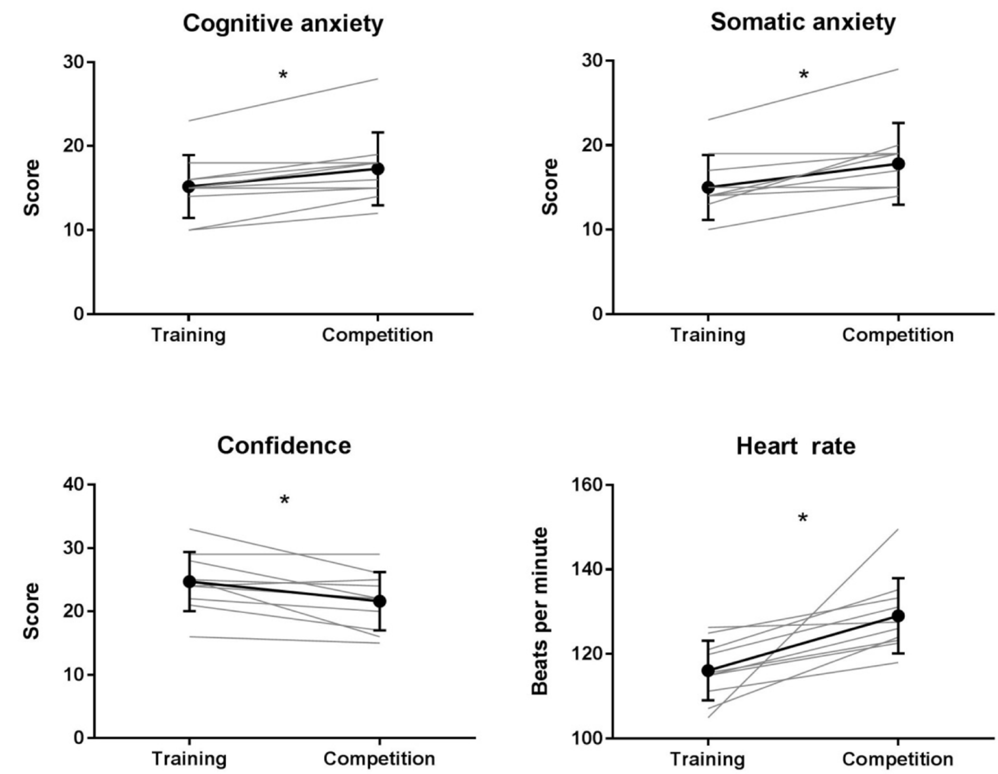

FIGURE 1 | CSAI-2 factors: cognitive anxiety, somatic anxiety and confidence, and one minute pre-fight heart rate average for training and competition fights. Mean results and standard deviations are presented in bold, individual results are presented in light gray. *Indicates a significant difference between conditions ($p < 0.05$).

affective and cognitive demands of competition and secondly whether the affective-cognitive demands observed in training impact on the representativeness of individual and interpersonal behavior relative to competition.

When fighting in training, participants reported lower levels of anxiety, arousal. and mental effort and reported different goals, suggesting that fighting in training does not recreate the cognitive and affective demands of competition. These decreased demands were associated with individual and interpersonal behavior of lower fidelity. In training, individual fighters performed fewer kicks and attacked from further away, whilst the fighter–fighter system generated larger IPDs. The data show reductions in cognitive and affective demands are associated with different individual and interpersonal fighting behavior in training. The discussion will first cover each factor individually (affect, cognition, and behavior) before discussing possible interactions between the three and the implications for the design of representative learning environments and skill transfer.

The Affective Demands of Training

The first aim of this study involved comparing the affective demands of fighting in training relative to competition. Results from the perceptual scales, interviews and pre-fight maximum heart rate were all congruent: fighting in training has reduced

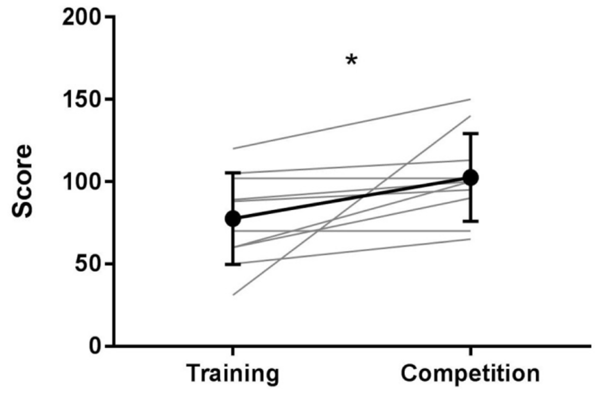

FIGURE 2 | Rating scale of mental effort results for training and competition fights. Mean results and standard deviations are presented in bold, individual results are presented in light gray. *Indicates a significant difference between conditions ($p < 0.05$).

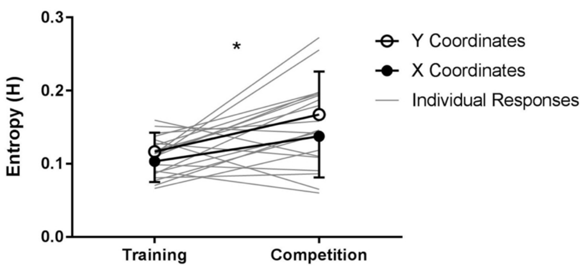

FIGURE 3 | Predictability of movement trajectories assessed using sample entropy (H) for training and competition fights. Mean results and standard deviations are presented in bold for both x and y coordinates, individual results are presented in light gray. *Indicates a significant main effect for condition ($p < 0.05$).

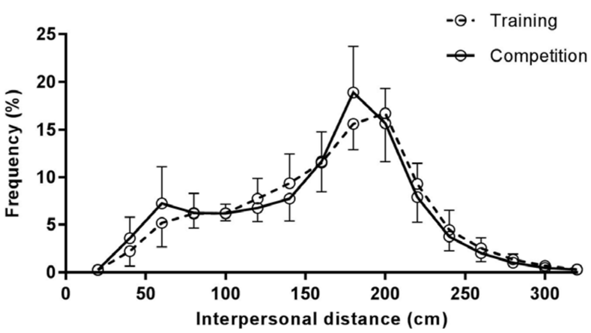

FIGURE 4 | Percentage of time spent at interpersonal distances in training and competition fights. Interpersonal distances are presented in 0.20 m bins.

affective demands relative to competition. The triangulation of these results suggests that fighting in training alone does not afford similar levels of arousal and anxiety as fighting in competition. Exemplar interview data reveals the extent of this issue with one fighter: "This is a common problem for me. I'm not very stimulated and I'm in a bad mood. Whenever

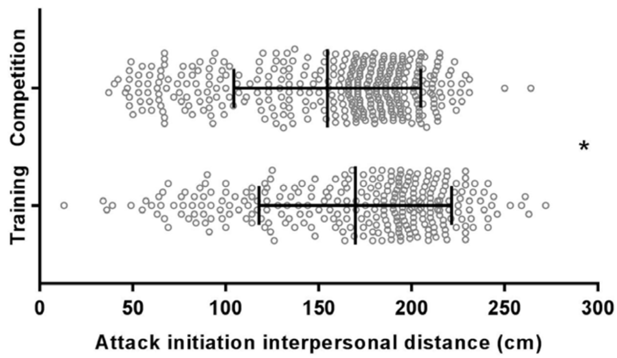

FIGURE 5 | Interpersonal distance of all attacks initiated in training and competition fights. Mean results and standard deviations are presented in bold, individual attacks are presented in light gray circles. The mean and standard deviation is presented. *Indicates a significant fixed effect of condition ($p < 0.05$).

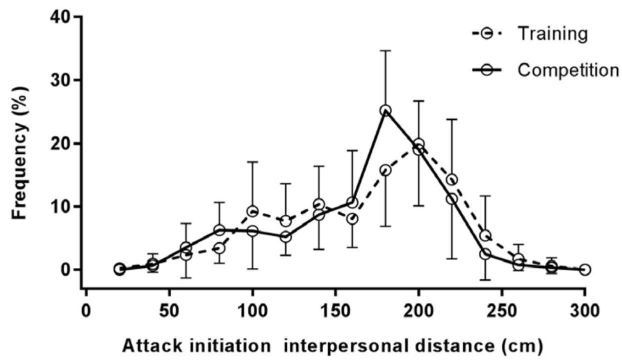

FIGURE 6 | Percentage of attacks initiated from interpersonal distances in training and competition fights. Interpersonal distances are presented in 0.20 m bins.

I'm fighting<players of own nationality> I struggle to get stimulated – I am not challenged." And: "I'm not in the zone, this isn't how I would want to feel in competition." This finding is in line with previous work that has demonstrated differences in arousal and anxiety between training and performance environments (Haneishi et al., 2007; Bridge et al., 2013; Fernandez-fernandez et al., 2015).

During the training fights participants reported a reduced frequency of emotions. These results support the dynamic nature of emotions in sport which suggests emotions emerge and decay based on performance situations (Cerin et al., 2000; Hanin, 2003; Ria et al., 2011; Martinent et al., 2012). One of the key practical applications of ALD is the need to design training tasks that emotionally engage athletes regardless of valence. The reduced number of emotions experienced by athletes in training suggests that fighting in training may not be as engaging compared to competition, perhaps due to absence of stimulating competition-factors like prizes, judges and a crowd. Overall, these results may have implications for the transfer of skills between performance settings. Learning to cope with emotions created by performance

TABLE 4 | Synthesized interview data from the competition condition relating to affective-cognitive differences between environments.

	Competition	
Dimensions	**Themes**	**EUM examples**
Arousal (20 EUMs)	High individual arousal	Feel 'switched on' and ready to fight
		Feeling fast
	High fight intensity	Defend high intensity attack from opponent
		Lift fight intensity to match opponent
Mental challenge (38 EUMs)	Problem solving	Thinking about tactics/techniques that might be useful
		Hypothesis test possible tactical/technical solution
	Opponent unfamiliarity	Surprised by opponents actions
		Unsure what tactics/techniques will be successful
	Difficulty executing own techniques/tactics	Difficulty executing technique or tactic
		Opponent able to absorb attack
Pressure (38 EUMs)	Task pressure	Under pressure due to position on the court
		Under pressure due to the score
	Opponent pressure	Feel uncomfortable due to the aggressive nature of opponent
		Concerned about head kick from opponent

TABLE 5 | Synthesized interview data from the training condition relating to affective-cognitive differences between environments.

	Training	
Dimensions	**Themes**	**EUM examples**
Low arousal (27 EUMs)	Low individual arousal	Unsuccessfully attempt to enhance arousal level
		Feeling sluggish
	Low fight intensity	Low intensity attack from opponent
		Avoiding engagement
Low mental challenge (33 EUMs)	Use established knowledge of opponent	Select tactic/technique based on prior knowledge of opponent
		Anticipate opponents behavior based on prior knowledge
	Not challenged by opponent	Able to absorb opponents attack
		Have established attack/defense solution ready

environments such as competition can be as important as a learning technique (Pinder et al., 2015). Research assessing the affective demands of learning environments shows that superior transfer of performance is observed when the practice environment closely simulates these demands (Nieuwenhuys et al., 2009; Nieuwenhuys and Oudejans, 2011).

The Cognitive Demands of Training

The current results suggest that training fights were less cognitively demanding compared to competition. This was evident in participants' perceptions of mental effort, which was significantly lower in the training fight. Further, a dimension related to mental challenge emerged from the interview data in both training and competition. In training participants reported a low mental challenge as they used prior knowledge of their opponent to aid their own action selection and to predict what their opponent would do. For instance, one participant mentioned "If I push him on the back foot he will do something stupid. He doesn't have a good left leg under so I know I can attack. I know his game and what he's trying to do." Contrastingly, in competition, participants were less familiar with their opponents so spent time determining what their opponent was trying to do. "I'm trying to get him to move backward. I'm cutting[2] and he's not moving. I'm thinking what's going on? Normally if I cut, he should move back, but he's not. So I'm trying to process the whole thing and I'm thinking I need to change my tactics." These results confirm previous work on in-competition courses of action which showed table tennis players spent time constructing and validating knowledge of their opponent and strive to build a model of their opponents weaknesses and intentions (Sève and Poizat, 2006). Our findings extend this literature by showing that in training against familiar opponents, players are less likely to cognitively problem solve compared to when they are fighting unfamiliar opponents in competition. In the future it would be interesting to examine whether these changes in cognitive demands would still be observed when players are fighting a familiar opponent in competition. Overall, the triangulation of these results suggests

[2]The cut kick is a Taekwondo kicking technique.

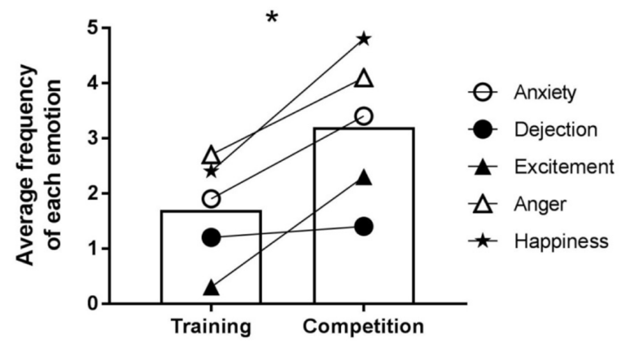

FIGURE 7 | Average frequency of each recalled in-fight emotions for training and competition fights. *Indicates a significant fixed effect for condition.

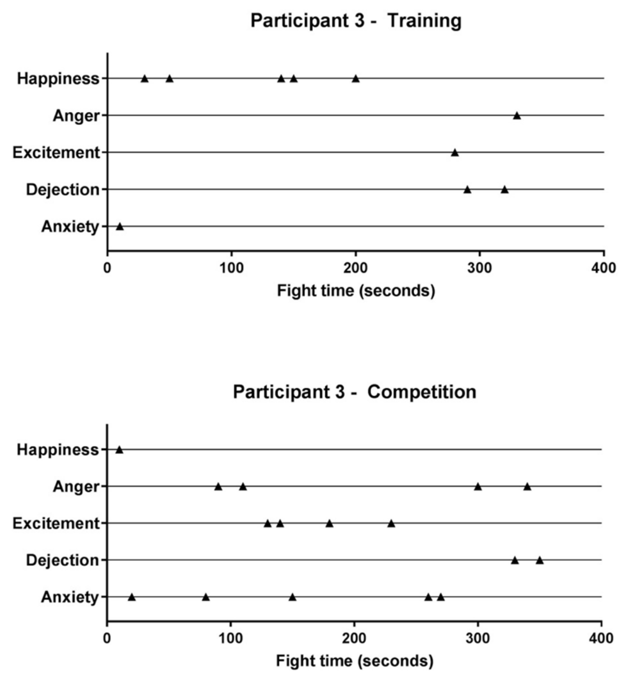

FIGURE 8 | Exemplar data for the temporal arrangement of recalled in-fight emotions for training and competition fights.

that simply fighting in training is not as cognitively demanding as fighting in competition. This has potential implications for training design, where tasks should be appropriately challenging to the individual to facilitate skill learning (Guadagnoli and Lee, 2004).

Individual and Interpersonal Behavior

The second aim of this paper was to assess whether the affective and cognitive demands of the training environment were associated with changes in the fidelity of individual and interpersonal fighting behavior. Behaviors are of low fidelity when they are not representative of those observed in a reference environment (Stoffregen, 2007). When behavior in training tasks is of low fidelity compared to competition, it is likely to compromise the transfer potential of sporting skills (Pinder et al., 2009; Barris et al., 2013). The results of this study reveal that the individual and interpersonal actions of the fighters were different in training. In training, participants kicked less, initiated their attacks from further away and displayed more predictable movement displacement. The interpersonal coordination of fighters was also different as the fighter–fighter system generated larger IPDs.

The larger IPDs generated by the fighter–fighter system in this study would suggest that different actions are afforded and supported in training. In the combat sports, action selection is based on the scaled distance between a striker and their target (Hristovski et al., 2006). Certain distances afford and support specific striking actions. For instance, intermediate IPDs encourage flexible behaviors by affording a greater variety of striking actions (Hristovski et al., 2006). However, at larger IPDs (those approaching and exceeding an individual's maximum reach) fewer actions are afforded, and at a critical distance, no striking actions are supported (Hristovski et al., 2006). At these larger IPDs, athletes exhibit less flexible action solutions, perhaps explaining why fewer kicks were recorded in the training environment. Simply put, the distances that fighters spent their time at in training does not afford the same number of actions as the closer distances in competition did, nor does it afford players as many opportunities to develop the flexible action solutions required at smaller IPDs.

These differences may also have implications for perceptual attunement and the way learners educate their attention (Michaels and Jacobs, 2007). A key aspect of learning is attuning to the most useful sources of information to support the selection and control of action (Fajen et al., 2009). As learners progress, the information they use evolves in a Darwinian sense as more useful sources of information are identified (Michaels and Jacobs, 2007). Therefore, if participants spend their time at larger IPDs, they may not be afforded opportunities to attune to the most useful sources of information. The results of this study suggest that when fighting in training, Taekwondo athletes are not placed under the same levels of perceptual stress as in competition, where they are forced to co-adapt to opponents movements which are more unpredictable and occur at closer distances. This has possible negative implications for transfer given that players are not practicing adapting to opponents at IPD representative of competition.

These results highlight how emergent behavior may be shaped by a complex interaction between affect, cognition, and action (Headrick et al., 2015). For instance, behavior in the training environment is associated with lower levels of arousal and anxiety interacting with reduced cognitive demands to constrain the type of fighting behavior that was observed: fewer attacks and more time spent at IPDs further away from their opponent. These results align with earlier work in sport, which highlights how changes in affect constraints the way people perceive and act within the world (Pijpers et al., 2006). An ecological dynamics approach would suggest that learning is the product of continued agent–environment interactions that lead to the emergence of functional patterns of behavior (Fajen and Warren, 2003). This means that sportspeople adapt to the environment and social situations they find themselves participating in (Oudejans and Pijpers, 2009; Rietveld and Kiverstein, 2014). This highlights the importance of designing practice simulations that adequately represent the affective and cognitive constraints and demands of the competition environment.

Implications for Training Design and Transfer

These findings highlight a limitation of the focus on preserving or simulating perceptual information from competition to enhance skill learning and transfer (Pinder et al., 2011b). Previous work has focused largely on the information stimulus and action responses of learners; however, these results suggest that practice design is a complex issue and requires consideration of other factors such as affect and cognition (Pinder et al., 2015). For instance, fighting in training satisfies principles of representative design as it is predicated upon the same 'information' (i.e., another opponent) as the competition environment. However, when fighting in training, Taekwondo athletes are clearly solicited by a different field of affordances, which is evident in the low fidelity action responses. To ensure transfer it has been suggested that training tasks should be assessed not by the representativeness of information, but instead by the affordances on offer and the performances they support (Araujo and Davids, 2015). Araujo and Davids (2015) argued that behavior of lower fidelity is acceptable if it 'emerges under the constraints of the competitive performance environment. However, for this to be true, our data suggests we may need to also consider not just the informational properties, but the affective and cognitive constraints and demands (Headrick et al., 2015).

One way to sample affordances that solicit representative action, cognitive and affective responses is through following a principled approach such as ALD (Headrick et al., 2015). One of the claims of ALD is that practitioners need to sample, predict and plan for the potential affective and cognitive circumstances in competition. Practically, ALD suggests creating scenarios and vignettes sampled from the competitive environment so that athletes think, feel, and act like they would in competition (Headrick et al., 2015). Therefore, sampling the affordances that consider affective and cognitive demands from the performance environment is an important principle that should be satisfied for the transfer of behavior between settings (Araujo and Davids, 2015).

CONCLUSION

This study showed that fighting in training does not adequately simulate the affective and cognitive demands of fighting in competition. These reduced demands are associated with individual and interpersonal behavior of low fidelity relative to competition. Therefore, we highlight the importance of considering the often overlooked aspects of affect and cognition when designing representative practice environments. Simply fighting in training does not simulate the constraints and demands of fighting in competition due to lower levels of anxiety and arousal, decreased mental challenge, and different movement behavior. Consequently, this is likely to negatively impact on skill transfer from training to competition.

AUTHOR CONTRIBUTIONS

MM, DF, IR, JH, and DM contributed to the design of the work. MM and DM acquired the data. MM, DF, IR, and JH contributed to the interpretation of the data. MM drafted the work. MM, DF, IR, JH, and DM revised the work critically. MM, DF, IR, JH, and DM approved the final version to be published. MM, DF, IR, JH, and DM agreed to be accountable for all aspects of the work.

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The Quiet Eye and Motor Expertise: Explaining the "Efficiency Paradox"

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It has been consistently reported that experts show longer quiet eye (QE) durations when compared to near-experts and novices. However, this finding is rather paradoxical as motor expertise is characterized by an economization of motor-control processes rather than by a prolongation in response programming, a suggested explanatory mechanism of the QE phenomenon. Therefore, an inhibition hypothesis was proposed that suggests an inhibition of non-optimal task solutions over movement parametrization, which is particularly necessary in experts due to the great extent and high density of their experienced task-solution space. In the current study, the effect of the task-solution space' extension was tested by comparing the QE-duration gains in groups that trained a far-aiming task with a small number (low-extent) vs. a large number (high-extent) of task variants. After an extensive training period of more than 750 trials, both groups showed superior performance in post-test and retention test when compared to pretest and longer QE durations in post-test when compared to pretest. However, the QE durations dropped to baseline values at retention. Finally, the expected additional gain in QE duration for the high-extent group was not found and thus, the assumption of long QE durations due to an extended task-solution space was not confirmed. The findings were (by tendency) more in line with the density explanation of the *inhibition hypothesis*. This density argument suits research revealing a high specificity of motor skills in experts thus providing worthwhile options for future research on the paradoxical relation between the QE and motor expertise.

Keywords: gaze behavior, motor learning, quiet eye, task-solution space, inhibition hypothesis

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INTRODUCTION

Expertise in sport is characterized by consistently superior performance of an athlete over a long period of time (e.g., Starkes, 1993). Based on the great efforts that have been put toward the study of motor-skill learning over the last decades (for an overview, e.g., Baker and Farrow, 2015), superior visual behavior has been identified as a hallmark of expertise (e.g., Ericsson, 2017). In this regard, experts show more fixations of longer durations on task-relevant areas and, conversely, fewer fixations on task-irrelevant areas. In addition, experts utilize longer saccades and shorter fixation latencies to task-relevant objects (Mann et al., 2007; Gegenfurtner et al., 2011).

The quiet eye (QE) – defined as the final fixation or tracking gaze at a task-relevant location prior to the initiation of the final phase of the movement (Vickers, 2007) – is a phenomenon that exemplifies expertise-related differences in fixation behavior (Vickers, 1996). In a typical QE study, Causer et al. (2010) investigated the visual behavior of elite and sub-elite athletes in trap shooting. They found longer relative QE durations for hits (M = 60.7%) than for misses (M = 56.5%).

Moreover, elite shooters showed longer relative QE durations (M = 62.6%) than their less-skilled counterparts (M = 54.7%). Likewise, Causer et al. (2017) reported longer QE durations in trials with a low (M = 1180 ms) than in trials with a high radial error (M = 845 ms) in a golf-putting task. To date, the QE has been studied in more than 25 different motor tasks (Vickers, 2016) and a number of reviews (e.g., Causer et al., 2012; Wilson et al., 2015) as well as meta-analyses (Mann et al., 2007; Lebeau et al., 2016; Rienhoff et al., 2016) suggest the significance of this phenomenon.

Despite the robustness of the empirically identified phenomenon and some progress over the recent years (for an overview, e.g., Gonzalez et al., 2015), the mechanisms underlying the QE effect are still not well-understood. This particularly concerns the paradoxical finding of increasing QE durations with increasing motor expertise that was labeled the "efficiency paradox" by Mann et al. (2016). On the one hand, this paradox is based on the observation that motor expertise is generally characterized by an economisation of behavior and an "automatization" of underlying control processes (e.g., Fitts and Posner, 1967). Such an efficiency increase is, for example, reported by Maslovat et al. (2011) who showed decreased reaction times – indicating decreased processing demands – in retention tests after learning a one-handed aiming task (for an overview, see McMorris and Graydon, 2000). On the other hand, with respect to the QE, Williams et al. (2002) explain their finding of increased QE durations in billiards as a function of task difficulty, with increasing demands for the fine-tuning of the movement. However, if expertise is characterized by an economisation of control processes and if, as suggested by Williams et al. (2002), the QE reflects the time needed for information processing over motor control, then a reduction rather than an extension of the QE duration should be expected with growing expertise.

Consequently, Klostermann et al. (2014a) proposed an alternative explanation of the QE phenomenon that is still rooted in the cognitive domain but does not emphasize the amount of information that needs to be processed over the QE interval. Drawing on the selection-for-action mechanism proposed by Neumann (1996; see also Allport, 1987, as well as Cisek and Kalaska, 2010), rather a "shielding mechanism" over the QE period is suggested that inhibits the preparation of non-optimal task solutions such that only the optimal movement variant is executed. To this effect, the QE would simultaneously support the continuous process of action selection from the distributed representations of response options (see also Cisek and Kalaska, 2010, p. 278). On the basis of this functionality, it can be hypothesized that the increasing number of alternative task solutions gathered over years of practice comes with increasing shielding demands that, in turn, lead to the prediction of longer QE durations for experts than for novices or near-experts. Hence, the *inhibition hypothesis* as proposed by Klostermann et al. (2014a) offers a straightforward explanation to the finding of increasing QE durations with increasing motor expertise.

When attempting to empirically test the *inhibition hypothesis*, first off, one must elaborate in which way the assumed shielding process might be hindered by a task-solution space of an experienced expert. In this regard, two variables become relevant. On the one hand, the QE of an expert might be increased due to the *extension* of his/her task-solution space, meaning that task variants far from the "standard" solution had been experienced in such a way that these solutions are combined in one single space. On the other hand, the QE duration might also be prolonged as a function of the *density* of the task-solution space, meaning that a lot of different task variants very close to the "standard" solution had been experienced that thus allow the expert to better fine-tune the movement and perform the task with low variance.

Findings recently reported by Horn et al. (2012) can be interpreted to support the extent explanation of the *inhibition hypothesis*. In their study, participants performing a dart-throwing task with random practice showed longer QE durations than participants with a blocked-practice protocol. Because random practice is suggested to enhance the formation of rules over the entire task-solution space (Magill and Hall, 1990), random practice can be understood as extending the gathered experience over the task-solution sub-spaces. When illustrating this argument with the example of basketball throws from a variety of different positions: if throws from positions A, B, and C are practiced in a blocked fashion, players can be expected to form separate rules for each position which results in separate task-solution sub-spaces for positions A, B, and C. If, however, the positions are randomly varied, players can be expected to conceive the positions as belonging to one and the same task which results in the formation of rules for one single task-solution space. It should be noted that the two players do not differ with respect to their individual space's density but rather regarding the extent of the abstracted space. When being required to perform a throw from position B, the player with the more extended task-solution space then needs to shield the current movement variant against more alternative solutions than the player with the less extended task-solution space. Consequently, on the basis of the *inhibition hypothesis*, longer QE durations can be expected for random practice than for blocked practice.

However, since Horn et al. (2012) only measured performance effects, it remains unclear whether the reported findings also hold for motor learning. Consequently, the current study sought to extend the findings of Horn et al. (2012) by (1) introducing a retention test. Further, considering the expertise-related context, (2) a significant prolongation of the learning phase seemed advisable. Finally, (3) more differentiated treatments were compared that better meet the specific requirements of the extent explanation. To this end, two groups of participants trained a far-aiming ball-throwing task with the non-dominant hand. Whilst the low-extent group practiced a small number of task variants in a block-wise fashion as in the Horn et al. (2012) study, the high-extent group trained a large number of task variants, which were presented in a structured rather than a random order to further push participants to abstract rules over the entire task-solution space rather than over separate subspaces (see Hossner et al., 2016). The main prediction for the group comparison concerns the QE variable, as we expected longer durations in post-test and retention test for the high-extent group when compared to the low-extent group. In order to guard this prediction from potential contamination by confounding variables, task variants needed to be chosen for the test phases that could be expected to lead to comparable amounts of learning for both groups. Therefore, with regards to motor learning, it was only predicted that both groups improved performance from pretest to post-test and retention test. In cases of performance differences, however, this effect would be needed to be considered as a confounding variable, meaning that a more pronounced QE extension of the high-extent group could alternatively be explained by the higher motor expertise.

MATERIALS AND METHODS

Participants

Nineteen male (age: 22.5 ± 1.4 years) and 11 female (age: 21.0 ± 1.0 years) right-handed sport-science students volunteered in the study and received course credits in return. The participants were assigned to one of two intervention groups on the basis of their pretest throwing performance and gaze behavior. All participants had self-reported normal or corrected-to-normal vision, and all were unaware of the research question. Written informed consent from the participants were obtained in advance. This study was carried out in accordance with the 1964 Declaration of Helsinki. The protocol was approved by the ethics committee of the Faculty of Human Sciences of the University of Bern.

Apparatus

A 10-camera Vicon-T20 system (200 Hz, VICON Motion Systems Limited, Oxford, United Kingdom) assessed participants' throwing performance as well as the movements of the throwing arm. For this reason, balls were manufactured from retro-reflective fabric that is detectable by the VICON cameras and a rigid cluster composed of four retro-reflective markers was attached to the throwing arm.

The gaze behavior was assessed with a mobile eye-tracker (220 Hz, EyeSeeCam, EyeSeeTec GmbH, Fürstenfeldbruck, Germany). For power supply and data transfer, the EyeSeeCam was connected via an active FireWire extension (GOF-Repeater 800, Unibrain, San Ramon, CA, United States) to a MacBook Pro (Apple, Cupertino, CA, United States), which was connected to the VICON workstation for the synchronization of EyeSeeCam and VICON data. Three additional VICON markers attached to the EyeSeeCam recorded the three-dimensional (3D) translation and rotation of the participant's head. Combining the head movements with the vertical and horizontal rotations of the left eye – assessed by the EyeSeeCam via reflection of infrared light from the pupil and the cornea – a 3D gaze vector was calculated in the laboratory frame of reference. The accuracy of the EyeSeeCam system amounts to 0.5° of visual angle with a resolution of 0.01° RMS within 25° of the participant's field of view (Kredel et al., 2015).

At the beginning of each test session, the EyeSeeCam was calibrated by consecutively fixating five dots. The positions of the dots were calculated based on the current 3D translation and rotation of the participants head and were then accordingly displayed on a life-size screen (height: 2.0 m, width: 3.5 m) with gaps of 8.5° of visual angle between horizontally or vertically neighboring dots. The accuracy of the gaze measurement was verified at the beginning and halfway through each test block of 16 trials. The EyeSeeCam was recalibrated if the point of gaze deviated more than 1° of visual angle from one of the points of the calibration grid.

The target stimuli to be hit were displayed on a life-size screen (height: 2.0 m, width: 3.5 m) with an LCD projector (Epson H271B LCD Projector, Nagano, Japan). Standing with their feet shoulder-width apart, the participants were positioned at a distance of 3.1 m to the screen. On their right side, a box was positioned at hip height that contained numerous retro-reflective balls (50 mm in diameter). At a distance of 2 m behind the participants, two loudspeakers (Microspot Multimedia CP 250, Microspot, Moosseedof, Switzerland) were installed that played audio stimuli for signaling the beginning of the each throwing attempt, thereby forcing participants not to hasten through the data-acquisition phase and rather focus on accuracy in each single trial.

All stimuli were programmed with Mathworks Matlab 2016a (The Mathworks, Inc., Natick, MA, United States) and rendered with Magix Video Pro X3 (Magix Software GmbH, Berlin, Germany). Data analyses were conducted with Mathworks Matlab 2016a and IBM SPSS Statistics 24 (IBM, Armonk, NY, United States).

Procedure

The study was conducted in the institute's sensorimotor laboratory in which participants had to attend 10 individual sessions of about 45 min each. After having read the instructions, the participants were equipped with the marker cluster and the EyeSeeCam. Following the first calibration, the test or intervention session started. Participants' task was to always throw a ball as precisely as possible at a target (size: 240 mm in diameter) by performing a pendulum-like underhand throwing technique with the non-dominant (i.e., left) hand. As depicted in **Figure 1**, 11 targets were used that were arranged in a vertical line on the screen at equal distances of 200 mm and at heights ranging from 2200 mm (P1) to 200 mm (P8). In the practice sessions, two targets (PA, PB) were used for the low-extent group and eight targets (P1–P8) for the high-extent group. In the test sessions, both groups had half of the trials aimed at the training targets of the low-extent group (upper target: 1800 mm; lower target: 600 mm) and the other half at a target that had been trained by neither the low-extent nor the high-extent groups (middle target: 1200 ms).

In the first and last session, respectively, the pre- and retention tests were conducted. After a warm-up block of eight trials (2 x upper/lower targets, 4 x middle target; random order), two test blocks of 16 trials each were executed (4 x upper/lower targets, 8 x middle target; quasi-randomized order with each target appearing not more than three times in a row). In each test trial, a fixation cross was presented for 1000 ms at the height of the middle target PC either 900 mm to the left or to the right of the vertical line of the screen (randomized order; see **Figure 1**). Followed by an audio signal, the current target was presented at one of three positions (upper/middle/lower target). The target

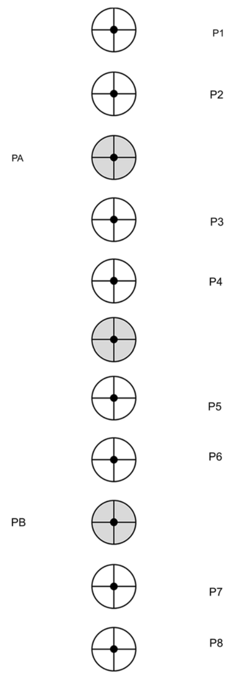

FIGURE 1 | Target positions for the practice phases of the high-extent group (P1–P8) and the low-extent group (PA, PB) as well as for the test phases (highlighted in gray). In the beginning of each trial, a fixation point was presented either to the left or the right for 1000 ms (black dots). Following an audio signal, the fixation point disappeared and the target for the current trial was presented for 6000 ms.

disappeared after 6000 ms to prevent any time pressure of the participants.

Beginning with the second session, the group-specific interventions commenced, with six blocks of 16 trials per session, resulting in a total of 768 intervention trials per participant. For the high-extent group, the targets P1–P8 were presented in a structured order by moving stepwise through the task-solution space from top to bottom and back again in each block. For the low-extent group, only targets PA and PB were presented in a blocked order by beginning each block with eight trials aimed at PA before changing to PB. The last intervention session was completed with the post-test, which was conducted after a short break following the last intervention trial and was structured as described above for the pre- and retention tests.

Due to the time-consuming intervention phase as well as restricted availabilities, individual schedules needed to be coordinated with each participant. Resulting from these arrangements, the first intervention session was conducted about 6 days after the pretest session (low-extent group: 5.7 ± 0.8 days; high-extent group: 6.1 ± 0.8 days), about 4 days elapsed between each of the eight intervention sessions (both intervention groups: 4.3 ± 0.1 days), and the retention test session followed about 5 days after the post-test (low-extent group: 4.9 ± 0.4 days; high-extent group: 4.7 ± 0.4 days). After the retention test, the participants were thanked and debriefed about the objectives of the study.

Measures

Trials with technical difficulties in data collection (pretest: 0.4%; post-test: 1.1%; retention test: 2.8%) and trials without a valid QE registration (pretest: 4.9%; post-test: 11.2%; retention test: 6.6%) had to be excluded from further data analyses. In addition, one participant from the low-extent group was not able to complete the intervention due to an injury and thus had to be removed from the analyses.

Throwing Performance

Throwing performance was obtained by computing radial-error scores. To this end, for each trial, the position of the ball at the moment of ball impact and the position of the center of the target disk were assessed, with the latter computed by converting the relative position of the target in the video scenes into the screen frame of reference. The moment of impact was detected by the negative peak in the ball's acceleration curve (cf. Klostermann et al., 2014b). For the pretest, post-test, and retention test, the performance measure aggregated all 32 test trials.

Quiet Eye

The QE measure was derived from both the gaze data and the synchronized kinematic data of the throwing movement. To this end, the raw gaze data were first filtered with a Median Bandpass Filter (window size: 10 frames, cut-off frequencies 1 and 10 Hz) and the kinematic data of the throwing arm's marker cluster were smoothed with a 41 point, 3rd order Savitzky–Golay filter. From the resulting 3D gaze data in the laboratory frame of reference, a screen-intersection point was calculated to provide a gaze location in the screen frame of reference for each time step (i.e., 5 ms). By use of a dispersion-based algorithm (Nyström and Holmqvist, 2010), fixations were identified if the resulting gaze path was stable within an area of 1.2° of visual angle for at least 120 ms. The QE duration was defined as the duration of the final fixation at the target before the initiation of the forward swing which, in turn, was determined as the first instant in time the average position of the arm marker cluster moved forward after having reached the backmost position (cf. Klostermann et al., 2014b). For the pretest, post-test, and retention test, the average QE duration was calculated from the total 32 test trials.

Statistical Analyses

QE duration and throwing performance were analyzed with mixed-factorial ANOVAs with time of measurement (3) as the within-participant factor and intervention group (2) as the between-participant factor. In cases of sphericity assumption violations, Greenhouse–Geisser corrections were applied. *A posteriori* effect sizes were computed as partial eta squared, η_p^2, and Cohen's *d*-values.

RESULTS

Throwing Performance

As illustrated in **Figure 2**, both intervention groups improved throwing performance from pre- to post-test and maintained

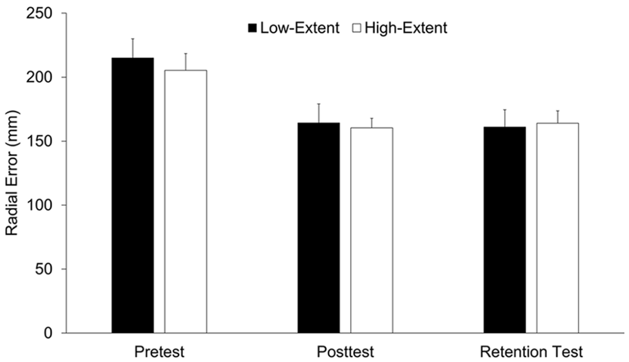

FIGURE 2 | Throwing performance of the two intervention groups (low-extent vs. high-extent) as a function of time of measurement (pretest, post-test, retention test). Error bars indicate standard error.

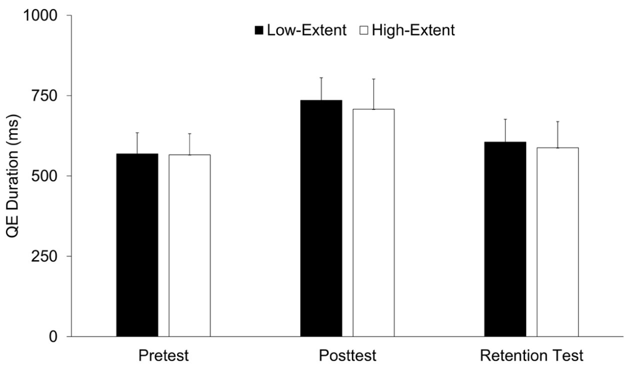

FIGURE 3 | Quiet eye (QE) duration of the two intervention groups (low-extent vs. high-extent) as a function of time of measurement (pretest, post-test, retention test). Error bars indicate standard error.

performance in retention. Consequently, a main effect for time of measurement was revealed, $F(1.37,36.95) = 29.45$, $p < 0.05$, $\eta_p^2 = 0.52$, with significantly more accurate throws in post-test and retention when compared to pretest (all *p*s < 0.05, all *d*s > 1.2), but no significant differences between post-test and retention test ($p = 0.93$, $d < 0.01$). Further, main and interaction effects failed to reach the pre-determined level of significance (all *p*s > 0.68, all $\eta_p^2 < 0.01$). In particular, the error scores in post-test and retention test did not differ between groups (all *p*s > 0.82, all *d*s < 0.08, all $1\text{-}\beta < 0.08$).

Quiet Eye

As shown in **Figure 3**, a main effect for time of measurement was revealed for QE duration, $F(1.61,43.45) = 5.09$, $p < 0.05$, $\eta_p^2 = 0.16$. Independent of the intervention, participants had longer QE durations in post-test when compared to pretest and retention test (all *p*s < 0.05, all *d*s > 0.58). No significant difference was found between pretest and retention test, $t(29) = 0.48$, $p = 0.63$, $d = 0.10$. Further main and interaction effects were non-significant (all *p*s > 0.87, all $\eta_p^2 < 0.01$).

DISCUSSION

The classical finding of longer QE durations with increasing motor expertise seems rather paradoxical, especially when considering the suggestion of optimized information processing caused by a QE prolongation. However, the *inhibition hypothesis* offers an explanation for this paradox as it relates the better explored task-solution space of experts to the increased requirement to shield the optimal movement variant against alternative movement parametrisations. The hypothesis that the QE is needed to finalize this shielding process was tested by comparing the QE durations of two groups with different extents of task-solution sub-spaces after extensive practice. More precisely, we expected the participants of a low-extent group, due to their blocked-practice treatment, to abstract rules for separate subspaces whilst the structured-practice treatment of the participants of a high-extent group was expected to result in the abstraction of rules for one single task-solution space. As a consequence of the higher extent of the task-solution space, the requirements regarding the shielding of the current task variant against – a larger number of – alternatives was expected to be higher for the high-extent than for the low-extent group. Hence, we predicted longer QE durations in post-test and retention test for the high-extent group when compared to the low-extent group.

The performance results showed that both groups threw more accurately in post-test and retention test, illustrating a stable motor-learning effect for both groups. The fact that both groups did not differ in performance after learning confirms the successful implementation of fair learning and test conditions. Consequently, the QE findings can be discussed exclusively with regards to the experimental manipulations, which should be highlighted because superior skill acquisition in one or the other groups would have been a strong alternative explanation for respective QE differences.

As predicted, participants showed longer QE durations in post-test when compared to the pretest, however, this gain completely vanished in the retention test. First, this unexpected finding implies that the results reported by Horn et al. (2012) should be interpreted in terms of performance but not as learning effects. Consequently, the longer QE durations revealed for the random-practice group in their study might indeed reflect increased response-programming demands, but cannot be understood as being caused by a behaviorally stable QE extension (see also, e.g., Williams et al., 2002). Second, the instability of the QE effect was surprising, in particular, because earlier training studies with similar retention intervals quite consistently reported QE-learning effects. For example, Vine and Wilson (2010) trained novices in golf putting either with coupled QE-technique instructions or with technical instructions only. Both groups showed stable QE durations in the 2-day-delayed and in the 5-day-delayed retention test. However, unlike the study at hand, the technically-instructed participants also received guidance to maintain head stability after club-ball contact (p. 366).

Thus, it might be speculated that long-lasting effects in QE learning depend on respective verbal guidance during training. Consequently, from a practical viewpoint, future research should give further consideration to this relation.

It could be argued that the unexpected lack of temporally stable QE effects might devastate the basic rationale of the present study because the missing "efficiency paradox" at the retention test might not allow to explain the paradox for principle reasons. Indeed, we acknowledge that an intervention-induced QE prolongation in conjunction with a performance improvement would have been highly desirable. However, it also should be noticed that the present study focuses on a hypothetical mechanism underlying a QE prolongation and, as a matter of course, the lack of an empirically found QE prolongation does not rule out that certain aspects of the supposed mechanism are empirically detectable. Hence, we would like to state that it is still worthwhile to discuss group differences in the present study because it might be that the experimentally induced differences in inhibition demands result in measurable differences on the level of the dependent variable (especially in the post-test). However, when comparing the two intervention groups based on this argument, it needs to be recognized that also the core finding of this study was not in line with our prediction because both groups did not differ in QE duration, neither in the post-test nor in the retention test and even after a considerably extensive training phase of more than 750 trials. Of course, this negative result cannot be taken as empirical support of the inhibition hypothesis.

Two explanation can be offered for this lack of group differences. First, it may be argued that 750 practice trials did not suffice to stimulate the formation of different task-solution spaces. The counter-argument against this way of thinking would be that, in other studies, QE effects have been found with far less amount of practice trials (e.g., 320 trials in Vine and Wilson, 2010). Nevertheless, the present study aimed on considerably smaller differences in the group treatments so that the amount-of-practice argument must be acknowledged.

However, a second explanation for the absence of group differences should also be considered. This explanation refers to the fact that the present study focused on question whether the *extension* of the task-solution space – to a lower or a higher degree – affects inhibition demands and, in turn, QE durations. Thus, it might not be the extent factor that best explains the assumed increased inhibition demands, but rather the *density* factor, meaning that it would be less important that experts form elaborate rules that cover the entire (large extent) task-solution space. Inhibition would rather be needed on a more fine-grained level *within* sub-spaces in which the acquired experiences are densely packed such that it is particularly hard to shield the chosen movement variant against immediately neighboring alternatives.

It can be argued that this latter explanation is even – at least by tendency – supported by the data at hand because the low-extent group, for which a denser exploration of the task-solution space around the practiced targets can be expected than for the high-extent group, shows a slightly longer QE duration (∼30 ms on average) in post-test and retention test when compared to the high-extent group. As additionally calculated, this difference particularly surfaces when separately analyzing the trained (upper/lower) and the non-trained (middle) targets, with the effect appearing by tendency more pronouncedly for the trained targets (∼50 ms on average). Thus, it could be speculated that the high amount of practice condensed the task-solution space in the specifically practiced regions. However, as already argued above, the total amount of about 750 practice trials might not have been enough to yield a significant effect in the present study. When comparatively considering, for instance, the 100s of hours NBA players practice free-throws, this experience can definitely be expected to result in a very dense task-solution sub-space due to the massive amount of broadly similar task executions. Consequently, in order to perform this task at the highest level, it may still be hypothesized that a long QE period is needed to shield the finally chosen task solution against very similar but less successful variants.

It should be noted that the density argument developed would also be well in line with research in the motor-performance domain in which a high specificity of motor skills in experts was revealed. For example, Keetch et al. (2005) found that basketball players taking free-throw shots from the original distance performed better than would be predicted by the relationship of the accuracies of set shots attempted at different distances. This especial skill is assumed to represent a very specific, well-learned movement pattern, a "general motor program" (Keetch et al., 2008) which, in the context at hand, implies a dense task-solution sub-space. Regarding the above-sketched relation to the QE duration, this effect would lead to the prediction that QE durations in expert basketball players should increase as a function of task demands (i.e., with increased distance to the basket, cf. Williams et al., 2002). However, referring to the density assumption of the *inhibition hypothesis*, it can also be expected that the QE duration at the immensely practiced free-throw distance should be longer than would be predicted by the relationship among other throwing distances. Such experiments are well-planned for implementation in the near future.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SYSTEMATIC REVIEW
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A Systematic Review of Commercial Cognitive Training Devices: Implications for Use in Sport

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Background: Cognitive training (CT) aims to develop a range of skills, like attention and decision-making, through targeted training of core cognitive functions. While CT can target context specific skills, like movement anticipation, much CT is domain general, focusing on core abilities (e.g., selective attention) for transfer to a range of real-world tasks, such as spotting opponents. Commercial CT (CCT) devices are highly appealing for athletes and coaches due to their ease of use and eye-catching marketing claims. The extent to which this training transfers to performance in the sporting arena is, however, unclear. Therefore, this paper sought to provide a systematic review of evidence for beneficial training effects of CCT devices and evaluate their application to sport.

Methods: An extensive search of electronic databases (PubMed, PsychInfo, GoogleScholar, and SportDiscus) was conducted to identify peer-reviewed evidence of training interventions with commercially available CT devices. Forty-three studies met the inclusion criteria and were retained for quality assessment and synthesis of results. Seventeen studies assessed transfer effects beyond laboratory cognitive tests, but only 1 directly assessed transfer to a sporting task.

Results: The review of evidence showed limited support for far transfer benefits from CCT devices to sporting tasks, mainly because studies did not target the sporting environment. Additionally, a number of methodological issues with the CCT literature were identified, including small sample sizes, lack of retention tests, and limited replication of findings by researchers independent of the commercial product. Therefore, evidence for sporting benefits is currently limited by the paucity of representative transfer tests and a focus on populations with health conditions.

Conclusions: Currently there is little direct evidence that the use of CCT devices can transfer to benefits for sporting performance. This conclusion, however, stems more from a lack of experimental studies in the sporting field and a lack of experimental rigor, rather than convincing null effects. Subsequently, there is an opportunity for researchers to develop more reliable findings in this area through systematic assessment in athletic populations and major methodological improvements.

Keywords: cognitive training, brain training, attention, sport, working memory, sport performance

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TABLE 1 | Description of cognitive functions targeted by CT training devices included in the systematic review.

Cognitive function	Description *(and tests)*
Working memory (WM)	A limited cognitive capacity that is responsible for temporarily holding information for active manipulation. Consists of visuospatial and phonological components, which are supervised by a central executive. WM underpins any functions that require storage and use of information. *Digit, letter, and spatial span tasks that require information to be held during a simultaneous mental load (e.g., tone counting), also N-back, Operation Span Task.*
Executive function (EF)	A multi-component construct that consists of a range of processes involved in the planning, organization, coordination, implementation, and evaluation of many non-routine activities. Plays a key role in allocating attention and higher-level functions. *Wisconsin Card Sorting Test, verbal fluency test.*
Inhibition	A sub-function of WM and aspect of executive function which actively suppresses irrelevant or unwanted information. *Stroop test, Posner Flanker task, Go/NoGo.*
Shifting/Switching	An aspect of executive function responsible for switching between multiple tasks. May be a function of WM. *Wisconsin Card Sorting Test, Trail Making Test.*
Divided attention	The ability to attend to and process two tasks or sources of information at the same time, e.g., two spatial locations. Requires shifting function. *Multiple object tracking, dual-task paradigms.*
Selective attention	The ability to attend to some stimuli while disregarding others that are irrelevant to the task at hand, for example, an individual's ability to search for a single letter among an array of distracting and irrelevant letters. Requires inhibition function. *Visual search, dichotic listening*.
Sustained attention	One's ability to maintain a focus of attention on one task for a sustained period of time. *Sustained Attention to Response Task.*
Fluid intelligence	The domain general ability to solve new problems and reason. *Wechsler Adult Intelligence Scale, Raven's Progressive Matrices.*
Crystalline intelligence	The ability to use learned knowledge and experience. *Sentence completion, verbal classification.*
Processing speed	Time taken to take in, process and respond to information. Can be domain specific, e.g., visual or verbal. *Useful field of view, reaction times, Paced Auditory Serial Addition Test.*
Short term memory (STM)	The temporary, limited capacity, passive store that holds information to be used in WM. Also referred to as episodic memory. *Span tasks, Corsi Block Test.*
Reasoning	The process of making judgments or conclusions based on logical processing. Very similar to fluid intelligence. *Tower of London, Tower of Hanoi.*

INTRODUCTION

Rationale

Over the past 10 years, cognitive training (also known as brain training, perceptual training, attention training, or mind training) has boomed, both as a research topic, and as a commercial product. The overall cognitive training (CT) and assessment market is currently worth $1.98 billion (US) and set to rise to over $8 billion by 2021 (marketsandmarkets.com, 2017). Currently, however, it is unclear to what extent device popularity and marketing claims align with scientific evidence. While many commercial CT (CCT) programmes are based on well researched cognitive tasks that have shown trainability (Shipstead et al., 2012; Harrison et al., 2013; Melby-Lervåg and Hulme, 2013), marketing claims suggest more extensive benefits for boosting general brain power and aiding daily mental function (Simons et al., 2016). Additionally, companies cite scientific evidence for their products, which often relates to the basic cognitive tasks rather than direct testing of their device.

CCT devices that allow the user to download an application or log on to a website and immediately begin training can be referred to as "off-the-shelf" devices. They require no instruction or expertise to use, and can often be run on just a mobile phone or computer. Such devices are highly appealing for sport, as they claim to enhance a range of skills, such as attention, speed of processing, decision-making and problem solving, and can be practiced at the athlete's convenience. Given the recent proliferation of these devices and controversy in the academic literature regarding their efficacy, we aim to provide a systematic appraisal of the peer-reviewed evidence for CCT devices. As these devices hold particular interest for developing the cognitive skills of athletes, we will also evaluate the evidence for transfer to the sporting domain.

CT consists of systematic practice on tasks intended to develop abilities such as working memory and attention, for transfer to other tasks and settings (Simons et al., 2016). Domain-general CT, which seeks to develop core functions applicable to a multitude of tasks, can be distinguished from context-specific CT such as training perceptual-cognitive abilities using the expert performance approach (Ericsson, 2003), which targets cognitive skills in a specific task (e.g., tennis serve anticipation). Further, the aforementioned commercial devices are distinct from the, often bespoke, methods used exclusively for research (e.g., Jaeggi et al., 2011; Ducrocq et al., 2016, 2017). Here, we are primarily concerned with commercially available methods that aim to enhance domain general abilities. The scientific rationale for CT largely stems from the concept of "neuroplasticity," which claims that the brain, much like a muscle, can change and adapt to challenges, and that targeted conditioning of a specific region will cause a sustained development in size and/or functional capacity (Draganski et al., 2004). Such adaptation, evident in both young and old (Mahncke et al., 2006; Schlaug et al., 2009), could facilitate a wide range of benefits that are supposedly harnessed through CT, including memory, attention, processing speed, fluid intelligence, problem-solving, and learning abilities (Simons et al., 2016) (see **Table 1** for descriptions of cognitive functions). The end goal of CT is to achieve (1) improvements in the cognitive function that was trained (near transfer); (2) improvements in other associated or "overlapping" cognitive functions (e.g., after training working memory, are improvements in attentional control achieved?); and finally, (3) improvements in the performance of tasks in the real world that utilize those cognitive functions (far transfer) (Simons et al., 2016). As such, context general CT relies heavily on the proposition of domain generality; that is, the belief that training-related improvements in domain-specific abilities will transfer onto more general cognitions and skills (Baddeley, 1986; Dahlin et al., 2008).

In order to evaluate the efficacy of current commercially available devices, it is necessary to outline the criteria through which existing research will be appraised. In order to determine causal effects, only studies in which training interventions are used will be considered. Of these, randomized, double-blind clinical trials provide the gold standard. A recent review of CT by Simons et al. (2016) outlines five key questions for assessing the evidence for a training device:

1. Has the training demonstrated transfer of training to other laboratory tasks that measure the same cognitive function as the training?
2. Has the training demonstrated transfer to relevant real-world tasks?
3. Has the training been evaluated using an active control group whose members have the same expectations of training benefits as the members of the experimental group?
4. How long are the trained skills retained?
5. Have the purported benefits of the training been replicated by research groups other than those selling the product?

These questions will be central to our assessment of the current literature on commercial devices. Firstly, the device must demonstrate robust evidence that it does indeed enhance the cognitive function it purports to train, through near transfer to similar tests. If not, subsequent considerations are immaterial. Secondly, and crucially for applications to sport, it must show evidence of transfer to real-world tasks. Thirdly, good experimental design requires the use of *active* control groups where participants expect a training benefit. Simons and colleagues identify the poor use of control groups in much CT research, where the use of passive controls means that training effects may be due to the expectations of the training group. Fourthly, if CT makes use of "neuroplasticity," changes in cognitive function in response to training can lead to long term neural changes, which should be retained over time (Park and Bischof, 2013). Finally, much research on commercial devices has been conducted by researchers linked to the companies selling the products. Therefore, in order for research to be considered reliable, the findings should be replicable by researchers independent of the company. These critical questions will be used to identify the strength of evidence for each training device.

CT is typically adopted in the following contexts: (1) compensatory—to overcome or circumnavigate cognitive deficits (Rapport et al., 2013); (2) restorative—to rediscover or restore lost cognitive functions; or (3) additive—to enhance or build upon existing cognitive functions (Ward et al., 2008). Benefits for sport fall into the third context. Currently, however, commercial devices have received little direct testing in athletes or other healthy populations, but considerable testing in older adults and populations with health conditions, where the device aims to overcome deficits in cognitive function. As such, most of the existing findings relate to compensatory or restorative rather than additive ergogenic effects. These findings remain imperative for evaluating the general effectiveness of CT devices, but generalizing to athletes is more difficult. Therefore, reviewed studies will be divided based on the use of young and healthy (additive) versus aged and non-healthy (compensatory/restorative) samples. In doing this, we aim to answer two questions; (1) Is there reliable evidence for any far transfer benefits (all adult populations), following training with CCT devices? (2) Is there reliable evidence for transfer to sporting tasks, following training with CCT devices?

Performing optimally in sport requires a range of cognitive skills, like selective attention (Abernethy, 1987), divided attention (Memmert, 2009) and working memory (Furley and Memmert, 2010), particularly when under pressure (Eysenck and Wilson, 2016). Recent findings suggest that training these functions may transfer to sport, as Ducrocq et al. (2016) demonstrated that training on a bespoke attentional task targeting the inhibition function of working memory improved pressurized volley performance in recreational tennis players. Perceptual-cognitive training, a form of CT that aims to train perceptual and sensory functions responsible for decision-making and anticipatory skills, has also shown cognitive benefits. Typically, life-sized video is used to replicate key situations from the performance environment, enabling trainees to develop the cognitive functions that are utilized in the real world (Williams et al., 2002). This approach has demonstrated benefits for skills like anticipation (see Broadbent et al., 2015 for review). Alternatively, vision training, such as Quiet Eye Training, uses videos of eye movements to teach expert-like gaze strategies to novices. This approach has shown substantial benefits in perceptual-motor as well as perceptual-cognitive tasks (see Vine et al., 2014 for review). Consequently, there is robust evidence for enhancing sporting performance through other methods of cognitive enhancement. The fundamental question is whether these benefits can also be achieved by CCT devices that purport to train domain general abilities (as Jaeggi et al., 2011; Ducrocq et al., 2016), rather than task specific perceptual or attentional abilities?

Research Question

CT can take several forms, based on the purpose of the device and method of training. In particular, commercial devices, like smart phone based braining training games, can be distinguished from non-commercial devices, such as bespoke methods for research (e.g., Jaeggi et al., 2011; Ducrocq et al., 2016, 2017). Additionally, CT can be either truly domain general, or context-specific, such as training of sport specific perceptual-cognitive abilities (Broadbent et al., 2015) and task-specific visual training (Vine et al., 2014). While these methods hold promise for sport, they are highly specialized and often require expert instruction, limiting potential for general usage. Therefore, we aim to review devices that are commercially available for use by a range of sportspeople, and target domain-general skills. CCT devices have the potential to provide an affordable and convenient way of regularly training cognitive skills. This ease of use, in combination with the far-reaching marketing claims, means that CCT devices can be attractive to coaches and athletes. It is currently unclear, however, if these devices can provide reliable transfer to sporting skills. Therefore, we aim to systematically review existing evidence for the use of these devices. Specifically, we firstly assess evidence for performance enhancement across a range of adult populations, and secondly evidence for potential benefits in the sporting arena. We also aim to evaluate study quality to inform future research in this area.

METHODS

Search Strategy

The methodology employed for the systematic review was based on the guidelines described by Khan et al. (2003). The aim of the review was to summarize and synthesize peer-reviewed research relating to the effectiveness of CCT devices in adult populations, firstly relating to compensatory/restorative[1] effects, and secondly with regards to potential transfer to sport. Only devices claiming to directly train domain general cognitive function were reviewed. For instance, there is evidence for the beneficial effects of exercise and mindfulness training for cognitive function (Cassilhas et al., 2007; Howells et al., 2016), but our search was restricted to devices specifically designed for CCT. Additionally the search was restricted to studies investigating performance enhancement in adult populations. To this end, an electronic search of PubMed, PsycInfo, GoogleScholar, and SPORTDiscus databases was conducted, for research relating to CCT devices, up to, and including, September 2017. The initial search was performed in PubMed and adapted to the other databases. Key search terms were *cognitive, brain, working memory,* or *attention,* combined with *training,* and excluded titles containing *children.* Research sections of websites for CCT devices identified in the database search were an additional source of papers. These included the websites for Neurotracker, Cogmed, Cognifit, Lumosity, Posit Science, and Dynavision. Further studies were identified through searching reference lists. The retrieved results were initially assessed for relevance based on their title and abstract, with studies that were ineligible, irrelevant, or duplicates removed. Next the remaining results were screened based on the full-text article, with further ineligible or irrelevant results removed.

Selection of Studies

Included studies were required to meet the following criteria: (1) test a commercially available device, (2) be in a peer-reviewed, English language journal, (3) use adult participants (18+ years of age), (4) use a training intervention (i.e., assigned groups to device practice for any time duration), (5) assess either near or far transfer[2], and (6) accurately represent the commercial device (i.e., when a device employs multiple subtasks, all tasks were used and training groups did not use more than one CT device).

The identification and selection of papers was guided by the four-phase flow diagram of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA: **Figure 1**).

Data Extraction and Quality Assessment

After all articles fitting the search criteria were obtained, they were assessed for quality and key data was extracted for the summary table (**Tables 3A,B**). Data extraction summarized the following information from each paper: authors; participant population; name of the training device; was an active control group used (if yes, what); was a near transfer test included (yes/no); was a far transfer test included (yes/no); was a retention test used (yes/no); were researchers independent of the company marketing the device (yes/no); which cognitive functions were assessed (**Table 1** for descriptions); summary of findings. For consistency, discussion and crosschecking of included studies was carried out amongst the authors.

Study quality was determined by evaluating the internal and external validity of the selected studies. Items for assessing study quality (Appendix 2 in Supplementary Material) were taken from the Quality Index (Downs and Black, 1998), the Epidemiological Appraisal Instrument (Genaidy et al., 2007) and Durant's (1994) checklist for the evaluation of research articles. The five critical questions relating specifically to CT research taken from Simons et al. (2016) review were also included. This formed a 22 item checklist that was scored 1 when a criterion was met and 0 when it was not (or was unknown). This gives a maximum score of 22 for the highest possible quality. The quality assessment was primarily conducted by one author, with queries discussed among the remaining authors (Appendix 1 in Supplementary Material).

RESULTS

Search Results

The initial database searches returned 125,867 papers which, after screening for relevance and matching to inclusion criteria (**Figure 1**), resulted in 43 papers to be reviewed against the quality assessment criteria (Appendix 2 in Supplementary Material).

Characteristics of Included Studies

The included studies resulted in seven devices for review, these were (with number of studies); Cogmed (15), Lumosity (9), Insight and Brain Fitness by Posit Science (6), Cognifit (4), Neurotracker (4), Nintendo Big Brain Academy and Brain Age (4), and Dynavision (1). The participant samples included populations that were healthy and those with health conditions, 27 with participants from healthy young (<60 years) or old (>60 years) adult groups, four focusing on ADHD, nine on brain injury and cognitive impairments, two on cancer survivors and one on participants living with depression. There was one study with

[1]Older adult samples were generally classified as compensatory/restorative when participants were over 60 years of age, but this was somewhat guided by the intentions of individual studies.

[2]We have classified far transfer as any test that was not a laboratory cognitive test. In several cases this included self-report of daily functioning and symptoms of health conditions. Any self-report tests are identified in the results.

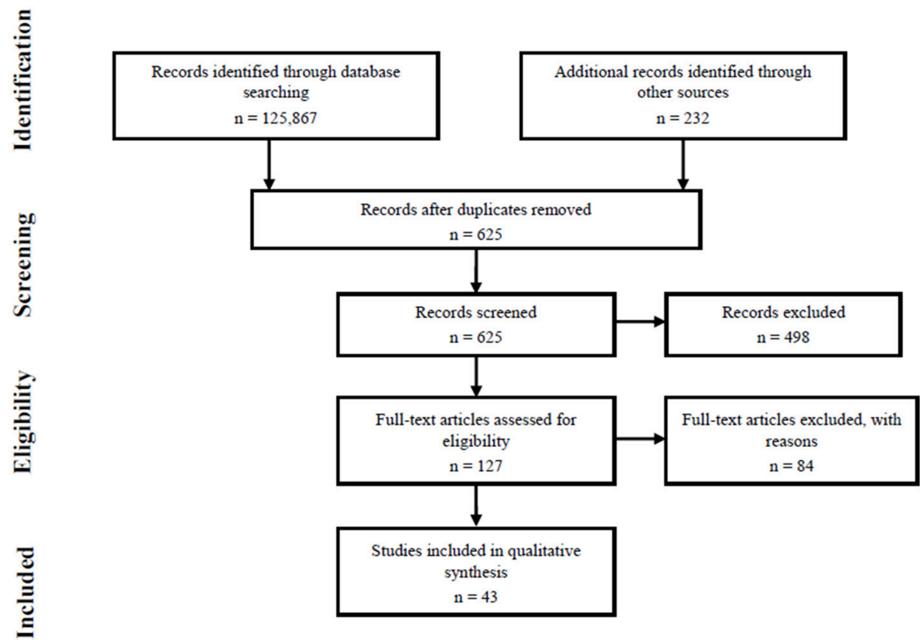

FIGURE 1 | Four-phase PRISMA flow diagram.

participants from the armed forces and only one in a sporting population.

Twenty-one studies assessed far transfer[3], that is, to a measure other than a cognitive test, such as driving ability or soccer passing. Fourteen of these, however, were self-report measures such as quality of life, perceived cognitive function and health condition symptoms. The non-self-report transfer measures were expert ratings of motor skill and safety to drive, ability to perceive human motion, sleep quality, soccer passing ability, and two direct neural measures. Only two studies did not assess near transfer, both of which were studies assessing Neurotracker focusing on far transfer.

Summary of Evidence for CT Devices

An overview of each CCT device is provided in **Table 2**, and a summary of findings from each study is included in **Table 3A** (compensatory/restorative effects) and **Table 3B** (additive effects). Here we give an overview of the evidence for each device, in relation to the five critical questions.

Cogmed

Cogmed was found to have the most extensive research base with 15 studies matching the criteria, many of which recruited populations with cognitive impairments. Several showed good evidence for near transfer effects, for instance, Åkerlund et al. (2013), Björkdahl et al. (2013), and Dunning and Holmes (2014) all found greater improvement on working memory tasks in the training group than controls. There were, however, null findings regarding working memory improvements in the studies of Gropper et al. (2014), Liu et al. (2016, 2017), and Mawjee et al. (2015). Additionally there were few findings showing improvements in related areas, such as executive function (but cf. Hellgren et al., 2015). With regards to testing far transfer, the Cogmed studies used almost exclusively self-report outcomes, such as quality of life and health condition symptoms. The one exception was Metzler-Baddeley et al. (2016) who found changes in cortical thickness as a result of training. Some of the Cogmed studies provided the best examples of an active control group (Brehmer et al., 2012; Dunning and Holmes, 2014; Metzler-Baddeley et al., 2016), with participants given the same (but non-adaptive) tasks as the trainees. Additionally, two studies assessed skill retention (Brehmer et al., 2012; Gropper et al., 2014) and several of the positive findings came from independent research groups.

Overall, there is good evidence, albeit with some null findings, for near transfer effects following Cogmed training. Some studies also found this to extend to self-rated improvements in everyday life, but there were no studies extending the observed working memory benefits to tasks representative of daily life or sporting activities.

Lumosity

Like Cogmed, several of the nine included Lumosity studies used populations with health conditions (Finn and McDonald, 2011; Charvet et al., 2015; Wentink et al., 2016), but the device has also been tested in healthy populations more relevant to sport. In particular, a large trial of 4,715 participants ranging from 18 to 80 years (Hardy et al., 2015) provides a more

[3]Some papers used "far transfer" to refer to enhancement of a cognitive function that was not directly trained, but here, due to the overlapping nature of concepts like working memory, executive function, and fluid intelligence, we restrict the term to real-world tasks or benefits.

TABLE 2 | Summary of devices identified in the systematic review.

Device	Target participants	Device description	Cognitive function(s) trained	Delivery of training
Cogmed (www.cogmed.com/)	Children and adults with memory and attention problems.	A market leader, Cogmed has been adopted by numerous intervention studies for memory and attention impairments (e.g., Brehmer et al., 2012; Åkerlund et al., 2013; Dunning et al., 2013).	WM capacity, general attentional abilities.	Mobile and computer application. Tasks are typical of traditional cognitive tests, such as digit and letter span and focus heavily on working memory. The tasks are described as "adaptive," as they become progressively harder as users improve.
Lumosity (www.lumosity.com/)	General population and those with memory deficits.	One of the leading sources for online brain training, providing over 40 brain training games.	Speed of processing, memory, attention, flexibility, and problem-solving.	Website and Mobile application. Uses a range of games based on cognitive tests, focusing on speed of processing.
Posit Science (www.brainhq.com/)	General population.	Two brain-training products from Posit Science were identified in the review, Brain Fitness and InSight, which are now part of the BrainHQ programme.	Speed of processing, WM.	The speed of processing games used by Posit Science are based on a useful field of view task used in a large clinical trial (the ACTIVE trial, Ball et al., 2002).
Cognifit (www.cognifit.com/)	General population, and those with declining function.	Initially focused on cognitive training for driving performance, Cognifit claims to measure, train, and properly monitor various applied cognitive skills and their relation to neurological pathologies.	Numerous cognitive skills including working memory, divided attention, and processing speed	Online and mobile application. Visual, auditory, and cross-modal tasks including puzzles, problem solving, and reaction time games.
NeuroTracker (www.neurotracker.net/)	Athletes and military.	Used by elite teams in sports such as Soccer and American Football. Training is based upon 3D multiple object tracking (Pylyshyn and Storm, 1988) which requires processing of dynamic stimuli.	Attention, WM, and visual information processing speed.	The user tracks target 3D balls among distractors, presented on a 3D television or in a VR headset. The number of targets and speed of balls adaptively increases with practice.
Nintendo Brain Age (http://brainage.nintendo.com)	General population.	The first product to bring "brain training" to a mass market. based largely on a 2003 book of puzzles and exercises by neuroscientist Ryuta Kawashima.	WM capacity and associated functions (e.g., concentration, focus).	Available in "App" format and its traditional console-based platform. Brain Age uses mini-games that require players to complete math problems quickly, read aloud, or perform other spatial, verbal, and arithmetic tasks.
Dynavision (www.dynavisioninternational.com/)	Medical, athletic and military.	Designed to improve visuo-motor as well as cognitive skills. The product is marketed as a training apparatus and as a tool for concussion diagnosis, rehabilitation, and return to play decisions.	Vision, cognition, motor control, concentration, decision-making.	Wall-mounted, computer-driven light board fitted with 70 lit buttons. Requires users to recurrently tap the buttons, when lit, as quickly as possible.

TABLE 3A | Summary of compensatory and restorative studies (older adults and populations with health conditions).

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Ackerman et al., 2010	78 healthy adults (mean 60.7 yrs)	Wii Big Brain Academy	Reading exercises	Yes	No	No	Yes	Fluid and crystalline intelligence, processing speed	There was an effect of training on measures of processing speed ($ps < 0.01$) and fluid intelligence (verbal tests) ($ps < 0.01$), but there was no benefit for the TG compared to the control group for any measures.
Åkerlund et al., 2013	47 participants with impaired WM following traumatic brain injury (47.7 ± 11.3 yrs)	Cogmed	No	Yes	Yes (SR)	No	Yes	STM, WM	Both TG and control improved on digit span (STM). The TG showed a significantly greater improvement in digit span ($p = 0.045$). TG did not show greater improvement on other measures of WM (spatial span, sequence memory). There was no self-reported change in executive function or psychological health for either group.
Ballesteros et al., 2014	30 healthy older adults (57–80 yrs)	Lumosity	No	Yes	Yes (SR)	No	Yes	Processing speed, selective attention, EF, spatial working memory, episodic memory	TG showed greater improvement than controls in oddball task performance (selective attention), speed of processing and Wechsler memory ($ps < 0.05$), but not EF, spatial WM or self-reported wellbeing.
Björkdahl et al., 2013	45 adults with WM deficits following brain injury (51.0 ± 11 yrs)	Cogmed	No	Yes	Yes	Yes	Yes	STM	TG showed significant improvement in STM (digit span) following training ($p = 0.003$), with no change in the control group. Both groups improved on therapist ratings of motor skill.
Brehmer et al., 2011	23 healthy older adults (mean 63.7 yrs)	Cogmed	Non-adaptive version of training task	Yes	No	No	No	WM, sustained attention, inhibition, STM reasoning	Interaction effects indicated greater gains in divided attention and WM (span tasks) for the TG ($p < 0.05$). This was not found for inhibition, STM and reasoning. Training gains were related to changes in neural activation.
Charvet et al., 2015	20 participants with cognitive impairment due to MS. (39.8 ± 11.5 yrs)	Lumosity	Computer games	Yes	Yes	No	Yes	Memory, processing speed	There was a significant difference between TG and active controls post-training in composite cognitive score ($p = 0.02$) but not for individual tests (e.g., WAIS, Corsi blocks). TG also performed better on a motor function task ($p = 0.01$).
Edwards et al., 2013a	74 adults (>40 yrs) with Parkinson's disease (68.9 ± 8.1 yrs)	InSight, Posit Science	No	Yes	Yes (SR)	No	No	Visual speed of processing	TG showed significantly greater improvements in visual processing speed (useful field of view) ($p = 0.032$). TG did not differ from controls in self-reported cognitive performance or depressive symptoms.

(Continued)

TABLE 3A | Continued

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Edwards et al., 2013b	67 healthy older adults (74.0 ± 7.5 yrs)	InSight, Post Science	No	Yes	Yes (SR)	No	No	Visual speed of processing	TG showed significantly greater improvements in visual processing speed (useful field of view) ($p = 0.043$) than wait-list controls. There was no effect of training on self-reported social or cognitive function.
Finn and McDonald, 2011	16 older adults with mild cognitive impairment (72.7 ± 7.1 yrs)	Lumosity	No	Yes	Yes (SR)	No	Yes	Sustained attention, WM, set shifting, visual memory	TG showed greater improvement on sustained attention, but not WM, memory (pattern recognition) or shifting (set shifting). Also no effect on subsequent training of waitlist controls. No effect on self-report of mood.
Gropper et al., 2014	62 university students with ADHD or learning disabilities (28.0 ± 7.2 yrs)	Cogmed	No	Yes	Yes (SR)	Yes	Yes	WM, sustained attention, selective attention, reading and mathematics comprehension	There was no effect of training on WM (digit span), sustained or selective attention or mathematics and reading comprehension ($ps > 0.05$). There were similarly no group differences at 2-month follow-up. There was a reduction in self-reported ADHD symptoms.
Haimov and Shatil, 2013	51 older adults with insomnia (65–85 yrs)	Cognifit	Simple computer tasks	Yes	Yes	No	No	Range of tests including: memory, divided attention, inhibition, shifting, WM, processing speed	TG showed improvements in several functions, including memory ($p < 0.001$), divided attention ($p < 0.05$), processing speed ($p < 0.01$), visual WM ($p < 0.001$). The TG showed greater improvements than the active control in memory ($p < 0.001$), visual ($p < 0.001$), and auditory ($p < 0.001$) WM. TG also showed improvements in sleep quality.
Hellgren et al., 2015	48 adults with acquired brain injury (mean 43.7 yrs)	Cogmed	No	Yes	No	No	Yes	WM, processing speed, sustained attention, divided attention	The TG improved on all tests of WM and attention ($ps < 0.001$). TG reported increased quality of life ($p < 0.001$). No control group comparison.
Hyer et al., 2016	68 older adults (>65 yrs) with memory impairment	Cogmed	Non-adaptive version of training task	Yes	No	Yes	Yes	WM, executive function	The TG showed greater improvements than active controls on one of two WM span tests ($p = 0.01$), but not on an executive function test.
Kesler et al., 2013	41 women with history of breast cancer (56.0 ± 7.0 years).	Lumosity	No	Yes	No	No	Yes	Executive function, WM, processing speed	The TG showed significantly greater improvement than controls in EF (WCST) ($p = 0.008$) and processing speed (symbol search) ($p = 0.009$) but not WM (digit span) ($p = 0.57$).

(Continued)

TABLE 3A | Continued

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Klavora et al., 1995	10 participants (45–80 yrs) unsafe to drive following stroke	Dynavision	No	Yes	Yes	Yes	Yes	Processing speed	There was a significant improvement in performance on the trained task ($ps < 0.05$) and an increase in the proportion of participants rated as safe to drive.
Legault and Faubert, 2012	41 healthy older adults (64–73 yrs, mean 66.3)	Neurotracker	Perceptual task (contrast detection)	No	Yes	No	No	None	At a distance of 4 m the TG showed significantly better perception of partially masked human motion than active controls ($p = 0.040$). There was no difference at 16 m.
Leung et al., 2015	209 healthy older adults (70.1 ± 6.4 yrs)	Brain Fitness, Posit Science	Educational programme	Yes	No	No	Yes	Sustained attention, WM, verbal STM,	The TG showed greater improvement on one of two sustained attention tests ($p = 0.026$) and on working memory ($p = 0.012$) but not STM.
Liu et al., 2016 (study 2)	102 adults with ADHD (18–35 yrs)	Cogmed	No	Yes	No	No	Yes	WM, general intelligence	No effect of training group on changes in WM (delayed match to sample test) ($ps > 0.05$).
Liu et al., 2017	88 young adults with ADHD (23.7 ± 3.3 yrs)	Cogmed	No	Yes	No	No	Yes	WM, fluid intelligence	No transfer to response control in Go/NoGo task.
Lundqvist et al., 2010	21 adults with acquired brain injury (43.3 ± 9.8 yrs)	Cogmed	No	Yes	Yes (SR)	Yes	Yes	Divided attention, inhibition, switching, WM.	TG showed significant improvements in measures of WM, inhibition, switching, and divided attention immediately post-training ($p < 0.001$ to $p = 0.002$) and at 20-week follow-up ($p < 0.001$ to $p = 0.002$). There was no change in passive control group. TG also improved self-ratings of occupational performance.
Mawjee et al., 2015	97 young adults (18–35 yrs) with ADHD (23.9 ± 3.4 yrs)	Cogmed	No	Yes	Yes (SR)	No	Yes	WM, STM, processing speed	There were no differences between TG and controls following training. There was also no difference in self-reported ADHD symptoms and cognitive failures.
Mayas et al., 2014	27 healthy adults (57–77)	Lumosity	No	Yes	No	No	Yes	Alertness and distractibility	There was no effect of group (TG v control) on digit categorization performance in the oddball task. The TG significantly improved from pre to post in distractibility ($p = 0.05$) and alertness ($p = 0.04$).
McDougall and House, 2012	41 healthy older adults (74.6 ± 8.5)	Nintendo Brain Age	No	Yes	No	No	Yes	Intelligence	Sub-tests of the WAIS only showed a benefit for backward digit span ($p<.05$). There was no effect for vocabulary, block design, arithmetic and forward digit span. There was no effect of more frequent use.

(Continued)

TABLE 3A | Continued

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Nouchi et al. (2012)	28 healthy older adults (69.1 ± 2.4 yrs)	Nintendo Brain Age	Video game	Yes	No	No	Yes	Executive function, WM, processing speed	Following training, the TG showed significantly greater improvements in EF (*ps* = 0.001–0.006) and processing speed (*ps* = 0.005–0.014). There was no difference in WM (digit span) improvement between groups ($p > 0.05$)
Peretz et al., 2011	155 healthy older adults (68 ± 7 yrs)	Cognifit	Video games	Yes	No	No	No	Overall cognitive performance	There was a significant improvement in overall cognitive score in the TG ($p < 0.05$) and the active control ($p < 0.05$). There was no difference in improvement between groups.
Preiss et al., 2013	31 participants with unipolar and bipolar depression (44.2 ± 14.2 yrs)	Cognifit	No	Yes	Yes (SR)	No	No	WM, shifting, inhibition, divided attention, STM, executive function	There was no difference between TG and controls for WM, shifting, inhibition, divided attention, STM, or executive function (Stroop, WCST). Improvements in self-report of depressive symptoms.
Rass et al., 2015	56 methadone maintenance patients (43.4 ± 8.0 yrs)	Cogmed	Non-adaptive version of training task	Yes	Yes (SR)	No	Yes	WM, STM, processing speed, reasoning, inhibition	Greater WM (digit span, OSPAN) improvements in the TG than controls ($p = 0.003$). No group differences in improvement in processing speed (trail making), inhibition or reasoning. TG reported less drug use post-training than active controls ($p = 0.045$).
Siberski et al., 2015	32 adults with intellectual and developmental disabilities (40.5 ± 11.0 yrs)	Cognifit	Video games	Yes	No	No	No	Divided attention, inhibition, shifting, processing speed, WM	The TG improved in measures of monitoring ($p = 0.017$), visual WM ($p = 0.003$), and processing speed ($p = 0.038$) but not divided attention, shifting (WCST), or inhibition (Stroop). There were no group differences for any measure post-intervention.
Smith et al., 2009	487 healthy older adults (>65 yrs)	Brain Fitness, Posit Science	Educational training	Yes	No	No	No	Cognitive assessment battery (inc. attention and memory), WM	The TG showed greater improvement than controls in the cognitive battery ($p = 0.02$) and WM task ($p = 0.006$).
Strenziok et al., 2014	42 healthy older adults	Brain Fitness, Posit Science	Video games	Yes	No	No	Yes	Reasoning, WM, STM.	The TG showed a significant improvement in reasoning (WAIS matrix) scores ($p < 0.05$) but no improvement in WM (letter number sequencing).

(Continued)

TABLE 3A | Continued

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Von Ah et al., 2012	82 breast cancer survivors (56.5 ± 8.5 yrs)	InSight, Posit Science	Memory training	Yes	Yes (SR)	Yes	No	Memory, speed of processing	TG showed enhanced processing speed (useful field of view test) in comparison to passive controls post-training ($p = 0.040$) and at 2-month follow-up ($p = 0.016$). Also improved memory post-training ($p = 0.0004$) and at follow-up ($p = 0.010$). TG improved self-reported cognitive functioning ($p = 0.042$).
Wentink et al., 2016	107 adults (45–75 years) recovering from stroke	Lumosity	No	Yes	Yes (SR)	Yes	Yes	WM, inhibition, fluid intelligence	TG outperformed controls in one of four WM tests ($p = 0.02$) and an inhibition test ($p < 0.001$) post-training. At 16-week follow-up there were no group differences in WM, inhibition, attention, and fluid intelligence tests. Also no differences in self-reported cognitive failures or quality of life.

*Transfer to tasks other than laboratory cognitive tests.

SR, self-report outcome; WM, working memory; STM, short-term memory; EF, executive function; TG, treatment group; OSPAN, Operation Span task; WCST, Wisconsin card Sorting Task; WAIS, Wechsler Adult Intelligence Scale; ADHD, Attention deficit hyperactivity disorder; MS, Multiple Sclerosis; ps, multiple p-values.

Quality assessment color key: Strong (80+%) | Fairly strong (70–79%) | Moderate (60–69%) | Weak (50–59–%) | Very weak (40–49%)

generalizable sample. In this study, the training group showed greater improvements than active controls (crossword puzzles) in a range of cognitive tests assessing working memory, executive function, and attention. Across the studies there was good support for the benefits of Lumosity training for near transfer in several cognitive functions, such as speed of processing (Ballesteros et al., 2014), working memory (Hardy et al., 2011), and executive function (Kesler et al., 2013). There were also some null findings for near transfer, but in a small sample (Finn and McDonald, 2011). Regarding far transfer effects, Charvet et al. (2015) found improved motor skill in multiple sclerosis patients, but other studies found no change in self-reported wellbeing (Ballesteros et al., 2014) or mood (Finn and McDonald, 2011).

The study of Hardy et al. (2015) provided easily the largest cohort of the studies in this review, but as participants were already Lumosity users, who were compensated with Lumosity membership, these findings should be viewed with caution. Nevertheless, many of the findings were independent of those manufacturing the product. Overall, despite support for near transfer, there was no evidence of retention, and there has been limited assessment of real-world transfer or additive benefits, the key criteria for generalizing to sport. Findings of improved motor function suggest potential benefits, however this was observed in a population living with multiple sclerosis. Overall there is little evidence that Lumosity training can transfer to tasks beyond the lab.

Posit Science

All six studies meeting the review criteria reported positive effects of Posit Science training for near transfer, mainly in older adults. Improvements in processing speed (Edwards et al., 2013a,b), working memory (Smith et al., 2009; Leung et al., 2015) and short-term memory (Von Ah et al., 2012) were found, predominantly in older adults. Tests of transfer were confined to self-report measures with no real-world tasks relevant to sport, and only weak benefits were found. While Von Ah et al. (2012) found a marginal benefit for perceived cognitive function, Edwards et al. (2013a,b) observed null effects. Several studies used active controls, such as educational training (Smith et al., 2009; Leung et al., 2015) , and positive findings have been replicated by independent researchers (Strenziok et al., 2014; Leung et al., 2015). As was the case for most devices, no retention of skills was assessed. Overall, studies supported near transfer effects for compensatory/restorative training, but no evidence for additive effects.

Cognifit

Four studies were identified that directly assessed Cognifit training, across healthy older adults, adults living with intellectual disabilities, adults living with insomnia sufferers and participants living with depression. Three of the four studies found evidence for near transfer benefits (Peretz et al., 2011; Haimov and Shatil, 2013; Siberski et al., 2015), but there were several null effects across these studies and one other showing exclusively null effects (Preiss et al., 2013). The only test of far transfer was self-rated improvement in depressive symptoms (Preiss et al., 2013), which did indicate benefits. These studies generally used appropriate

TABLE 3B | Summary of studies using healthy and elite populations (additive studies).

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Brehmer et al., 2012	55 younger adults (mean 26.0 yrs) and 45 older adults (mean 63.8 yrs)	Cogmed	Non-adaptive version of training task	Yes	No	Yes	No	WM, sustained attention, inhibition, STM, reasoning	TG showed greater improvement in WM tasks (forwards and backwards span) than controls ($p = 0.01$ and $p < 0.001$). TG also showed greater improvement in sustained attention, but not inhibition, STM or reasoning. Group differences remained at 3 month follow-up
Dunning and Holmes, 2014	45 students (18–21 yrs)	Cogmed	Non-adaptive version of training task	Yes	No	No	Yes	WM, STM	Interaction effects indicated greater gains on verbal and visuospatial WM (span tasks) and verbal STM for the TG over active and passive controls ($ps < 0.05$), but not for visuospatial STM.
Gibson et al., 2013	20 undergraduate students	Cogmed	No	Yes	No	No	Yes	WM	Two TGs displayed significantly greater recall on items from primary ($p < 0.05$) and secondary memory ($p < 0.01$) than passive controls.
Hardy et al., 2011	23 participants (mean 57.0 yrs)	Lumosity	No	Yes	No	No	No	Spatial WM and divided visual attention	TG improved significantly from pre to post in divided attention ($p < 0.001$) and significantly more than controls ($p = 0.027$). TG improved significantly in forward spatial WM, ($p = 0.032$), significantly more than controls. They also improved reverse spatial span ($p = 0.008$). There was no change in letter memory, ($p = 0.517$).
Hardy et al., 2015	4715 Lumosity users (18–80 years; 39.2 ± 15.1 yrs)	Lumosity	Crossword Puzzles	Yes	Yes (SR)	No	No	Overall battery (inc. STM, WM, grammatical and arithmetic reasoning, response inhibition, selective attention)	Significantly greater improvement on battery in TG ($p < 0.001$). Largest effects in inhibition and arithmetic reasoning. Also significantly greater improvement in self-reported cognition and emotional status, ($p < 0.001$).
McNab et al., 2009	13 healthy males (20–28 yrs)	Cogmed	No	Yes	No	No	No	WM	Training improved WM capacity ($p < 0.001$). No comparison group. Improvements were associated with cortical dopamine binding.
Metzler-Baddeley et al., 2016	40 adults (26.5 ± 6.6 yrs)	Cogmed	Non-adaptive version of training task	Yes	Yes	No	Yes	WM, inhibition, grammatical reasoning, general intelligence, multi-tasking	The TG showed significantly greater improvement in two measures of WM ($ps < 0.001$), but not in tests of inhibition, grammatical reasoning, general intelligence, and multi-tasking. Adaptive training related to structural brain changes measured through Magnetic Resonance Imaging.

(Continued)

TABLE 3B | Continued

Article	Sample (completed)	Device	Active Control	Near transfer test	Far transfer* test	Retention test	Independent of company	Cognitive outcomes	Findings
Nouchi et al., 2013	32 young adults (20.7 ± 1.2 yrs)	Nintendo Brain Age	Video game	Yes	No	No	Yes	Fluid intelligence, EF, WM, STM, processing speed	The TG showed greater improvements than active controls in EF (*ps* $<$ 0.001–0.002), WM (OSPAN) (*ps* = 0.003–0.008) and processing speed (symbol search) (*ps* = 0.004–0.006). Active controls showed greater improvement in sustained attention ($p = 0.01$) and visuo-spatial ability ($p = 0.009$). No improvement in fluid intelligence or STM for either group.
Parsons et al., 2016	20 University students (23.3 ± 2.7 yrs)	Neurotracker	No	Yes	Yes	No	No	Selective and sustained attention, processing speed, STM, WM, inhibition	TG showed significant improvements in sustained attention ($p = 0.007$), inhibition ($p = 0.004$), WM ($p = 0.02$), and STM ($p = 0.008$) (WAIS tests). TG also showed decreased EEG power in theta, alpha and delta bands, primarily in frontal cortex.
Romeas et al., 2016	23 soccer players (21.7 ± 0.5 yrs)	Neurotracker	Soccer videos	No	Yes	No	No	None	TG showed significantly greater improvement than controls in passing accuracy ($p = 0.044$), but not dribbling or shooting. There was a significant increase in self-reported confidence in decision making in the TG ($p = 0.012$) but not controls.
Vartanian et al., 2016	41 Armed Forces personnel (21–50 years)	Neurotracker	Dual n-back	Yes	No	No	Yes	WM	TG showed significant increases in word ($p = 0.005$), visual ($p = 0.05$), and matrix ($p = 0.015$) span tasks. There was no improvement in active and passive control groups.

Transfer to tasks other than laboratory cognitive tests.

SR, self-report outcome; WM, working memory; STM, short-term memory; EF, executive function; TG, treatment group; OSPAN, Operation Span task; WCST, Wisconsin card Sorting Task; WAIS, Wechsler Adult Intelligence Scale; ADHD, Attention deficit hyperactivity disorder, MS, Multiple Sclerosis; ps, multiple p-values.

Quality assessment color key: Strong (80+%) Fairly strong (70–79%) Moderate (60–69%) Weak (50–59–%) Very weak (40–49%)

active control groups, principally other computer games (Peretz et al., 2011). Unfortunately there was no test of retention and all studies were conducted by researchers with ties to Cognifit. Overall, the evidence for near transfer effects was relatively weak, and there was no evidence of transfer to tasks representative of sport.

Neurotracker

Four studies investigating Neurotracker were included in the review, although the website lists further studies indicating that Neurotracker ability correlates with sporting (Faubert, 2013; Mangine et al., 2014), driving (Michaels et al., 2017), and surgical (Harenberg et al., 2016) performance. The research base for Neurotracker differs somewhat from those of Cogmed, Lumosity, and Posit Science, which have focused almost exclusively on near transfer effects. Only two of the Neurotracker studies actually tested near transfer effects; Parsons et al. (2016) found improvements in sustained attention, inhibition and working memory following training, while Vartanian et al. (2016) similarly found improvements in several measures of working memory. There is, conversely, more evidence for far transfer effects, and greater use of young and healthy populations, in comparison to other devices.

Firstly, Parsons et al. (2016) found training effects to be accompanied by changes in resting state brain function, primarily decreased theta, alpha, and delta EEG bands in the frontal cortex following 10 training sessions. Secondly, among older adults with impairments in perceiving biological motion, Legault and Faubert (2012) found significant improvements in identifying point light walkers (coordinated moving dots that simulate human motion) at a distance relevant for collision avoidance. Of most relevance for current purposes, is a study by Romeas et al. (2016) which provided the only study in this review to directly test transfer to a sporting task. Romeas et al. (2016) found significant improvements in coach ratings of passing accuracy following Neurotracker training, however, the small sample size (<10 per group) and the null effects for dribbling and shooting should, however, be taken into account. Three of the four studies used appropriate active controls, such as a working memory task, but there was no testing of retention.

Overall, the evidence for far transfer effects and sporting benefits in particular is more promising than most devices. Transfer effects have been found for perception of motion and soccer passing, with EEG suggesting measurable changes in neural activity. Nonetheless the evidence for near transfer is weaker than other devices, and studies have, for the most part, used small samples and been conducted by researchers connected to the company.

Nintendo's Brain Age

Four studies included in the review assessed Nintendo's Brain Age and Big Brain Academy, which provided mixed findings for near transfer effects. Two studies, conducted by Nintendo's researchers, found improvements in executive function, processing speed, and working memory following training, relative to computer game controls (Nouchi et al., 2012, 2013). Conversely, Ackerman et al. (2010) found no benefit to the training group above controls, and McDougall and House (2012) found null effects across most sub-measures of the Wechsler Adult Intelligence Scale. Therefore the evidence for even near transfer effects is weak. Additionally, there are no studies testing far transfer effects of Nintendo's products or retention of abilities. Hence, there was little support for this device and no evidence for sporting transfer.

Dynavision

One study, conducted by independent researchers, was identified that employed a Dynavision training intervention. There is currently little evidence regarding the cognitive functions that are directly targeted by Dynavision as the one included paper inferred improvements in processing speed from the trained task, and did not employ other cognitive measures (Klavora et al., 1995), so there is no evidence of near transfer. There is, however, initial evidence for far transfer, as Klavora et al. (1995) found 10 participants assessed as unsafe to drive following a stroke, to show significantly improved driving ability following training. Unfortunately, this study did not use an active control group, or assess retention of the improvement in driving. Overall the evidence base for this device is weak, as even near transfer to other cognitive tasks is yet to be established and there has been no test of sporting transfer.

Quality Assessment

Scores ranged from 40.9 to 81.8%, with a mean of 62.2% (Appendix 1 in Supplementary Material). Overall, studies scored highly in items relating to the tasks used, basic design, making clear hypotheses, reporting the main findings, assessment tasks, and measuring near transfer. The lowest scoring item was inclusion of a transfer task representative of real-world performance, which was only achieved in four studies. Additionally, only seven studies included justification of sample size, and only eight assessed retention of trained skills. Other issues that were poorly addressed were consistent reporting of effect sizes and the generalizability of findings, due to many studies using niche or non-healthy populations. Eighteen of the 43 studies were carried out by researchers with known connections to the companies.

DISCUSSION

The aim of this systematic review was firstly to evaluate the evidence that currently exists for the effectiveness of CCT devices, and secondly the evidence for transfer to sporting performance. In principle, regular training of key cognitive abilities may hold great value for sporting scenarios, which place high demand on attentional and processing resources, requiring decisions to be made under pressure (Ducrocq et al., 2016). Currently, however, there is a gulf between scientific findings and marketing claims. Therefore, we aimed to provide a rigorous overview of the peer-reviewed evidence for these devices. With regards to our stated aims, the CCT devices showed limited evidence for far transfer effects in general, and evidence of additive effects relevant to sport was particularly scarce, mainly because only one study directly assessed transfer to a sporting task.

Summary of Evidence

The premise of CT is that training of core cognitive abilities will transfer to other tasks and environments. As such, while there was good evidence for near transfer effects in many devices (as has been found in other reviews; Melby-Lervåg and Hulme, 2013), this is not sufficient to conclude overall device effectiveness. Within the compensatory/restorative studies there was limited evidence for far transfer effects beyond the trained tasks, and where transfer tests were used, they often consisted of self-reporting of symptoms. This is a particular problem given the sporadic use of active control groups. Overall, evidence is currently weak for real world benefits from CCT devices, even in deficit populations where we might expect the largest effects. With regards to the narrower focus on potential sporting benefits, the evidence reviewed provides little indication that CCT devices can transfer to the sports field. Firstly, the number of studies using tasks and populations that can be generalized to sport was almost null, with only one study directly using a sporting transfer task. Secondly, the lack of transfer across all populations is not encouraging for athletes who are seeking additive effects. The underwhelming quality of the studies assessed means that positive effects cannot yet be ruled out, but there is little current evidence for them.

Based on the results of the review, the findings relating to Cogmed, Lumosity, Cognifit, and Posit Science[4] could be grouped together due to similarity of training method and published evidence. These devices use online or app-based games, which closely mimic traditional cognitive tasks, such as memory span and dual load tasks. Their evidence base for near transfer effects is fairly strong, and these devices likely enhance working memory, processing speed, executive function, and attention in laboratory based tasks (Melby-Lervåg and Hulme, 2013). There was, however, very little testing of far transfer effects or retention of trained skills. Whether far transfer tasks have been employed, but remain in the "file drawer" due to null effects, cannot be known. Therefore, these devices hold little promise for benefiting sporting performance.

Outside of this group, Neurotracker provided a training option that included a greater perceptual element and aimed to be more representative of sporting skills. In comparison to other devices, there was relatively little direct testing of near transfer effects, but findings are rather more promising for transfer to real-world tasks. Studies provided initial evidence for enhancing human motion perception (Legault and Faubert, 2012) and soccer passing (Romeas et al., 2016); an indication of far transfer that was absent from the first group of devices. Studies with this device are yet to assess retention effects, following a period without device use. As such further study is required to understand whether beneficial effects rely on persistent use, or can be achieved from a single intervention. In addition, Dynavision training, which similarly included a perceptual element, has been linked to improvements in driving ability (Klavora et al., 1995), but here the evidence was relatively weak. Consequently, while these findings certainly warrant further consideration, firm conclusions cannot yet be drawn as these studies suffer from the same methodological issues discussed previously. In summary, adopting any of the reviewed devices for training athletes would be based on a belief in the principles of domain generality and neuroplasticity rather any conclusive evidence of transfer effects. While these devices may benefit performance in similar, laboratory-based tasks, there is currently weak evidence of their value for sport.

[4]Nintendo's device could also be included here, but its evidence base is somewhat weaker.

Quality Assessment

Quality assessment scores (Appendix 1 in Supplementary Material) suggest that, overall, the studies in this area display several methodological issues. Some particular concerns include basic experimental design issues like calculation of sample size. A number of the papers reviewed (13) had small samples (<15 per group) with no power analysis as justification. As a result, many of the studies in this area are likely underpowered, meaning the positive findings that do exist have an increased chance of being erroneous (Button et al., 2013). Additionally, many studies included batteries of cognitive tests, which created a multiple testing issue that was, in general, ignored. Preregistration[5] of planned analyses would be a major step forward in avoiding an ad hoc approach to assessing training effects in this area (Simons et al., 2016).

Methodological choices of the included studies have also limited the conclusions that can be drawn about transfer to sport. In particular the lack of representative real-world tasks and assessment of retention mean that extending findings to sporting scenarios is problematic. Similarly, participant populations often had cognitive deficits, limiting generalizability to healthy populations, where effect sizes may well be smaller. For CCT devices to provide convincing evidence for sporting benefits, these questions must be addressed in future studies.

Future Directions

Future work in this area should focus on the devices that hold the greatest promise for sporting transfer, namely those with a perceptual-cognitive element, more representative of the demands of sport. More studies are required that use athlete populations (rather than cognitively impaired) and test transfer to more representative tasks. Studies must, however, take note of the methodological issues that are prevalent in this area (Simons et al., 2016). As this literature is particularly prone to selective reporting of tests and results, preregistration of accurately powered trials is imperative. The use of adequate active control groups must also be improved, to allow a fair comparison of training effects. CT is an area where much research to date could claim to be "exploratory," but in order to move toward any kind of reliable evidence, a more systematic approach, which rectifies many of the methodological issues, is required.

Limitations

As with any systematic review, the conclusions must be taken within the context of the search criteria. Other methods of training cognitive function are available, such as transcranial

[5]Recording intended methods and analyses prior to data collection.

direct stimulation, mindfulness, and exercise interventions. Additionally, amalgamations of interventions were not included, hence the efficacy of combined training strategies cannot be ruled out. There are also a large number of excluded studies which use non-commercially available devices. These studies may report more convincing methods or effects, indeed much working memory training research is more rigorous (see Melby-Lervåg and Hulme, 2013; Ducrocq et al., 2016). We suggest, however, that a focus on commercial devices was warranted given their growing popularity, easy access, endorsements, and the confusion about their effectiveness in the sporting community.

CONCLUSIONS

In this systematic review we aimed to evaluate the evidence currently available for CCT devices. Through assessing study quality and synthesizing the available results, it is apparent that there is limited evidence that improvements found in lab-based cognitive tasks transfer to real world benefits. In particular, the very limited use of populations and tasks representative of sport means inferences about CCT effectiveness for athletes are unreliable. Additionally, we identified a series of methodological issues within the CCT literature, such as use of appropriate controls, small sample sizes, lack of retention tests and limited replication of findings by independent researchers. Companies promoting CCT products must address these issues in order to make scientifically valid claims about device effectiveness, while those in the sporting community looking to adopt the use of these products should seek to verify device claims with a healthy degree of skepticism.

AUTHOR CONTRIBUTIONS

All authors contributed to the review design, search criteria, and writing of the paper. DH and SV conducted the paper search and assessment.

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Motor and Gaze Behaviors of Youth Basketball Players Taking Contested and Uncontested Jump Shots

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In this study, we examined the effects of a defender contesting jump shots on performance and gaze behaviors of basketball players taking jump shots. Thirteen skilled youth basketball players performed 48 shots from about 5 m from the basket; 24 uncontested and 24 contested. The participants wore mobile eye tracking glasses to measure their gaze behavior. As expected, an approaching defender trying to contest the shot led to significant changes in movement execution and gaze behavior including shorter shot execution time, longer jump time, longer ball flight time, later final fixation onset, and longer fixation on the defender. Overall, no effects were found for shooting accuracy. However, the effects on shot accuracy were not similar for all participants: six participants showed worse performance and six participants showed better performance in the contested compared to the uncontested condition. These changes in performance were accompanied by differences in gaze behavior. The participants with worse performance showed shorter absolute and relative final fixation duration and a tendency for an earlier final fixation offset in the contested condition compared to the uncontested condition, whereas gaze behavior of the participants with better performance for contested shots was relatively unaffected. The results confirm that a defender contesting the shot is a relevant constraint for basketball shooting suggesting that representative training designs should also include contested shots, and more generally other constraints that are representative of the actual performance setting such as time or mental pressure.

Keywords: visual search strategy, representative design, perception, motor behavior

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INTRODUCTION

In sports, the ability of performers to use information from the environment to select and execute an appropriate action is essential to high-level performance (Williams and Ericsson, 2005; Williams et al., 2011). This ability is based on an accurate and efficient relationship between perceptual and motor processes, termed the "perception–action coupling" (Gibson, 1979; Michaels and Beek, 1995). Due to the dynamic and fast-paced nature of sport settings, opportunities for action emerge and disappear as individuals interact with their environment. Performers need to learn to continuously adapt their behavior to the changing task constraints, and consequently the design of appropriate task constraints is a major issue in research and learning perceptual-motor skills.

Representative design is a concept initially proposed by Brunswik (1956) and states that in research tasks should be created in such a way that the task constraints represent the behavioral setting to which the results are intended to be generalized (Dicks et al., 2009; Pinder et al., 2011). Recent studies show significant changes in movement and gaze behavior under different experimental task constraints accompanied by varying degrees of perception–action coupling. Findings of meta-analyses of perceptual-cognitive skill in sports have shown that expertise effects are more apparent under *in situ* task constraints than in less representative conditions (Mann et al., 2007; Travassos et al., 2013). For example, Dicks et al. (2010) showed that soccer goalkeepers made more penalty saves and fixated earlier on the ball and for longer periods of time in an *in situ* condition where actual interception was required compared to responding to a video simulation involving limited movement. Such findings have major implications for the creation of experimental and learning designs in sports (Pinder et al., 2011; Travassos et al., 2012).

Even when using natural sports performance settings, ensuring that the task constraints are representative is not easy since small changes in task constraints can lead to significant changes in performance outcomes and movement responses (Hristovski et al., 2006; Pinder et al., 2011; Travassos et al., 2012). In invasion sports, immediate opponents offer relevant constraints on action possibilities. A defender (almost) by definition has considerable perturbing effects upon the actions of an attacker. Therefore, in research and training, tasks requiring the performer to execute a skill against an opponent may provide a more representative design of the actual performance setting (Brunswik, 1956; Pinder et al., 2011; Gorman and Maloney, 2016). However, there is only a limited number of studies comparing contested and uncontested conditions (for examples, see Rojas et al., 2000; Hughes et al., 2010; Rivilla-Garcia et al., 2011; Orth et al., 2014; Gorman and Maloney, 2016; Klostermann et al., 2017). These studies generally reveal that players change their movement behavior when facing a defender in various sports (e.g., Rojas et al., 2000; Hughes et al., 2010; Rivilla-Garcia et al., 2011).

The influence of a defender on motor performance of basketball shots has been demonstrated by the findings from empirical research (Rojas et al., 2000; Gorman and Maloney, 2016). For example, Rojas et al. (2000) found that when professional basketball players perform a jump shot against a defender trying to contest the shot, the speed, release height, and release angle of the ball were increased. These are all likely adaptations to reduce the chance of the opponent blocking the ball. Similarly, Gorman and Maloney (2016) found that a defender led to faster shot executions, longer jump times, and longer ball flight times. Furthermore, these changes in motor execution were accompanied by a decrease in shooting accuracy of over 20%. However, the shooting accuracy was based on just six trials in each of five different shot types, meaning that hitting one shot more or less resulted in a change in shooting accuracy of 16.7%. Nonetheless, even at the elite level of the NBA, the proximity of a defender influences shooting accuracy. When NBA players have a wide open shot (i.e., the defender is more than 6 ft away), the average shooting accuracy of three-point shots is 38.1%; for open shots (4–6 ft), this is 35.4%; for tight shots (2–4 ft) 31.2%, and for very tight shots (0–2 ft), this is 26.4% (NBA Advanced Stats, 2016–2017 data[1]).

One possible cause for the reduced shooting accuracy against an opponent may be the visual control of the basketball shot. Visual control of basketball shooting has been examined in the static task of free throw shooting and in more dynamic tasks like taking jump shots. Vickers (1996) examined the gaze behavior of basketball players during static free throws, and found that experts' duration of the final fixation before the initiation of the movement was significantly longer than for lesser skilled performers. This phenomenon called quiet eye is defined as "the final fixation or tracking gaze that is located on a specific location or object in the task space within 3° of visual angle (or less) for a minimum of 100 ms. The onset of the quiet eye occurs prior to a critical final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms, therefore the quiet eye can carry through and beyond the final movement of the task" (Vickers, 2016, p. 1–2). The quiet eye period reflects the time needed to set the parameters of the movement to be executed (preprogramming; Vickers, 1996; Williams et al., 2002), and suggests an open-loop process for controlling the shooting movements (Ripoll et al., 1986; Vickers, 1996).

However, a number of studies by Oudejans et al. (2002, 2005; de Oliveira et al., 2006, 2007, 2008) challenged this finding and found evidence for online visual control of the basketball shot. Using the dynamic task of basketball jump shooting, Oudejans et al. (2002) found that shooting with late vision (i.e., vision occluded until the last ± 350 ms before ball release) was as good as shooting with full vision, while early vision (i.e., vision occluded during the last ± 350 ms) resulted in a decrease in performance. These results imply that the final shooting movements were controlled by continuous pick-up and use of visual information until ball release, and shows that the last ± 350 ms before ball release are necessary and sufficient for accurate shooting. This was confirmed in the study by de Oliveira et al. (2008) who examined the final fixation on the rim in basketball jump shooting. They used a slightly different definition of the final fixation on the rim than that of quiet eye as (i) the onset of the final fixation on the rim does not have to be prior to initiation of the final shooting movement (e.g., the extension of the shooting arm in basketball shooting), as long as it is prior to ball release, and (ii) the offset is never later than ball release because after ball release the shooter cannot control the ball anymore, implying that vision after ball release is useless for movement control of that shot. The gaze results corroborate the view that basketball shooting is largely controlled online by vision, that is, visual information is picked up and used during movement execution.

To date, the influence of a defender on the visual control of basketball shots has only been examined by Klostermann et al. (2017). They compared quiet-eye behavior of intermediately skilled and highly skilled basketball players in contested vs. uncontested game situations, and found that the absolute quiet

[1] stats.nba.com

eye duration did not significantly differ between contested and uncontested shots. Still, a longer relative quiet eye duration was found for the contested compared to the uncontested shots. However, as relative quiet eye duration is defined as absolute quiet eye duration divided by the total movement time, this merely reflected a change in total movement time from 1178 ms in the uncontested condition to 519 ms in the contested condition rather than a change in absolute quiet eye duration. Furthermore, in the "uncontested game situation," shots were taken from one position after making a dribble, while in the contested game situation, jump shots could be made after a dribble or pass in three vs. three small sided game situations (Klostermann et al., 2017, p. 3). Actions preceding the jump shot (pass or dribble) may influence the shooting accuracy (Oudejans et al., 2012a). In addition, data collection lasted until participants reached six hits and six misses leading to a wide range of number of shot attempts varying from 12 to 56, and a differential basis for calculating shooting accuracy. Finally, the method of analysis of gaze behavior was unclear. The duration of phases and the starting moments of a phase were used interchangeably. Also, the onset and offset of quiet eye were calculated as relative values in relation to the beginning of the final extension of the shooting arm. This is practically less interesting than the timing of the final fixation in relation to the moment of ball release, as that is the moment at which control over the ball ends (cf. Rojas et al., 2000; Oudejans et al., 2002; Gorman and Maloney, 2016).

The purpose of the present study was to examine the influence of a defender contesting the shot on (motor) performance and gaze behavior of talented youth players taking basketball jump shots. The accuracy of the shots were recorded as well as several measures of movement and gaze behavior, including shot execution time, jump time, ball flight time (similar to the study of Gorman and Maloney, 2016), and the duration and timing of the final fixation on the rim prior to ball release. It was hypothesized that an approaching defender would decrease the shooting accuracy and would cause changes in movement variables that are required to prevent the shot from being blocked by the defender (Rojas et al., 2000; Gorman and Maloney, 2016). In line with earlier studies, we expected faster shots, higher jumps, and longer ball flights in the contested compared to uncontested shots. As for gaze behavior we expected shorter relative, but more importantly also absolute final fixations on the rim indicative of hampered visual control of the shot.

MATERIALS AND METHODS

Participants

A total of 13 talented female basketball players participated in this study [a number comparable to similar studies on basketball shooting, Gorman and Maloney, 2016 (n = 12), Klostermann et al., 2017 (n = 15 and 8), Oudejans et al., 2002 (n = 10), and Rojas et al., 2000 (n = 10)]. The average age of the participants was 16.8 years (SD = 1.8 years). The participants were all enrolled in the national basketball talent program and national youth team, and had an average of 8.0 years (SD = 1.8 years) of playing experience. Their average seasonal statistics were 44.5% for field goals, 18.5% for three-point shots, and 59.3% for free throws. The experiment was approved by the scientific and ethical review committee of the Faculty of Behavioral and Movement Sciences of the Vrije Universiteit in Amsterdam and all participants gave their written informed consent prior to the experiment; parental consent was provided for participants younger than 16 years.

Equipment

All trials were recorded with a GoPro camera (Hero 3, black edition, GoPro, Inc., United States) that was positioned on the side line of the court and in line with the free throw line (**Figure 1**). The SensoMotoric Instruments eye tracking glasses (SMI; Teltow, Germany; binocular, 30 Hz) were used to record the gaze behavior of the participants. The glasses were either connected to a mobile recording unit which was carried in a waist bag (with data storage on a hard disk in the recording unit, and a wireless live view on a laptop) or via a 5-m-long usb-cable to a laptop. In both cases, the participants were able to move freely. Prior to testing, the eye tracking glasses were calibrated using a three-point calibration and the calibration was checked and adjusted if needed prior to each series of 12 shots. The test took place at the regular training facilities of the national basketball talent program. Official FIBA regulation court, basket, and women's basketball (size 6) were used.

Procedure and Design

Participants were assigned to matching pairs by the head coach based on playing position, height, and skill level. The participants performed a brief warm-up including some shooting drills prior to testing. The test consisted of a total of 24 shots in both the contested and uncontested condition, and these comprised 12 shots from the left and 12 shots from the right side of the court. The test conditions and playing side of the court were counterbalanced across participants. The test took approximately 20 min to complete per pair of participants.

Every trial started with a signal from one of the experimenters. The participant moved toward the elbow (i.e., corner of the free throw line) to receive the pass from the experimenter who was positioned on the other elbow (see **Figure 1**). The participant was instructed to shoot immediately after receiving the pass. In the contested condition, the defender ran out to defend the shot, but only after the starting signal given by the experimenter. This allowed sufficient time for the defender to reach the participant and contest the shot. Defenders were instructed to contest the shot without making actual contact with the participant. They made a so-called close-out with one arm and hand up in the air. In the uncontested condition, the defender remained standing on the restricted arc. The participants and defenders were instructed to perform the test in a game-like manner with the same speed and intensity as they would normally show. If the pass to the participant was reckoned to have considerable disadvantages for the participant or the defender made contact with the participant, the trial was repeated.

Data Analyses

Shooting accuracy was determined for both the contested and uncontested condition by summing the number of successful

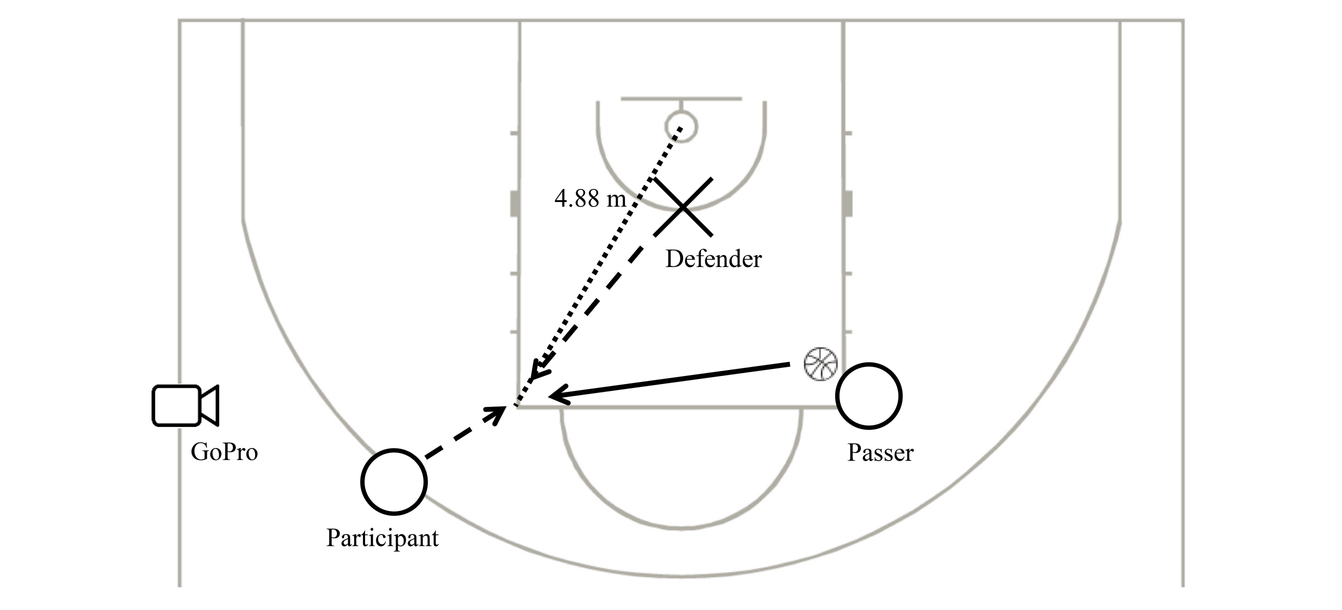

FIGURE 1 | Schematic top view of the experimental setup. Shooting from the left side is depicted. Participant (the shooter) steps in and receives the ball from the passer and takes a shot. In the contested condition, the defender (cross) steps in toward the participant to contest the shot. In the uncontested condition the defender stays in her original location.

shot attempts and dividing it by the number of test trials. The recordings of the SMI eye tracking glasses were synchronized with the video footage of the GoPro camera using Adobe Premiere Pro. These synchronized video files were analyzed frame by frame for the duration of each trial using Dartfish. Identical to Gorman and Maloney (2016), three movement variables were extracted from the video recordings: shot execution time, jump time, and ball flight time. Shot execution time was measured from the moment when the ball first touched either of the shooter's hands, to the moment when the ball first lost contact with the shooter's shooting hand during the execution of the shot (i.e., moment of ball release). Jump time was measured from the moment when both of the shooter's feet first left the floor to go up for the jump shot, to the moment when either of the shooter's feet first resumed contact with the floor after the ball was shot. Ball flight time was measured from the moment when the ball left the shooter's hand (i.e., moment of ball release) to the moment when the ball first touched (or would have touched) either the rim or backboard.

The synchronized video footage was also used to analyze gaze behavior of the participants. A fixation was defined as gaze maintained on any location for a period equal to or in excess of 100 ms or three sequential frames (cf. Williams and Davids, 1998; Savelsbergh et al., 2002; Vaeyens et al., 2007a,b). We determined the fixations on the locations rim and defender, and were especially interested in the *final* fixation on the rim before ball release [following the same definition as de Oliveira et al. (2008), which deviates in some regards from the definition of quiet eye, see section "Introduction"]. Relative final fixation duration and relative occlusion duration were calculated by dividing the absolute values by the shot execution time. The onset and offset of the final fixation on the rim were calculated in relation to ball release (e.g., 100 ms means 100 ms before ball release). As visual control ends at the moment of ball release, the offset could not occur after ball release. In case gaze was still fixated at the rim at the moment of ball release, the offset was coded as 0 ms.

The video footage was randomly assigned to two experimenters who coded the movement variables and gaze behavior. A total of 48 randomly selected trials were coded by both experimenters to assess inter-observer reliability, and it was found that on average the ICC = 0.98, $p < 0.001$ for the movement variables and $\kappa = 0.91$, $p < 0.001$ for gaze behavior, indicating excellent agreements (Hallgren, 2012).

Statistical Analyses

Shooting accuracy in the contested and uncontested condition was analyzed using a paired samples *t*-test. The three movement phases, and the seven variables of gaze behavior were analyzed using separate repeated measures ANOVAs with the factors condition (contested vs. uncontested) and outcome (hits vs. misses). For the factor side of the field (left vs. right), analyses revealed no significant effects. Therefore, this factor was excluded from the analyses reported in this paper, also because this factor was not of principal interest. For all ANOVAs, significant main and interaction effects were followed up by Bonferroni corrected pairwise comparisons. Effect sizes were reported as partial eta squared (η_p^2), and the significance level was set at 0.05.

As the results revealed that there were large individual differences in response to the approaching defender, we were interested to examine this further. We therefore, *a posteriori*, created two sub-groups based on the shooting accuracy because six participants showed lower shooting accuracy in the contested condition than in the uncontested condition, and six participants showed higher shooting accuracy in the contested than in the uncontested condition. We therefore classified them as the worse and better group, respectively. One player showed identical shooting accuracy in the contested and uncontested conditions. Therefore, she could not be classified as worse or better and was excluded from the *a posteriori* group analyses. We realize that this procedure of creating groups is neither common nor desirable. However, we believe that the averaging out that occurred conceals relevant findings. In the end, the final test in this study is not about differences in shooting accuracy between these groups but the accompanying differences in gaze behavior. We will first present the results for the group as a whole after which we will also present the analyses with the *a posteriori* created groups.

RESULTS

Shooting Accuracy

The mean shooting accuracy of the participants was 52.2% (SD = 8.1%) in the uncontested condition and 51.3% (SD = 15.0%) in the contested condition, $t(12) = 0.199$, $p = 0.85$, $r = 0.06$, ns, giving the impression that an approaching defender did not affect shooting accuracy.

Movement Phases

The movement phases are displayed in **Table 1**. The analysis of shot execution time showed a significant main effect of condition, $F(1,12) = 39.87$, $p < 0.001$, $\eta_p^2 = 0.77$, revealing that contested shots were performed significantly faster than uncontested shots. The main effect for outcome and the condition x outcome interaction effect were not significant, both $Fs < 0.24$, $ps > 0.63$. For jump time, also a significant effect for condition was found, $F(1,12) = 32.00$, $p < 0.001$, $\eta_p^2 = 0.73$, indicating that the jump time of contested shots was longer than for uncontested shots. The main effect for outcome and the condition x outcome interaction effect were not significant, $F(1,12) = 4.05$, $p = 0.07$, $\eta_p^2 = 0.25$, and $F(1,12) = 0.04$, $p = 0.84$, $\eta_p^2 = 0.00$, respectively. The ball flight time also differed as a function of condition, $F(1,12) = 9.76$, $p < 0.05$, $\eta_p^2 = 0.45$, with a significant longer ball flight time for contested shots than uncontested shots. There was also a significant effect of outcome, $F(1,12) = 6.80$, $p < 0.05$, $\eta_p^2 = 0.36$, indicating that the ball flight time of hits was shorter than of misses. The condition x outcome interaction effect was not significant, $F(1,12) = 0.16$, $p = 0.70$, $\eta_p^2 = 0.01$.

Gaze Behavior

Gaze behavior of the participants is displayed in **Table 1**. The ANOVA for final fixation duration revealed a significant main effect for condition, $F(1,12) = 14.554$, $p < 0.05$, $\eta_p^2 = 0.559$; the final fixation was shorter in the contested condition than in the uncontested condition. The main effect for outcome and the condition x outcome interaction effect were not significant, both $Fs < 0.78$, $ps > 0.39$.

For the relative final fixation duration, a significant main effect for condition was found, $F(1,12) = 7.00$, $p < 0.05$, $\eta_p^2 = 0.37$. Again a shorter relative final fixation duration was found in the contested condition than in the uncontested condition. The main effect for outcome and the condition x outcome interaction effect were not significant, both $Fs < 0.80$, $ps > 0.39$.

For final fixation onset, a significant main effect for condition was found, $F(1,12) = 14.78$, $p < 0.05$, $\eta_p^2 = 0.55$; the final fixation onset was later in the contested condition than in the uncontested condition. The main effect for outcome and the condition x outcome interaction effect were not significant, $Fs < 1.01$, $ps > 0.33$. For final fixation offset, no significant main nor interaction effects were found, $Fs < 2.99$, $ps > 0.11$.

The analyses of the occlusion duration and the relative occlusion duration did not reveal significant effects, all $Fs < 2.13$, $ps > 0.17$.

For the fixation duration on the defender, a significant main effect for condition was found, $F(1,12) = 8.87$, $p < 0.05$, $\eta_p^2 = 0.42$, with participants fixating longer on the defender in the contested condition than in the uncontested condition. The main effect for outcome and the condition x outcome interaction were not significant, $Fs < 0.46$, $ps > 0.51$.

A Posteriori Analyses

As mentioned, to further accommodate the individual differences in performance response to the approaching defender, we *a posteriori* created the two sub-groups, the worse and better groups. Their mean (and SD) shooting accuracy, movement phases, and gaze behavior variables for the uncontested and contested conditions are displayed in **Table 2**. We first checked the creation of the subgroups using an ANOVA on the shooting accuracy. A significant condition x group interaction effect was found, $F(1,10) = 21.11$, $p < 0.001$, $\eta_p^2 = 0.68$. In line with how the groups were created, the participants with worse performance showed lower shooting accuracy in the contested condition than in the uncontested condition, $p < 0.05$, whereas the participants with better performance showed higher shooting accuracy in the contested compared to the uncontested condition, $p < 0.05$. The shooting accuracy of the worse and better groups was not significantly different in the uncontested condition, $p = 0.12$, but it was in the contested condition, $p < 0.05$. The main effect for condition, $F(1,10) = 0.11$, $p = 0.75$, as well as the main effect for group, $F(1,10) = 1.86$, $p = 0.20$, were not significant.

For shot execution time, jump time, and ball flight time, the main and interaction effects involving group were not significant, all $Fs < 0.64$, $ps > 0.44$. Thus, all participants (worse and better) showed shorter shot execution time, longer jump time, and longer ball flight time for contested than uncontested shots (see original analyses).

The ANOVA for final fixation duration revealed a significant main effect for condition, $F(1,10) = 14.34$, $p < 0.05$, $\eta_p^2 = 0.59$; the final fixation was shorter in the contested condition (M = 345 ms, SD = 180 ms) than in the uncontested condition (M = 412 ms, SD = 203 ms). The condition x group interaction effect was marginally significant, $F(1,10) = 4.87$, $p = 0.052$, $\eta_p^2 = 0.33$. A shorter final fixation duration was found in the contested condition than in the uncontested condition for the participants with worse performance, $p < 0.05$, but not for the participants with better performance, $p = 0.29$. The main effect for group was not significant, $F(1,10) = 0.02$, $p = 0.90$.

TABLE 1 | Mean (*SD*) duration of the movement phases and gaze behavior variables for hits and misses in the uncontested and contested conditions. For definitions of the phases and durations, we refer to the text (see section "Data Analyses").

	Uncontested			Contested		
	Hits	**Misses**	**Average**	**Hits**	**Misses**	**Average**
Movement phases						
Shot execution time (ms)	898 (107)	894 (96)	896 (100)	819 (93)	816 (72)	817 (82)
Jump time (ms)	250 (63)	247 (61)	249 (61)	278 (53)	276 (54)	277 (52)
Ball flight time (ms)	990 (55)	998 (57)	994 (55)	1014 (60)	1027 (69)	1021 (64)
Gaze behavior variables						
Final fixation duration (ms)	433 (246)	453 (202)	443 (221)	369 (181)	360 (206)	364 (191)
Rel. final fixation duration (%)	48 (26)	51 (22)	49 (24)	45 (22)	44 (26)	45 (23)
Onset final fixation duration (ms)†	555 (209)	565 (170)	560 (187)	503 (165)	469 (202)	486 (182)
Offset final fixation duration (ms)†	122 (140)	111 (131)	116 (133)	133 (120)	109 (113)	121 (115)
Occlusion (ms)	127 (86)	119 (89)	123 (86)	117 (70)	114 (73)	116 (70)
Rel. occlusion (%)	14 (10)	13 (10)	14 (10)	15 (9)	14 (9)	14 (8)
'Gaze on defender (ms)	0 (0)	8 (28)	4 (20)	61 (70)	49 (84)	55 (76)

†*Calculated relative to ball release with positive numbers indicating occurrence prior to ball release.*

TABLE 2 | Mean (*SD*) shooting accuracy, duration of movement phases, and gaze behavior variables for the participants with worse and better performance (in the contested compared to the uncontested condition), in the uncontested and contested conditions. For definitions of the phases and durations, we refer to the text (see section "Data Analyses").

Group	**Worse (*n* = 6)**		**Better (*n* = 6)**	
Condition	**Uncontested**	**Contested**	**Uncontested**	**Contested**
Shot accuracy (%)	56.3 (9.8)	41.0 (13.8)	48.6 (5.0)	61.8 (9.3)
Movement phases				
Shot execution time (ms)	896 (92)	823 (67)	890 (125)	812 (109)
Jump time (ms)	261 (68)	287 (54)	239 (67)	270 (61)
Ball flight time (ms)	985 (55)	1017 (69)	999 (64)	1015 (69)
Gaze behavior variables				
Final fixation duration (ms)	440 (265)	332 (205)	385 (137)	357 (169)
Rel. final fixation duration (%)	48.3 (27.7)	40.1 (24.5)	44.1 (17.8)	44.2 (20.6)
Onset final fixation duration (ms)†	501 (233)	429 (189)	574 (115)	533 (159)
Offset final fixation duration (ms)†	61 (64)	96 (84)	188 (164)	175 (138)
Occlusion (ms)	113 (107)	117 (93)	147 (67)	126 (55)
Rel. occlusion (%)	12.7 (11.3)	14.3 (10.9)	17.0 (8.2)	15.7 (7.0)
'Gaze on defender (ms)	0 (0)	131 (80)	0 (0)	67 (76)

†*Calculated relative to ball release with positive numbers indicating occurrence prior to ball release.*

For the relative final fixation duration, a significant main effect for condition was found, $F(1,10) = 7.39$, $p < 0.05$, $\eta_p^2 = 0.43$, as well as a significant condition x group interaction, $F(1,10) = 8.08$, $p < 0.05$, $\eta_p^2 = 0.45$. A shorter relative final fixation duration was found in the contested condition than in the uncontested condition for the participants with worse performance, $p < 0.05$, but not for the participants with better performance, $p = 0.93$. The main effect for group was not significant, $F(1,10) = 0.00$, $p = 0.99$.

For final fixation onset, a significant main effect for condition was found, $F(1,10) = 9.18$, $p < 0.05$, $\eta_p^2 = 0.48$. The final fixation onset was later in the contested condition (M = 481 ms, SD = 175 ms) than in the uncontested condition (M = 538 ms, SD = 179 ms). The main effect for group and the condition x group interaction effect were not significant, $Fs < 0.75$, $ps > 0.41$.

For final fixation offset, no significant main effect for condition nor group was found, $Fs < 2.32$, $ps > 0.16$, whereas the condition x group interaction was marginally significant, $F(1,10) = 3.68$, $p = 0.08$, $\eta_p^2 = 0.27$. By tendency, only the participants with worse performance showed earlier final fixation offset in the contested condition compared to the uncontested condition, $p = 0.08$ ($p = 0.48$ for the participants with better performance).

The analyses of the occlusion duration and the relative occlusion duration did not reveal significant effects, all $Fs < 3.66$, $ps > 0.09$.

For the fixation duration on the defender, a significant main effect for condition was found, $F(1,10) = 19.25$, $p < 0.05$, $\eta_p^2 = 0.66$, with participants, as mentioned, fixating longer on the defender in the contested condition than in the uncontested condition. The main effect for group and the condition x group interaction were not significant, $F\text{s} < 2.05$, $p\text{s} > 0.18$.

DISCUSSION

The purpose of this study was to examine the influence of an approaching defender on (motor) performance and gaze behavior of talented youth players taking basketball jump shots. Thirteen skilled youth basketball players performed shots from elbow distance under both contested and uncontested conditions, while concurrently wearing mobile eye tracking glasses to measure their gaze behavior. As expected, shot execution was faster, jump time was longer, and ball flight time was longer in the contested compared to the uncontested condition. These changes in movement execution were similar to the findings of Gorman and Maloney (2016) and seem to reflect the participants' attempts to adapt their movement to the approaching defender (Rojas et al., 2000; Gorman and Maloney, 2016; Klostermann et al., 2017). In practical terms, players shot faster, jumped higher, and propelled the ball with a higher arc toward the basket. These are all likely adaptations to reduce the chance of the opponent blocking the ball (Rojas et al., 2000). This confirms that the direct proximity of a defender influences motor behavior, and that this is an important consideration when designing representative shot trainings or study designs (see also Davids et al., 2008; Renshaw et al., 2010; Pinder et al., 2015).

However, in contrast to earlier findings (Gorman and Maloney, 2016; Klostermann et al., 2017), the behavioral changes in our study were not accompanied by an overall decline in shooting accuracy. Instead, it appeared that different participants were differentially affected by the presence of a defender, with six participants showing lower and six participants showing higher shooting accuracy in the contested compared to the uncontested condition. This suggests that not all players were successful in adapting their shot to the presence of the defender. The performance of some participants was actually hindered under influence of a defender, while other participants were able to successfully adapt to the varying task constraints and even managed to perform better. It is possible that shooting against a defender resulted in distraction from the main shooting task in some of the players. This is supported by the findings on gaze behavior as the *a posteriori* analyses revealed that the overall effects that were found for gaze behavior (i.e., shorter final fixations in the defended condition and earlier offset) were in fact only present for the participants who shot worse with a defender. This suggests that these participants missed out on the relevant visual information to control their shot, and this could explain the decrease in their performance when facing a direct defender.

In contrast, the participants with better performance did not show differences in gaze behavior between the contested and uncontested conditions. The duration of their final fixation on the rim was not affected and apparently remained sufficiently long. In addition, the timing of this final fixation did not change. Looking for an explanation for why they managed to actually improve their performance we can only speculate, for instance, that the defender led to better concentration and focus on the task. Alternatively, perhaps the defender provided an additional informational frame of reference (in the periphery) providing a better basis to perceive the distance to the rim and control the shot movements accordingly (Greenwood et al., 2016). This would fit the findings of Greenwood et al. (2016) who found that the umpire in cricket may provide a vertical reference point for the bowlers to regulate their run-ups. Future research is needed to determine whether the defender might provide such an informational constraint in basketball shooting. Overall, the results of the current study confirm the importance of the duration and timing of the final fixation for accuracy in far-aiming tasks like the basketball jump shot (Oudejans et al., 2002), and thus, of an optimal coupling between perception and action.

Klostermann et al. (2017) found a significant difference (i.e., increase) in relative quiet eye duration but not in absolute duration in the contested compared to the uncontested basketball shooting condition. As suggested in section "Introduction," the change in relative quiet eye duration probably merely reflected a change in movement execution time (the jump phase was more than halved from around 1000 to around 400 ms) rather than in absolute quiet eye duration making it hard to draw conclusions about the effect of a defender on the visual control of the basketball jump shot. The current study is the first study showing that the proximity of a defender can reduce the absolute duration and worsen the timing of the final fixation on the rim.

In general, we cannot conclude that the proximity of a defender acts as a direct visual distraction for shooters that causes performance decrements. Although we found that both players with worse and with better performance fixated longer on the defender in the contested than in the uncontested condition, there was no significant difference between these groups. Furthermore, not all participants fixated on the defender in the contested condition, only some of them did. These fixations were of short duration and often occurred early in the progression from catch to ball release. Thus, if any, it seems that the proximity of a defender resulted in an indirect distraction for some of the players: their critical fixation on the rim became shorter and this was accompanied by reduced shooting accuracy.

Note that we did not analyze the final fixation on the rim relative to biomechanics of the shooting action (e.g., arm flexion time, ready position time, and arm extension time) other than ball release [i.e., the moment at which (visual) control of the ball ends]. It is therefore not possible to determine when during the arm movements of the shooting action the final fixation on the rim occurred. Speculating from the results of Oudejans and Coolen (2003) who reported a duration of the final extension movement of about 200 ms (for male shooters), it seems that the final fixation started prior to this movement partially overlapping it. Future research is needed to investigate this coupling in more detail. It is also important to mention that not finding an overall negative effect on shooting accuracy (as was found in earlier research and in the NBA, see section "Introduction") may be related to the young age of the participants investigated. Although these players do belong to the talents of their age group, it is clear that they are still developing their skills. More research into the effects of a defender on shooting during different phases of development is needed as well as on the effects of the distance of the defender to the shooter as we now only investigated the two extremes of uncontested and contested shots.

Overall, the results of this study do indicate that our participants adapted their shooting movements to the proximity of a defender. This conclusion is consistent with those reported earlier in basketball (Rojas et al., 2000; Gorman and Maloney, 2016) and other sports (e.g., Rivilla-Garcia et al., 2011; Orth et al., 2014). For example, Rivilla-Garcia et al. (2011) showed that handball players adapted the ball velocity of the jump throw to the degree of opposition. However, we extended the existing literature by showing that some players were successful in these adaptations while others were not, and that this seemed to be related to their visual behavior. Players whose final fixations on the basket were affected in duration and timing showed a decrease in shooting accuracy, while players whose final fixations were unaffected did not show a decrease performance. Most important, the current study confirms that a direct opponent can change motor and gaze behavior of players in sport settings implying that it is essential to take this important constraint into account when creating representative tasks both for research and practice (see also Pinder et al., 2011, 2015). This is in line with the constraint-led approach advocated by Davids et al. (2008; Renshaw et al., 2010; Pinder et al., 2011), which takes its starting point in ecological psychology and the dynamical systems approach and the mutual relationship between performer and environment and the intricate coupling between perceiving and moving (Davids et al., 2008). In general, this implies that in investigating as well as training human movement, both the performer and the task should be embedded within the relevant constraints of the performance environment in order to obtain meaningful results.

Practical Implications

Athletes have to invest many hours of practice to perform at a high level, also to accurately and consistently perform specific sport skills like the basketball jump shot. However, not only the quantity of practice but also the quality of practice is important. For many athletes and coaches, an important question is: how to design these training sessions? The results of the present study and of previous studies suggest that creating representative tasks is an important consideration. Small changes such as the proximity of a defender result in differences in movement execution and for some players in differences in gaze behavior. Therefore, it is essential to also train the basketball shot with a defender applying more or less defensive pressure as that may simulate the circumstances under which players shoot in games. Of course, the presence of defensive pressure is only one of the (many) relevant constraints that need to be taken into account into representative training designs. Some other constraints to consider are the action prior to the shot (Oudejans et al., 2012a), time constraints (Belling et al., 2015), the timing and duration of vision on the rim (Oudejans, 2012; Oudejans et al., 2012b), and distance to the rim (Elliott and White, 1989; Elliott, 1992). Thus, in sports practice, it is important to design tasks with constraints that are representative of the actual performance setting, and this can include the proximity of an opponent but also other factors like time or mental pressure.

ETHICS STATEMENT

All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Scientific and Ethical Review Committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit in Amsterdam.

AUTHOR CONTRIBUTIONS

MvM and RO contributed to the design of the study, data collection, and manuscript revision. MvM performed data analysis and wrote the first draft of the manuscript.

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Concurrent Imitative Movement During Action Observation Facilitates Accuracy of Outcome Prediction in Less-Skilled Performers

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Skilled athletes can predict the outcome of actions performed by others, based on the kinematic information inherent in others' actions, earlier and more accurately than less-skilled athletes. Activation of the motor cortex during action observation indicates motor simulation of other's actions in one's own motor system; this contributes to skilled outcome prediction. Thus, the present study investigated whether concurrent movements during action observation that affect motor simulation influence the accuracy of outcome prediction, namely, whether concurrent imitative movement and self-movement enhance and inhibit accuracy, respectively, based on skill level. Twelve male varsity basketball players (skilled group) and twelve male college students with no special training in basketball (less-skilled group) were required to predict the outcome of a basketball free throw by another player based on the action kinematics in the following four conditions: prediction without any action (observation), prediction with right-wrist volar flexion with maximum speed (incongruent-action), prediction with concurrent imitative movement during observation by right-wrist flexion as if imitating the model's action (imitative-motion), or prediction with concurrent self-movement by right-wrist flexion as if shooting by oneself (self-motion). The results showed that the skilled group had degraded accuracy of outcome prediction in the self-motion condition compared to the observation condition. In contrast, accuracy in the less-skilled group was facilitated in the imitative-motion condition compared to the observation condition. The findings suggest that, at least in less-skilled participants, the appropriate motor simulation that relates to skilled prediction can be virtually induced by concurrent imitative movement during the prediction task, even if they have less experience of free throws. This effect in imitative movement is likely to occur by producing identical motor commands with observed action, thereby enabling the prediction of sensory consequences and outcome accurately via a forward model. We propose that traditional perceptual training with concurrent imitative movement is likely to be an effective way to develop visual- and motor-based hybrid outcome predictions that produce superior inferences in skilled athletes.

Keywords: outcome prediction, perceptual training, motor simulation, sports expertise, free throw

INTRODUCTION

A well-known feature of skilled athletes is their superior ability to make predictions (e.g., Abernethy et al., 1999; Williams et al., 2003; Hagemann et al., 2006; Savelsbergh et al., 2010). In ball games, such as basketball and soccer, earlier and more precise prediction of future states that arise from opponents' actions and/or the ball trajectory enables players to make more optimal and faster decisions in a dynamic environment. Indeed, the ability to make such predictions is a predictor of performance in real sports settings (Müller and Fadde, 2016). Therefore, the topic of how to improve prediction abilities has received attention for a considerable period in sports psychology and related domains.

Perceptual training has been proposed as an effective way of improving prediction abilities. The rationale of perceptual training is that skilled athletes who have superior prediction abilities can perceptually identify specific movement patterns inherent in opponents' actions that are associated with a specific outcome (i.e., anticipatory kinematic cues; Abernethy, 1990; Tenenbaum et al., 1999; Jackson et al., 2006; Abernethy and Zawi, 2007; Williams et al., 2009). Regarding kinematic-cue utilization, a basic training method is for learners to repeatedly predict the outcome of an opponent's actions (e.g., serve direction *after* racket-ball contact in tennis) in videos (i.e., a sports-specific scene that is filmed from a player perspective) that are occluded at various time points; after the prediction is made, the correct answer is provided as feedback. Thereby, learners develop associations between anticipatory kinematic cues and outcomes through intensive visual exposures. Various types of training methods have been tested recently, such as guided discovery and/or gaze cueing based on advance cue utilization; these have confirmed the effectiveness of perceptual training (e.g., Abernethy et al., 1999; Williams et al., 2003; Jackson and Farrow, 2005; Hagemann et al., 2006; Savelsbergh et al., 2010; Hopwood et al., 2011; Ryu et al., 2013).

In contrast, although learners accumulate knowledge about kinematic-outcome associations during perceptual training via *perceptual experience*, several recent studies have indicated the importance of *motor experience* for enhancing prediction abilities of athletes (Aglioti et al., 2008; Cañal-Bruland et al., 2012; Urgesi et al., 2012; Tomeo et al., 2013; Ikegami and Ganesh, 2014; Mulligan and Hodges, 2014; Makris and Urgesi, 2015; Mulligan et al., 2016a,b; Denis et al., 2017). Aglioti et al. (2008) reported that elite basketball players, who have considerable motor experience, could predict the shot outcomes of others based on the shooter's throwing kinematics more accurately than individuals with considerable visual experience (coaches or sports journalists) and novices (see also, Cañal-Bruland et al., 2012; Urgesi et al., 2012). In addition, Mulligan and Hodges (2014) found that outcome prediction in dart throwing was improved by motor learning of dart throwing itself, even when all visual information (e.g., own actions and dart trajectory after throwing) was completely excluded during learning. That is, skilled prediction is not developed merely via perceptual experience. Furthermore, recent evidence suggests that perceptual and motor experience develop different prediction mechanisms (Aglioti et al., 2008; Urgesi et al., 2012; Makris and Urgesi, 2015), namely visual- and motor-based prediction, respectively (Mulligan et al., 2016b). Motor experience more greatly improves prediction abilities based on kinematic cues than does perceptual experience such as observation of other's actions (Urgesi et al., 2012). Therefore, additional focus on the role of motor experience is needed to develop effective training of prediction abilities; however, few studies have focused on motor experience as compared to those that have considered perceptual experience.

The influence of motor development on perceptual predictions is consistent with the notion of bidirectional links between perceptual (observation of other's actions) and motor (execution of one's own actions) representations. It has been proposed that the perceptual and motor systems partly share the same representations (Prinz, 1990, 1997; Schütz-Bosbach and Prinz, 2007). Therefore, development of motor representations also affects the perception of the same action performed by others. Consistent with this notion, neuroscientific studies have shown that during prediction tasks, skilled athletes display enhanced activity of neural networks, including frontal, parietal, and temporal regions of the brain (Wright and Jackson, 2007; Aglioti et al., 2008; Abreu et al., 2012; Wu et al., 2013). These are activated both when executing one's own actions and while observing other's actions; the latter is referred to as the action-observation network (AON) and/or mirror neuron system (Gallese et al., 1996; Rizzolatti and Craighero, 2004; Iacoboni et al., 2005). Therefore, it has been proposed that motor activation during action observation contributes to the superior prediction abilities of skilled athletes (Aglioti et al., 2008; Abreu et al., 2012; Makris and Urgesi, 2015).

Interestingly, some studies have suggested that activation of the motor system during action observation changes depending on how observers monitor others' actions (i.e., the observers' intentions). Buccino et al. (2004) reported that neural activity during action observation is facilitated, including in the motor area, when participants observe with the intention of imitation. Additionally, motor activation during action observation can be facilitated through sensorimotor learning that has temporal and spatial congruencies between observed and executed behaviors (i.e., imitation; Catmur et al., 2007; Vogt et al., 2007; Heyes, 2010; Ménoret et al., 2013). In contrast, if self-focus is present, which may be elicited by engaging participants in a self-referential task before action observation, the motor activation that relates to the imitation is inhibited (Spengler et al., 2010). Additionally, observation of actions attributed to another agent facilitates motor-system activity, whereas observation of identical actions linked to the self does not (Schütz-Bosbach et al., 2006). That is, if others' actions are viewed with the intention of imitation (i.e., imitative movement), then action perception is facilitated.

In addition, Christensen et al. (2011) reported that when observers attempted to execute arm movements that were temporally and spatially congruent with those of an observed actor, the observer could accurately recognize the specific arm movement executed by actor, although they did not assume the effect of conscious cognitive processes such as intention. Nevertheless, this suggests that motor-based prediction might be changed by intention and similarity between observed and executed movement during action observation. More specifically, if an observer executes concurrent imitative movements, prediction accuracy is improved, because imitative movement is likely to facilitate spatial and temporal congruency with observed movement (Christensen et al., 2011; Springer et al., 2011) and enhance motor activation (Buccino et al., 2004). Further, if an observer executes concurrent self-focused movements, then prediction accuracy is degraded, because it would degrade congruency with observed movement and inhibit motor activation (Spengler et al., 2010).

Moreover, these effects come from concurrent imitative and self-focused movement (i.e., activate/inhibit motor simulation) and would be modulated depending on the skill level. As mentioned above, skilled athletes use motor simulation for predicting the action outcome of others. Therefore, no additional effect of imitative movement would be seen for skilled athletes in terms of prediction accuracy, because they already use a simulative process that would be induced by observing the action. In contrast, prediction accuracy would be degraded through concurrent self-focused movement because it would inhibit motor simulation processes in progress during the prediction task. On the other hand, for less-skilled people, imitative movement may facilitate prediction accuracy. Abreu et al. (2012) reported that activity of neural networks, including frontal, parietal, and temporal regions of the brain (AON network) were also activated in novices, although they demonstrate lower prediction ability. This implies that even novices engage in motor simulation during prediction tasks. It is believed that motor simulation enhances prediction accuracy according to the internal forward model, which enables us to predict future sensory consequences and outcomes based on an efference copy of issued motor commands (e.g., Mulligan and Hodges, 2014; Mulligan et al., 2016a,b). From the above evidence, it can be considered that novice and/or less-skilled people who have less motor experience can use motor simulation but that their motor commands created through observation are not likely to be accurate because they are less-developed. Therefore, the forward model would not produce appropriate predicted sensory consequences and outcomes. In other words, if individuals can produce the accurate motor commands during observation, then they can estimate the action outcomes correctly via the forward model. Taking these considerations into account, it may be that, in less-skilled individuals, concurrent imitative movement during action observation enhances the production of appropriate motor commands; thereby prediction accuracy will be temporarily improved. In contrast, concurrent self-focused movement in less-skilled individuals will not affect prediction accuracy if the motor simulation process is inhibited, because there was no reliance on motor-based prediction processes (Aglioti et al., 2008).

Thus, the purpose of the current study was to investigate how prediction accuracy is influenced by concurrent motor execution with different movement types during action observation. Accordingly, we recruited skilled basketball players, who were experts in motor-based outcome prediction (Aglioti et al., 2008; Abreu et al., 2012), and less-skilled players, who did not have such a prediction capability (e.g., Mulligan et al., 2016a). The occlusion technique was used to assess outcome-prediction capabilities: the participants made predictions about ball-landing locations near the hoop based on the actions of a model who performed basketball free throws. The task consisted of four conditions: observation without action, incongruent-action, imitative-motion, and self-motion. The observation condition was used to assess the baseline of prediction ability of each participant and to confirm the presence of skill-related differences in prediction ability. The incongruent-action condition was used to verify that the skilled athletes used motor-based predictions in the present study. Previous studies have demonstrated that incongruent actions degrade prediction accuracy in observers who use motor-based predictions, but not in observers who do not have such a capability (Mulligan et al., 2016a,b). Therefore, if skilled participants in the present study had motor-based prediction abilities, then their prediction accuracy would degrade, whereas if less-skilled participants did not have well-developed motor-based prediction abilities, then their prediction accuracy would be unaffected by their execution of incongruent actions. We hypothesized that prediction accuracy would be modulated by imitative-motion and by self-motion. Further, we hypothesized that these effects would vary, depending on the initial prediction ability (i.e., motor-based prediction ability).

MATERIALS AND METHODS

Participants

Twelve male basketball players (skilled group; M = 20.4 years, SD = 1.7) and 12 male varsity students (less-skilled group; M = 23.9 years, SD = 2.1) participated in this study. All participants had normal or corrected-to-normal visual acuity in both eyes and always used their right hand to shoot a basketball. The skilled group had been playing competitive basketball for 8–13 years (M = 10.8 years, SD = 1.7 years). The less-skilled group had experience in playing basketball in physical education class, but no members of this group had experienced systematized training and competitive activities for basketball. This study was approved by the Ethics Committee of the National Institute of Fitness and Sports in Kanoya and was consistent with the institutional ethical requirements for human experimentation in accordance with the Declaration of Helsinki. Prior to the measurement session, all participants were fully informed of the procedures and possible risks, as well as the purpose of the study, and their written informed consent was obtained.

Stimuli

To create occlusion video clips for this experiment, basketball free throws performed by a right-handed male basketball player who had 10 years of experience were digitally recorded using a hybrid camera (GC-PX1, JVC). The video camera was approximately 6 m from the player. A side-on perspective was recorded, such that the player and basketball hoop were visible. The player was requested to perform 50 trials each of three types of basketball free throws. First, the player performed prototypical moves in order to drop the ball through the hoop without touching it, that is, to successfully shoot ("in shot"). Second, the player altered the kinematics such that the trajectory of the ball fell short of the basketball hoop ("short shot"). Third, the player altered the kinematics such the trajectory of the ball went beyond the hoop ("long shot"). Additionally, the angles of the player's right wrist were recorded by 3D motion analysis (NDI, OPTOTRAK Certus) during the shot release. Aglioti et al. (2008) reported that expert basketball players could discriminate the outcome of free throws at the point when the ball left the shooter's hand and that their perceptual judgments relied on the kinematics of the model's hand movements. Thus, we selected twelve video clips from the 50 recorded trials, which were based on the analysis of the maximum angle of the player's wrist (in: $<90°$, short: $\geq 90°$, $<100°$, long: $\geq 100°$).

The stimulus movies were presented using a temporal-occlusion technique. All video clips were cut 66.6 ms after the frame in which the basketball left the player's hand. In addition, the ball was occluded to prevent participants from making judgments based on the ball trajectory. A movie consisted of a fixation cross (2 s), the edited free-throw video clip (approximately 2 s), and a white-noise video clip (3 s; **Figure 1**). In the experiment, a block of trials was constructed of 36 clips, namely twelve trials each of "in," "short," and "long" throws, which were randomly distributed among the 36 trials. Movie editing, composition, and compression were accomplished using Adobe Premiere Elements Pro CS4 software.

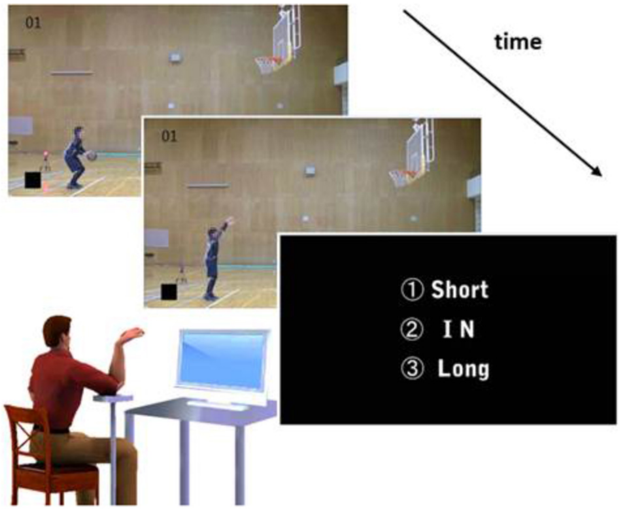

FIGURE 1 | Experimental apparatus and setup. Participants were required to predict shot outcomes using the kinematics of a model's basketball free throw, as viewed in movies in which the ball trajectory was occluded, in observation, incongruent-action, imitative-motion, and self-motion conditions. At the end of each movie presentation, three instruction frames appeared, which asked the participant to respond verbally as to where the basketball would land (i.e., "short," "in," or "long"). In the observation condition, participants predicted shot outcomes based on simple observation of the presented stimuli. In the incongruent-action condition, they executed right-wrist flexion with maximum speed. In the imitative-motion condition, they executed right-wrist flexion as if imitating the model's action. In the self-motion condition, they executed their right-wrist flexion as if taking the shot themselves. The model player gave us the consent for the publication of this image.

Task and Procedure

The participants were seated in front of a 21-inch display (EIZO, ColorEdge CG242W) at a distance of 1.5 m. They were required to predict the outcome of free throws and to make the verbal responses of "in," "short," and "long" after observing the occluded video stimuli. The task consisted of four conditions: observation, incongruent-action, imitative-motion, and self-motion. In the observation condition, participants predicted the shot outcomes based on simple observation of presented stimuli, consistent with previous studies (Aglioti et al., 2008). In this task, they received instruction from the experimenter as follows: "Please predict the outcome of free throws based on observed movies. In this case, you do not need to perform any concurrent action." We regarded scores for the observation condition as baseline prediction ability.

In the other three conditions, participants were required to execute simple hand movements concurrently during stimulus observation. Aglioti et al. (2008) reported that expert basketball players could discriminate the outcome of free throws based on the kinematics of the model's hand movements. Thus, we employed hand flexion of the right wrist as the concurrent movement execution. In the incongruent-action condition, participants executed their right-wrist flexion with their maximum speed. In the imitative-motion condition, they executed their right-wrist flexion as if imitating the model's action. In the self-motion condition, they executed their right-wrist flexion as if taking the shot themselves. Participants were instructed "Please predict the outcome of free throws with right-wrist flexion at your maximum speed" in incongruent-action, "Please predict the outcome of free throws with right-wrist flexion as if imitating the model's action" in imitative-motion, and "Please predict the outcome of free throws with right-wrist flexion as if taking the shot by yourselves" in self-motion. Furthermore, in the three concurrent-movement conditions, they were also instructed to perform concurrent movement (i.e., wrist flexion) so that their movement temporally matched with observed action. In these conditions, participants put their right elbow on a height-adjustable table. Their arm was maintained in position by themselves when they moved their wrist (**Figure 1**). Each condition included 36 trials (144 trials in total), which were randomly arranged. The instructions were provided before the 1st, 12th, and 24th trial in each condition by repetition. The order of conditions was randomly assigned in the skilled group and the order was matched in the less-skilled group. No accuracy feedback was provided during the experimental task.

Data Analysis

First, to replicate previous findings (i.e., the presence of skill-related differences in prediction abilities and the use of motor-based prediction in skilled athletes) and to test the effect of concurrent imitative and self-focused movement on prediction accuracy, we compared prediction accuracy (percentage of correct responses) among all experimental conditions, using a repeated-measures two-way 4 (experimental condition) × 2 (group) analysis of variance (ANOVA). The experimental condition was the within-subjects factor and group was the between-subjects factor. In the case of a significant interaction, unpaired t-tests with Bonferroni correction were used to examine the experimental conditions for which the difference between the skilled and less-skilled group was significant.

Additionally, to clarify individual differences in the effects of concurrent imitative and self-focused movement on prediction accuracy, correlations were obtained between the original prediction ability for each participant (i.e., prediction accuracy in the observation condition) and the change in prediction accuracy between the observation condition and each imitative-motion condition, and the self-motion condition. The threshold for significance was set at $p < 0.05$.

RESULTS

Figure 2 shows the prediction accuracies in the skilled and less-skilled groups in each condition. Consistent with previous findings (Aglioti et al., 2008), prediction accuracy in the skilled group was higher than in the less-skilled group (main effect of group: $F[1,22] = 45.9$, $p < 0.01$, $\eta_p^2 = 0.68$). Further, only the skilled group significantly decreased in prediction accuracy in the incongruent-action condition compared to the observation condition. According to previous findings (Mulligan et al., 2016a,b), this indicates that the skilled participants used motor-based prediction, while the less-skilled participants did not. That is, participants in the present study are suitable for testing the effect of concurrent imitative-motion and self-motion on prediction accuracy.

According to previous proposals regarding the characteristics of motor-system activation during action observation (Buccino et al., 2004; Schütz-Bosbach et al., 2006; Spengler et al., 2010), concurrent imitative-motion and self-motion should facilitate and inhibit motor simulation process, respectively. Furthermore, we expect that, because skilled athletes strongly rely on motor-based prediction (Aglioti et al., 2008; Mulligan et al., 2016a,b), they would not obtain additional effects through imitative movement compared to the observation condition, whereas degradation by self-focused movement would be stronger due to inhibition of motor simulation processes. In contrast, less-skilled people who did not have well-developed motor-based prediction would not be affected by self-focused movement, but their prediction accuracy would be improved by concurrent imitative movement that induces appropriate efference copy. A significant interaction ($F[3,66] = 5.44$, $p < 0.01$, $\eta_p^2 = 0.20$) and subsequent t-tests supported these expectations. In the skilled group, there was no significant difference between observation and imitative-motion conditions, while the prediction accuracy in the self-motion condition was lower than that in the observation condition ($p < 0.01$). In contrast, the less-skilled group demonstrated significantly higher prediction accuracy in the imitative-motion condition than the observation condition ($p < 0.05$), but there was no significant difference between self-motion and observation conditions. Thus, the results indicate that the skilled group lost prediction accuracy when they executed flexion of the right wrist while imagining themselves taking the shot. In contrast, predictions made by the less-skilled group were facilitated when they tried to imitate the model's hand action.

Additionally, to clarify individual differences in the effects of facilitation and degradation on prediction accuracy, correlations were calculated between the original prediction accuracy and the extent to which each participant's predictions were facilitated and/or degraded in each imitative and self-motion condition (**Figure 3**). A strong negative correlation between accuracy change and the original prediction accuracy was identified for imitative-motion in only the less-skilled group ($r = -0.76$, $p < 0.01$). In contrast, there was no significant correlation between the magnitude of degradation and prediction ability. That is, the amplitude of facilitation by imitative movement depends on the original prediction ability in less-skilled participants, while the amplitude of degradation does not depend on individual prediction ability, regardless of skill level.

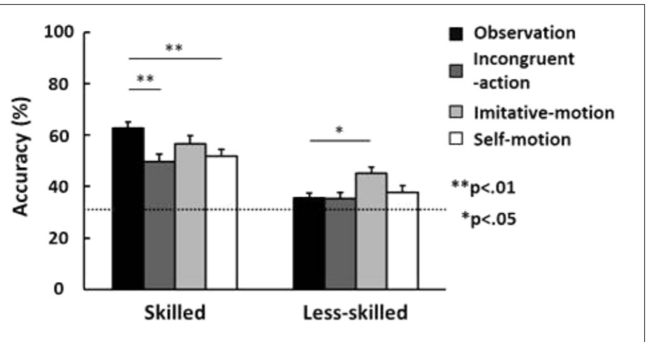

FIGURE 2 | Percentage of correct responses in each condition (observation, incongruent-action, imitative-motion, and self-motion) for the skilled and less-skilled groups. The horizontal dashed line indicates the chance level. Vertical error bars show standard errors. $^*p < 0.05$, $^{**}p < 0.01$.

DISCUSSION

This study investigated the influence of different types of concurrent motor execution during action observation on prediction accuracy. The main results showed that concurrent imitative motor execution facilitated prediction accuracy, only in less-skilled participants, who did not have well-developed motor-based prediction. In contrast, motor execution, or taking a shot on your own, degraded prediction accuracy only in skilled participants, who strongly relied on motor-based prediction. That is, the influence of imitative-motion and self-motion on prediction accuracy varied with skill level.

Previous studies have indicated that motor activation during prediction tasks that relates to motor simulation is linked to the superior prediction ability of skilled athletes (Wright and Jackson, 2007; Aglioti et al., 2008; Wu et al., 2013; Mulligan et al., 2016a,b). On the other hand, Abreu et al. (2012) reported that the activity of the AON network was also activated (i.e., motor simulation) in novices. From this evidence, we expected that their lower prediction ability comes from less-developed efference copy during motor simulation. Therefore, if they can produce

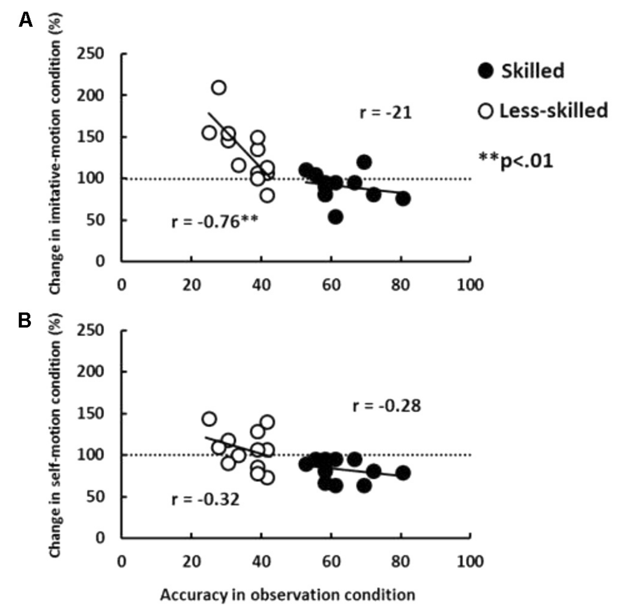

FIGURE 3 | Relationship between the change in prediction accuracy from observation condition to imitative-motion and self-motion conditions, and prediction accuracy in the observation condition. $^{*}p < 0.05$, $^{**}p < 0.01$.

accurate motor commands that relate to efference copy during observation by imitative movement, then they can estimate the action outcome correctly. As expected, in the less-skilled group, prediction accuracy in the imitative-motion condition (45.1 ± 8.1%) was higher than in the observation condition (35.7 ± 6.0%). In contrast, there was no significant difference in prediction accuracy between the observation and self-motion conditions (37.7 ± 9.2%; **Figure 2**). That is, prediction accuracy was facilitated only in the imitative-motion condition, even though the self-motion condition included a similar concurrent movement. This evidence suggests that imitative movement is likely a way to improve prediction abilities because it leads to very similar motor commands and/or efference copy with observed movement.

It has been proposed that motor activation during action observation indicates the activation of motor simulation and/or resonance mechanisms (Aglioti et al., 2008; Urgesi et al., 2012; Tomeo et al., 2013; Mulligan et al., 2016a,b), consistent with the neural-simulation hypothesis (Decety et al., 1994; Blakemore and Decety, 2001; Urgesi et al., 2010) and/or a bidirectional link between perception and action (Prinz, 1990, 1997; Schütz-Bosbach and Prinz, 2007). The core of the proposal is that the observation of an action leads to mirrored activation of parts of the neural network (representations) that are active during its execution. These enable a direct mapping of the visual representation of the other's actions onto one's own motor representations of the same action. Further, this mapping enables us to use the forward model (Mulligan et al., 2016a,b) that anticipates sensory consequences and outcomes during movement (Miall and Wolpert, 1996). That is, the observer understands the action by inferring the other's intentions and future actions by means of a process of simulation with forward model (e.g., Wolpert and Flanagan, 2001; Wolpert et al., 2003; Blakemore and Frith, 2005). As already mentioned, less-skilled participants exhibit motor activation (Abreu et al., 2012), although relatively less (e.g., Aglioti et al., 2008) during prediction tasks. With respect to improving prediction accuracy in less-skilled participants, concurrent imitative movement might assist such a simulative process by directly activating the motor command and/or efference copy that fed into the forward model via actual imitation of movement. Indeed, prediction accuracy in the skilled group was not altered by concurrent imitative movement, even though a different type of motor execution significantly degraded prediction accuracy. This implies that motor activations associated with imitation of actual movements did not interfere with the motor simulation induced by simple observation in skilled athletes. That is, both activations were identical and had similar functions with respect to action perception.

In addition, it has been suggested that motor simulation improves the reading of action kinematics performed by others (Aglioti et al., 2008; Urgesi et al., 2012; Mulligan and Hodges, 2014; Mulligan et al., 2016a,b). It is well known that the superior prediction in skilled athletes is associated with better reading of kinematic information inherent in opponents' actions (Abernethy and Zawi, 2007; Abernethy et al., 2008; Huys et al., 2009; Ida et al., 2011). Indeed, Aglioti et al. (2008) reported that expert basketball players could discriminate the outcome of free throws based on the kinematics of the model's hand movements. Accordingly, the present task only showed the model's throwing kinematics, by excluding information of the ball trajectory, and chose the stimulus based on the model's wrist angle (in: <90°, short: ≥90°, <100°, long: ≥100°). Therefore, prediction accuracy improvement following concurrent imitative movement is likely related to enhanced perception of action kinematics, which derives from motor simulation.

Interestingly, the correlational analysis indicated that the facilitation effect was larger in people with lower prediction accuracy in the observation condition (**Figure 3**). That is, the magnitude of improvement depended on the original prediction ability. A possible reason for this is that even less-skilled individuals use rudimentary motor-based action perception: if the effect of imitative movement simply activates the motor system, all less-skilled participants receive benefit in an all-or-nothing manner. According to the association-learning hypothesis of mirror activation (Heyes, 2010; Catmur, 2013), initially, sensory neurons with high-level visual properties are connected unsystematically to motor neurons with high-level motor properties. After a specific sensorimotor experience, such as imitation and action synchronous with others, activity in sensory neurons propagates to the motor neurons with which the sensory neurons have strong connections (i.e., complete mirror function; Catmur, 2013). That is, incomplete motor activation can be induced even when observers do not have the specific sensorimotor experience in question. Indeed, Abreu et al. (2012) found neural activity in the frontal–parietal system (the core of mirror activity) in both expert basketball players and novice observers during outcome prediction of basketball free throws (see also Aglioti et al., 2008; Wu et al., 2013). Thus, individual differences in prediction accuracy may derive from differences in the strength of connections between sensory and motor systems, rather than from whether motor activation itself occurs or not. Therefore, imitative movement might strongly affect participants with weaker connections between sensory and motor systems.

Another possibility is that imitative movement might increase attention toward essential kinematic information. As mentioned earlier, prediction ability is associated with utilization of kinematic cues. Thus, if participants cannot identify the essential kinematic cues during the task, it is difficult for them to predict action outcomes (i.e., low prediction accuracy). That is, people who demonstrated lower prediction accuracy in the observation condition might not have been aware of the kinematic cues inherent in the model's throwing action (i.e., wrist angle of the right hand). The imitative hand actions in the present study drew attention to the location that contained relevant cues. Therefore, prediction accuracy may have been improved by the awareness of the cues. However, the order of the experimental conditions was randomized in the present study. In this case, a significant correlation contingent on prediction accuracy did not appear, because if participants were aware of the kinematic cues before performing the observation condition, they would utilize this information in all conditions. Therefore, it seems that the individual differences in the magnitude of facilitation effects were associated with the strength of connections between sensory and motor systems.

In contrast, as shown in **Figure 3**, some less-skilled participants likely improved their prediction accuracy in the self-motion condition. Additionally, in the imitative-motion condition, some individuals did not improve their prediction accuracy. That is, these results imply that the facilitation of prediction accuracy in the imitative-motion condition was not caused merely by the intention of imitation. Christensen et al. (2011) asked participants to detect a waving arm defined by a point of light in a scrambled mask, while executing waving movements themselves. There was systematic tuning of facilitatory versus inhibitory influences of motor execution on biological-motion detection with respect to temporal and spatial congruency between observed and executed movements. Specifically, there was gradual transition between facilitatory and inhibitory interactions with decreasing temporal synchrony and spatial congruency. In addition, Catmur et al. (2007) posited that the bidirectional features are acquired following sensorimotor experience in which temporal and spatial congruencies exist between observed and executed behaviors. In their study, the participants did not explicitly receive instruction regarding imitation. Taking this evidence into account, it appears that the facilitation effect in the present study was not induced by the intention of imitation; rather, the amplitude of spatiotemporal similarity between observed and executed actions drove the prediction improvement. Nevertheless, the intention of imitation would increase the similarity between actions, as compared to execution of another concurrent movement. That is, concurrent imitative movement that induces high similarity between observed actions and executed movements would be effective for improving prediction accuracies. According to this view, the decrease in accuracy in the self-motion condition in the skilled group also arose from the dissimilarity between observed and executed movement. Since participants were told to execute their right-wrist flexion as if taking the shot themselves, their movement in the self-motion condition would have induced dissimilar movement to the model's action (i.e., conflicting efference copy) such as that induced by the incongruent condition. To verify this, further experiments that dissociate the intention and kinematic similarity and measurement of kinematics in concurrent movements are warranted.

From the data of the skilled group, the present study supports previous proposals that motor simulation contributes to skilled outcome prediction. Prediction accuracy in the skilled group (i.e., 62.8 $\pm$ 8.0% in the observation condition) was significantly degraded in the self-motion condition (51.9 $\pm$ 8.7%), but not in the less-skilled group. That is, the inhibition of motor activation caused by motor simulation degraded prediction accuracy only in skilled athletes. Further, as mentioned above, the skilled athletes were not influenced by concurrent imitative movement, unlike the less-skilled group. If the motor activation by imitative movement was not consistent with the simulative activation induced by observation, then prediction accuracy would also be degraded in the same manner as in other concurrent-movement conditions. Thus, these results indicate that skilled athletes rely on motor-based predictions (Aglioti et al., 2008; Urgesi et al., 2012; Mulligan et al., 2016a,b). In addition, the skilled participants demonstrated greater prediction accuracy than less-skilled individuals, even when motor activation was inhibited in the self-motion and incongruent-action conditions. This indicates that skilled athletes could predict the action outcomes using visual-based predictions. That is, skilled athletes may utilize visual and motor-based predictions to achieve more precise outcome prediction. This idea is consistent with a previous suggestion that action understanding is based on both visual recognition and motor behavior (e.g., Calvo-Merino et al., 2006).

We believe that perceptual training that incorporates concurrent imitative movement would be effective for novices in sports, although the present study did not assess long-term training *per se*. Mulligan et al. (2016a,b) showed that perceptual and motor experiences develop partially different mechanisms that underlie outcome prediction. They demonstrated that, although both perceptual (i.e., learning associations between visual kinematic cues and outcome) and motor (i.e., throwing darts on one's own) training improved outcome prediction, only the motor-training group was significantly affected by incongruent motor actions in the post-training test (Mulligan et al., 2016b). If perceptual and motor experiences educate exactly the outcome-prediction mechanisms, incongruent motor actions would affect the predictions of the perceptual group in the same manner as in the motor-training group. That is, perceptual and motor experience each likely establish specific mechanisms. Thus, skilled athletes, who have both perceptual and motor experiences, would develop both prediction modes. As mentioned above, our data also indicate that skilled athletes have a hybrid prediction-system. It appears that traditional perceptual training (visual experiences) with concurrent imitative movement (motor experiences) has the potential to develop both visual- and motor-based prediction abilities, although further direct evidence to support this proposal is needed.

The present study hypothesized that concurrent imitative and self-motion movement facilitate and/or inhibit motor-based prediction, respectively, based on the previous research that investigated the effect of intention (i.e., imitation/self-focus) on motor activation (Buccino et al., 2004; Spengler et al., 2010) and the effect of concurrent congruent/incongruent action during action observation on action recognition (Christensen et al., 2011). Christensen et al. (2011) stated that the observed effects (i.e., the effect of concurrent congruent/incongruent movement) seem to be independent of the attribution of agency for the observed action to oneself or another agent. Therefore, it is not clear which factors (i.e., intention and/or congruency) affected the prediction accuracy in the present study. Therefore, further studies are needed to isolate the effect of intention and similarity, such that each action is performed both with and without the "intention" to imitate or self-focus.

CONCLUSION

From the above evidence, we conclude that concurrent imitative movement during action observation transiently improves prediction abilities only in less-skilled individuals. This finding provides new insight into training methods that might improve prediction abilities in athletes. In addition, the paradigm (concurrent imitative and self-focused movement) of this study has the potential to contribute to future research into the mechanisms that underlie the superior prediction abilities of skilled athletes. In contrast, the results need validation using more complex movements, because the facilitation effect may derive from the similarity between observed and executed movements. If so, concurrent complex movements might adversely affect the development of prediction abilities because the higher complexity would necessarily involve lower similarity between observed and executed movements. This would induce the inhibitory effects that we observed in the self-motion and incongruent-action conditions. In addition, some researchers have suggested that the executed action itself provides a continuously updated reference by which the participants can effectively solve the task without the need for internal simulation (e.g., Springer et al., 2011). Further studies are needed to clarify the mechanism of enhancement in prediction through concurrent imitation because it is unclear from the results whether the less-skilled participants were actually using a type of motor-based simulation process.

AUTHOR CONTRIBUTIONS

SU carried out the experiments and initial drafting of manuscript. HN contributed to initial drafting and final revision of the manuscript. SU, HN, SI, and SM conceived and planned the experiments and discussed the results.

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The Perception of Deceptive Information Can Be Enhanced by Training That Removes Superficial Visual Information

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The ability to detect deceptive intent within actions is a crucial element of skill across many tasks. Evidence suggests that deceptive actions may rely on the use of superficial visual information to hide the basic kinematic information which specifies the actor's intent. The purpose of this study was to determine whether the ability of observers to anticipate deceptive actions could be enhanced by training which removes superficial visual information. Novice badminton players (n = 36) were allocated to one of three groups who performed perceptual training over 3 days, with the efficacy of training assessed using tests of anticipatory skill conducted at pre-test, post-test, and a 1-week retention test. During training, participants watched a series of non-deceptive badminton shots performed by actors, with the footage manipulated to display either (i) low spatial-frequency information only (*low-SF training group*; blurring to remove superficial information); (ii) high spatial-frequency information only (*high-SF training group*; an 'edge detector' to highlight superficial information); or (iii) normal vision (*normal-SF group*). Participants were asked to anticipate the direction of the shuttle when footage was occluded at the moment of racquet-shuttle contact. In the post-test, response accuracy (RA) when viewing deceptive trials was higher for the low-SF training group when compared to the normal-SF (control) training group (p = 0.005), with the difference retained in the retention test (p = 0.020). High-SF training resulted in greater performance at post-test (p = 0.038) but not retention (p = 0.956). The analysis of gaze provided some explanation for the findings, with the low-SF training group spending more time after training fixating on the location of racquet-shuttle contact than did the normal training group (p = 0.028). The findings demonstrate that training which conveys only the basic kinematic movements visible in low-SF information may be effective in learning to 'see-through' deceptive intent.

Keywords: deception, anticipation, perceptual training, interception, sport

INTRODUCTION

The ability to identify deceptive intent can be crucial in a variety of social contexts (Cañal-Bruland, 2017). For instance, during verbal communication it is important to be able to detect when others are lying (Ekman et al., 1999), or even when a person is dis-ingenuine in what they are saying (Vrij and Mann, 2004). Deceptive intent is also conveyed during *physical interactions* when observing the actions embodied within the movements of others (Jackson et al., 2006). This is particularly the case in a variety of sports, where deception is often used by athletes to fool their opponents into making an incorrect judgment about that athlete's true action intentions (Cañal-Bruland and Schmidt, 2009). But while athletes may invest considerable time in learning to *perform* deceptive actions (e.g., a rugby side step, change-up baseball pitch, or head fake in basketball), it is also important for athletes to learn to ignore or 'see through' this deceptive intent to avoid errors, and to better anticipate the genuine action intentions of their opponent.

Runeson and Frykholm (1983) were the first to investigate and report the ability of observers to detect deceptive intentions when watching others perform a motor task. Participants in their seminal study watched point-light displays of actors who lifted boxes onto a table, and in a subsequent experiment, watched actors who in some cases attempted to deceive observers by pretending that the box they were lifting was heavier than it actually was. The results revealed that not only were the observers able to accurately estimate the weight of the box when the actors performed genuine actions, but that the observers were also successful in detecting when the actors were attempting to deceive them. Given that the point-light displays conveyed only very basic information about the underlying kinematic pattern of body movements of the actors, these results highlight that information available from the basic kinematic signature of the actor can be sufficient for even novice observers to perceive the genuine action intentions of both deceptive and non-deceptive actions.

The ability to 'see through' deceptive intent is a skill that can be learned seemingly as a result of domain-specific experience (Jackson et al., 2006; Cañal-Bruland, 2017). As evidence, Jackson et al. (2006) tested the anticipatory skill of skilled and novice rugby players who watched video footage of opponents performing deceptive and non-deceptive side-step running actions. The results revealed that, when attempting to anticipate the direction in which the opponent would run, the skilled players were less susceptible to deception, meaning that they were better able to ignore the deceptive intent and anticipate the true action intentions of the opponent. The implication of this finding is that skilled performers are characterized by their better ability to discriminate deceptive from non-deceptive actions (Cañal-Bruland and Schmidt, 2009; Sebanz and Shiffrar, 2009; Abernethy et al., 2010a,b; Cañal-Bruland et al., 2010), but also that the ability to detect deception may be a learned skill that could be enhanced as a result of training.

In an effort to guide improvements when training to perceive deception, it is important to gain an understanding of how deceptive information is most effectively conveyed. Crucially, there is good reason to believe that deceptive intent is conveyed at least in part by the detailed *non-kinematic* information available such as the gaze direction and facial expressions seen when observing an opponent's action sequence. On the basis of Runeson and Frykholm's (1983) finding that deception was unsuccessful when observers viewed a point-light display of a box-lifting the action, Abernethy et al. (2010a,b) examined the ability of badminton players to anticipate the direction of deceptive and non-deceptive badminton shots when viewing both video clips and point-light displays of the same shots. The results revealed that watching videos, the observers' ability to discriminate deceptive from non-deceptive shots was worse than it was when watching the point-light displays. In other words, when watching the point light displays, the badminton players were less likely to be deceived than when watching the equivalent video clips. When watching video clips, a range of non-kinematic sources of information are available that are not seen when watching a point-light display, including information conveying contour, color, texture, and detail such as facial expressions and the direction of gaze. The clear implication from the findings from Abernethy et al.'s (2010a,b) studies is that deceptive intent can be conveyed largely via these *non-kinematic* sources of information. In contrast, the *kinematic* signature contains the specifying information that may be necessary for the anticipation of action outcomes, irrespective of whether deceptive intent is present or absent.

Given that deceptive intent is contained within non-kinematic information, a perceptual training approach that removes or degrades this non-kinematic information may hold promise as a means of improving the ability to anticipate deceptive actions. A considerable proportion of the non-kinematic sources likely to be useful for deception is contained within information that is highly detailed, meaning that clear vision would be required to resolve that information (e.g., facial expressions and gaze direction), whereas this is not necessarily the case for the more coarse kinematic information available from point-light displays. This means that information that *does* convey deception could be disambiguated from that which does not on the basis of the quality of the visual information relied on to convey it. An image, just like a sound, can be decomposed into component frequencies called *spatial frequencies*. When an image is blurred, the detailed high spatial frequency (SF) information is removed from the image so that only the low-SF information remains. Conversely, an edge-detecting 'high-pass' filter will produce an image of high-SF by removing the low frequency information. It is widely accepted that human observers prefer high SF information when making a conscious observation of an image (Harmon, 1973; DeValois and DeValois, 1990). Yet it appears that it is the low spatial frequency information that may be most useful for the perception of motor actions.

A small number of studies have demonstrated that an observer's ability to make judgments about moving or changing stimuli can be enhanced by blurring the vision of the observer (e.g., di Lollo and Woods, 1981; Luria and Newacheck, 1992; Jackson et al., 2009; Mann et al., 2010c; Ryu et al., 2015, 2016). A possible explanation for each of these studies is that the blur aided the perception of movement by removing the high SF information which observers are consciously drawn to, leaving only the low SF information most useful for the perception of motion. When examining the anticipation of motor actions, Jackson et al. (2009) found that a high level of full-field blur *increased* the ability of tennis players to anticipate the direction of an opponent's tennis serve. Similarly, Mann et al. (2010c) found that visual blur increased the capability of skilled cricket batters to verbally anticipate the direction of cricket balls bowled toward them. It was reasoned in those studies that the improvements in performance could have been attributable to the removal of high spatial frequency information, helping to draw attention toward the low-SF information most useful for predicting action outcomes. Therefore, a training approach that educates the attention of observers toward the low rather than high-SF information contained within an action sequence may be useful for increasing the observer's ability to avoid deception, and to therefore better perceive the genuine action intentions of an opponent.

The aim of this study was to determine whether the ability to anticipate actions in the presence of deception could be enhanced by training that removes superficial (high-SF) visual information. To this end, participants watched a series of badminton shots, with the aim to anticipate the direction in which the player hit the shuttle. Following a pre-test of anticipatory skill, novice participants were split into one of three training groups who received feedback when anticipating the outcome of movement sequence seen in footage showing (i) low spatial frequencies only, (ii) high spatial frequencies only, or (iii) normal vision (control condition). Only non-deceptive actions were seen during training in an effort to minimize any training benefits accrued as a result of exposure to deceptive actions, and to train participants to focus on the relationship between genuine motor actions and their action outcomes. When observing veridical (non-deceptive) movements, we expected all three training groups to equally improve their anticipatory ability at post and retention test, because the true action intentions of the actor were evident during training irrespective of the type of visual information participants learned to rely on. In contrast, because deceptive information is likely to be conveyed more strongly by high-SF information, we expected that low-SF practice would result in the greatest improvement of all groups when anticipating *deceptive* movements in the post-test, because it would train observers to attend to the low-SF information more closely associated with the movement outcome. We expected the remaining two groups to perform more poorly, because they would rely on the high-SF information which is more likely to lead to susceptibility to deception.

MATERIALS AND METHODS

Participants

Thirty-six participants (age M = 21.7 years, SD = 1.9) with limited experience playing badminton (M = 1.3 years, SD = 1.1) participated in this study. Participants were randomly assigned to one of three training groups: a *low-SF training* group (n = 12; playing experience M = 1.5 years, SD = 1.5); a *high-SF training* group (n = 12; playing experience M = 1.1 years, SD = 1.0); or a *normal-SF (control) training* group (n = 12; playing experience M = 1.4 years, SD = 0.9). The data for three participants were excluded from all analyses (one participant from each of the three groups, see ***Dependent Variables and Data Analysis), leaving the data from 33 participants in the final analysis. Ethical approval was obtained from the University of Hong Kong Human Research Ethics Committee prior to testing, with informed consent obtained prior to the commencement of the experiment.

Experimental Design and Procedures

Testing and Training Materials

Video clips

A series of video clips of badminton shots were used for the tests of anticipation and for the training footage. Five highly skilled players were recruited to be 'actors' for the purposes of recorded video footage. A digital video camera (Sony HDR-FX1 handicam) was used to record high-definition footage (1920 × 1080 pixel resolution) of strokes at 30 Hz, with the camera located at the center of the service court on the receiver's side and at a height of 1.6 m. The actors stood at the intersection of the service and the doubles long service line and returned serves using only overhead strokes toward one of four landing positions on the court: front-left, back-left, front-right, and back-right. Only shots that landed within the playing court were included to be used as test stimuli. Players performed a series of *non-deceptive* and *deceptive* shots toward each of the four locations. When performing non-deceptive shots, actors attempted to hit the shuttle toward the intended direction without any deceptive intent. When performing deceptive shots, actors hit the shuttle toward the intended direction, but in doing so attempted to deceive an observer into thinking that the shuttle would be hit toward a different location on the court using any form of deception they would use in a regular match (kinematic and non-kinematic deception including gaze and head direction). A coach and scientist who worked regularly with the athletes within their sport institute were both present during filming to verify whether each shot matched the requirements of the condition and were representative of a shot that would be played in a match. Only those shots that matched those requirements were included as test films in the experiment. For each landing position, separate shots were recorded to convey deceptive intent in terms of depth and direction (e.g., for the front-left landing position, separate shots were recorded to deceive the observer into thinking that the shot was directed toward the back-left and the front-right sections of the court). The positions of the player and camera were chosen to simulate the respective locations on a court that a hitter may be expected to play 'high-clear' or 'drop' shots toward the back and front of the court respectively, and where a receiver would be required to move to intercept the four shots recorded.

Each of the clips was digitized, with the frames saved as individual high-definition bitmap images. These images were subsequently edited using Matlab software (version R2014b; Mathworks, Natick, MA, United States). Custom code was written in Matlab that resulted in two different manipulations of spatial frequency: (i) low spatial frequency (low-SF) images;

FIGURE 1 | Demonstration of each of the three spatial frequency stimuli used in the training intervention; **(a)** Normal-SF information, **(b)** low-SF information only, and **(c)** high-SF information only.

and (ii) high spatial frequency (high-SF) images (see **Figure 1**). The normal images were the original (unfiltered) video images. When subtending the same visual angle as that experienced on-court, the normal images contained SF information ranging 0–22.7 cycles per degree (horizontally and vertically equating to 0–960 and 0–540 cycles per image respectively). HD video footage was chosen because standard definition video footage would have only contained spatial frequencies in the range of 0–12.1 cycles per degree. To generate the low and high-SF images, the normal bitmap images were respectively low- or high-pass filtered using a Gaussian filter with a cut-off of 4 cycles per degree. As a result, low-SF images were produced containing spatial frequencies ≈0–4 cycles per degree (**Figure 1b**), and high-SF images were produced containing spatial frequencies ≈4–22.7 cycles per degree (**Figure 1c**). To account for changes in brightness as a result of filtering, the brightness of both the low-SF and high-SF stimuli was matched to that of the original image. Each series of images was reconstructed into an HD video (1280 × 720 pixel resolution) using Sony Vegas Pro software (Version 13; Sony Creative Software, Middleton, WI, United States).

Test of anticipation

A total of 96 different video clips were used for the test of anticipation. To create the test, a selection of 32 video clips were chosen (8 deceptive and 8 non-deceptive from each of two actors; e.g., Mann et al., 2014), with each clip presented three times, but differing according to the moment of occlusion, either (i) one frame before contact between racquet and shuttle, (ii) at the moment of contact, or (iii) one frame after contact. The three occlusion times were chosen on the basis of pilot testing performed to establish occlusion point(s) at which pre-test performance would be above chance guessing levels but below the ceiling level. For each clip, participants were required to anticipate the landing position of the shuttle by pressing a button on a keyboard corresponding to one of the four landing positions. The order of trials was randomized. The test was conducted during the pre-test, post-test, and retention-test to assess the efficacy of the interventions.

Training material

A total of 360 video clips (all non-deceptive) were used for the training intervention. A set of 60 original clips (12 clips from each of the five performers) were occluded at each of the three occlusion times used for the test clips (i.e., 1 frame before, at contact, 1 frame after shuttle-racquet contact), with these 180 video clips shown two times across 4 different training sessions (i.e., a set of 90 video clips in each session, with all the clips randomized in each session). All five actors were shown during training to introduce novelty and minimize boredom. To provide explicit feedback about the direction of the shuttle during the training intervention, a replay of the clip was created that was edited to end 20 frames after the shuttle disappeared from the field of view. Moreover, feedback clips contained a schematic of a court overlaid on the upper-right hand corner of the screen, with the correct landing location marked with a red dot.

Eye movement registration system

An Eyelink II (SR Research Ltd., Mississauga, ON, Canada) was used at 250 Hz to check whether the eye movements of participants changed as a result of the different training interventions. The system was calibrated by asking participants to sequentially direct their gaze toward each of nine targets in a screen-based reference grid, and then validated in the same manner (acceptable error to <0.5°). Calibration was repeated if the error at any given point was >1°, or if the average error for all points was >0.5°. Eye movement data were analyzed using Data Viewer software (SR Research Ltd.).

Procedures

The experiment was conducted in four phases: a pre-test; intervention phase; post-test; and retention test. Participants were randomly assigned to one of three training groups: a *low-SF training* group; a *high-SF training* group; or a *normal-SF (control) training* group. Testing for each participant took 4 days in total, with the intervention taking place over three consecutive days. As a result, the pre-test and 1st training session were held on the 1st day, the 2nd and 3rd training sessions on the 2nd day, and the final training session plus post-test were held on the 3rd day. The retention test was scheduled 1 week after the post-test.

Pre-test

Participants sat with their head 60 cm from the Eyelink II display monitor (subtending a visual angle of 46.5° × 34.6°; screen size: 516 × 373 mm). Following the fitting and calibration of the gaze-registration system, an experimenter informed the participants of their task. Specifically, they were told they would see a series of video clips, each containing a badminton shot, and at the conclusion of each clip participants were required to predict as quickly and as accurately as possible in which quarter of the court that the shuttle would have landed, and to respond by pressing the corresponding button on a keyboard. Prior to testing, participants were given 12 practice trials to familiarize themselves with the test procedure. Then, they completed 96 test-trials which took approximately 30 min to complete.

Training intervention

The training intervention consisted of four training sessions of 90 video clips divided over three consecutive days. Just as it was for the test of anticipation, the task for participants during training was to predict for each clip the quarter of the court in which the shuttle would have landed. After watching each video clip, and recording their anticipated direction of the shuttle, 1 s of blank video was shown before the full (un-occluded) video clip was shown. The low-SF and high-SF training groups watched all clips with low and high spatial-frequency footage respectively, including the unoccluded feedback clips. The normal-SF training group watched the video clips with un-manipulated normal video footage. Each training session took approximately 30 min to complete.

Post-test and retention test

In the post and retention tests, participants were required to anticipate the shuttle direction for the same set of 96 clips shown in the pre-test, with the order of presentation of the clips following a different randomized order in each test.

Dependent Variables and Data Analysis

Performance Data

Response accuracy (RA) and response time (RT) were calculated to evaluate performance in the pre-, post-, and retention-tests. RA was calculated as the percentage of trials in which the predicted landing position matched the actual position of the shuttle, and RT was the mean time (in ms) that elapsed from the moment the clip occluded to the time the participant's keyboard response was registered. The raw data were initially screened, with one participant from the normal-SF training group excluded from all analyses because the participant, despite instructions, failed to respond at all in many clips, and as a result demonstrated consistently low RA across all the tests (lower than 2 SD below the mean). Moreover, one session of data from one participant in the low-SF training group, and one participant from the high-SF training group failed to save as a result of a technical issue, therefore the data from those two participants were also excluded from all analyses. In total, data from 33 participants were analyzed.

Gaze Behavior Data

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, to check 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. Finally, to assess whether the training altered the spatial locations toward which participants directed their fixations, the distribution of gaze across eight distinct areas of interest (AoI) was assessed for each trial by calculating the *percentage of total viewing time* spent viewing each of the eight areas. The eight AoIs chosen on the basis of pilot testing were: (i) shuttle, (ii) racquet, (iii) arm, (iv) hand and wrist, (v) shoulder, (vi) head, (vii) torso, and (viii) location of (racquet-shuttle) contact (to account for situations in which gaze moved toward this location in advance of the moment of contact). For the purposes of analysis, we placed boxes frame-by-frame around each of the AoIs to facilitate automatic coding of the location of gaze. That is, the Data Viewer software used the frame-by-frame boxes to determine the incidence and duration of fixations in each of the eight AoIs.

Statistical Analyses

In accordance with our aim to determine whether perceptual training would improve the ability to perceive action outcomes in the presence of deceptive intent, our analysis focuses on changes in RA and RT when viewing *deceptive* trials. We also report separately the findings for the non-deceptive trials to check whether the training also altered the ability to perceive actions in the absence of deceptive intent. The dependent variables measuring *RA* and *RT* were analyzed using separate 3 (Training group: normal-SF training, low-SF training, high-SF training) × 3 (Test occasion: pre-test, post-test, retention test) analyses of variance (ANOVAs) with repeated measures on the last factor. Gaze behavior data for the *mean fixation duration* and *mean saccadic amplitude* were analyzed using separate 3 (Training group) × 3 (Test occasion) ANOVAs with repeated measures on the last factor. The distribution of fixations toward the 8 AoIs (*percentage of viewing time*) were subject to a 3 (Training group) × 3 (Test occasion) × 8 (AoI) ANOVA with repeated measures on the last two factors. Further, the results for RA and RT collected during the training intervention were subject to a 3 (Training group) × 4 (Training session: first, second, third, fourth) ANOVA with repeated measures on the second factor to check for changes during training. Gaze data were not collected during training. Significant effects were further investigated using follow-up ANOVAs or planned comparison pairwise *t*-tests with Bonferroni correction where appropriate. Effect sizes were reported as partial eta-squared values or Cohen's *d* (Cohen, 1988), and a Greenhouse–Geisser correction was applied to the degrees of freedom when the assumption of sphericity was violated. Statistical testing was performed in SPSS with the alpha level for all comparisons set to $p = 0.05$.

RESULTS

Changes in Performance as a Result of Training

Deceptive Trials

A borderline interaction – with large effect size – between training group and test-time [training group × test occasion, $F(4,60) = 2.12$, $p = 0.09$, $\eta_p^2 = 0.124$] suggested that changes in the RA of the participants differed according to their type of training [main effect for training group, $F(2,30) = 3.65$, $p = 0.038$,

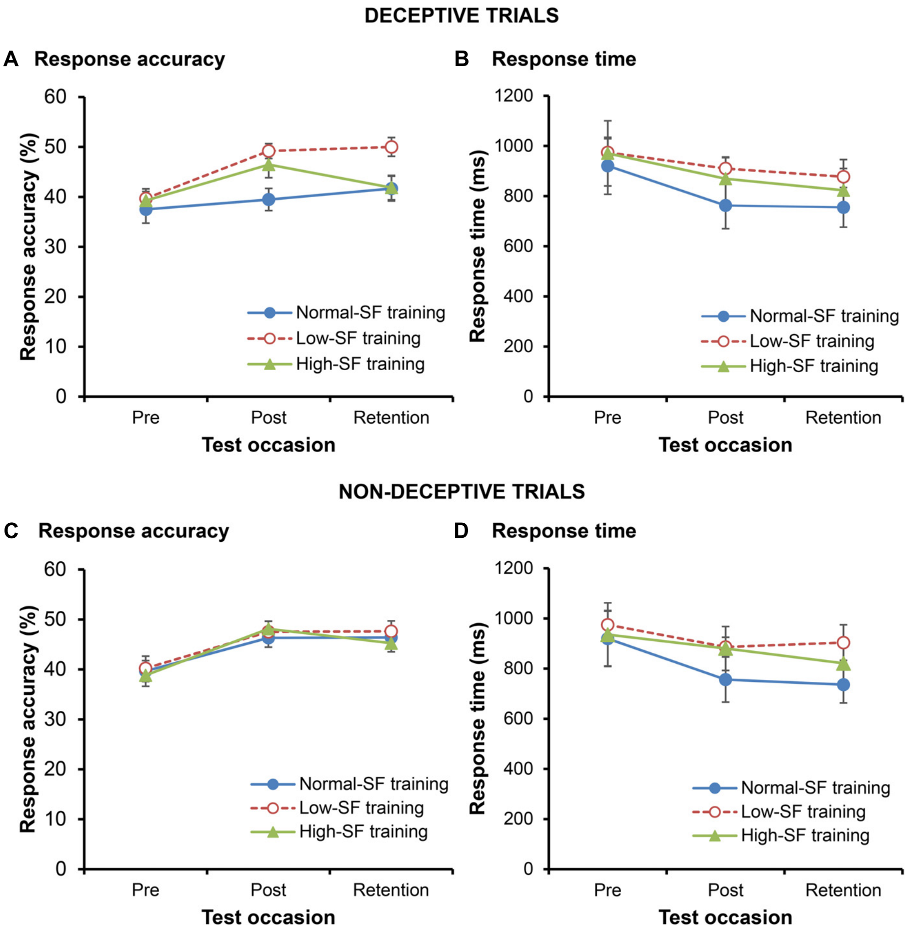

FIGURE 2 | Mean response accuracy and response time for deceptive **(A,B)** and non-deceptive **(C,D)** trials. Error bars indicate the standard error of the mean.

$\eta_p^2 = 0.195$; main effect for test occasion, $F(2,60) = 10.18$, $p < 0.001$, $\eta_p^2 = 0.253$]. Specifically, **Figure 2A** shows that the low-SF training group significantly increased their performance from pre- to post-test ($p = 0.008$, $d = 1.53$), and that their enhanced performance at post-test was retained in the retention test 1-week later ($p = 0.745$, $d = 0.13$). While the high-SF training group also increased their performance from pre- to post-test ($p = 0.023$, $d = 0.92$), it is doubtful that this was retained when comparing performance in the post and retention tests ($p = 0.075$, $d = 0.52$). In contrast, there was no change in performance for the normal-SF training group either from pre- to post-test ($p = 0.53$, $d = 0.23$) or from post- to retention-test ($p = 0.355$, $d = 0.27$). In support, the RA of the low-SF training group was greater than that of the normal-SF training group at both post-test ($p = 0.005$, $d = 1.46$) and retention test ($p = 0.02$, $d = 1.08$), and it was also higher than the high-SF training group at retention ($p = 0.023$, $d = 1.06$). The high-SF training group recorded higher RA than the normal-SF training group only in the post-test ($p = 0.038$, $d = 0.83$) and not at retention ($p = 0.956$, $d = 0.02$).

The differences in the performance of the groups following training could not be explained on the basis of changes in RT (**Figure 2B**). RTs for all three groups decreased following training, both in the post-test ($p = 0.045$, $d = 0.33$) and retention test ($p = 0.022$, $d = 0.40$) when compared to the pre-test [main effect for test occasion, $F(1.33,39.94) = 4.70$, $p = 0.027$, $\eta_p^2 = 0.135$]. There was no change in RT from post-test to retention test ($p = 0.383$, $d = 0.08$). However, the rate of change in RT as a result of training did not differ between the three training groups, with no significant interaction between training group and test occasion [$F(2.66,39.94) = 0.47$, $p = 0.685$, $\eta_p^2 = 0.03$; no main effect for training group, $F(2,30) = 0.56$, $p = 0.577$, $\eta_p^2 = 0.036$].

Non-deceptive Trials

In the non-deceptive trials, RA increased as a result of training [main effect for test occasion, $F(2,60) = 17.68$, $p < 0.001$, $\eta_p^2 = 0.371$], however, the degree of improvement did not differ between the three different training groups [**Figure 2C**; no group × test occasion interaction, $F(4,60) = 0.28$, $p = 0.892$, $\eta_p^2 = 0.018$; no main effect for training group, $F(2,30) = 0.17$, $p = 0.85$, $\eta_p^2 = 0.011$]. RA significantly increased from pre-test to post-test ($p < 0.001$, $d = 1.19$), and remained higher in the retention test than it was at pre-test ($p < 0.001$, $d = 0.94$), with no significant change from post-test to retention test ($p = 0.421$, $d = 0.15$).

Again, the improvements in RA as a result of training were accompanied by decreases in RTs [main effect for test occasion, $F(1.27,37.94) = 6.41$, $p = 0.011$, $\eta_p^2 = 0.176$] that did not differ according to the training intervention [no group × test occasion interaction, $F(2.53,37.94) = 0.27$, $p = 0.816$, $\eta_p^2 = 0.018$; no main effect for training group, $F(1,20) = 0.09$, $p = 0.767$, $\eta_p^2 = 0.004$]. RTs decreased following training ($p = 0.027$, $d = 0.34$), and remained lower in the retention test when compared to the pre-test ($p = 0.008$, $d = 0.43$). There was no difference in RTs between post-test and retention test ($p = 0.154$, $d = 0.11$).

Changes in Gaze Behavior as a Result of Training

There was no change in the duration of the fixations as a result of training for any of the three groups [**Figure 3A**; no main effect for training group, $F(2,30) = 0.40$, $p = 0.673$, $\eta_p^2 = 0.026$; no main effect for test occasion, $F(1.52,45.49) = 1.87$, $p = 0.173$, $\eta_p^2 = 0.059$; no interaction between group and test occasion, $F(3.03,45.49) = 1.70$, $p = 0.18$, $\eta_p^2 = 0.102$]. Similarly, there was no influence of the type of training on the change in the breadth of the search (**Figure 3B**). There was a borderline change in the mean saccadic amplitude across test occasions [main effect for test occasion, $F(2,60) = 2.98$, $p = 0.058$, $\eta_p^2 = 0.09$], though primarily because there was a tendency for larger saccades in the retention test when compared to the pre ($p = 0.036$, $d = 0.33$) and post-tests ($p = 0.066$, $d = 0.32$). Crucially, any changes between test occasions did not differ according to the type of training performed by the participants [no interaction between group and test occasion, $F(4,60) = 0.27$, $p = 0.893$, $\eta_p^2 = 0.02$; no main effect for training group, $F(2,30) = 0.08$, $p = 0.921$, $\eta_p^2 = 0.005$].

The analysis of the percentage of total viewing time that was directed toward each of the 8 AoIs revealed a significant main effect for area of interest, $F(1.33,39.78) = 147.74$, $p < 0.001$, $\eta_p^2 = 0.831$. Pairwise comparisons revealed that most time was spent with gaze directed toward the head of the opponent, followed by their racquet, torso, and the location of contact (**Figure 3C**). The interaction between the AoI and training group was close to significance [$F(2.66,39.78) = 2.61$, $p = 0.071$, $\eta_p^2 = 0.148$], as was the three way AoIs × training group × test occasion interaction [$F(4.96,74.38) = 1.93$, $p = 0.099$, $\eta_p^2 = 0.114$]. Separate two-way ANOVAs on each key area of interest were conducted. A significant training group × test occasion interaction was found for the time spent viewing the location of racquet-shuttle contact [$F(3.32,49.79) = 3.49$, $p = 0.019$, $\eta_p^2 = 0.189$], with the low-SF training group spending more time than the normal-SF training group fixating on the location of racquet-shuttle contact both in the post-test ($p = 0.028$, $d = 0.87$),

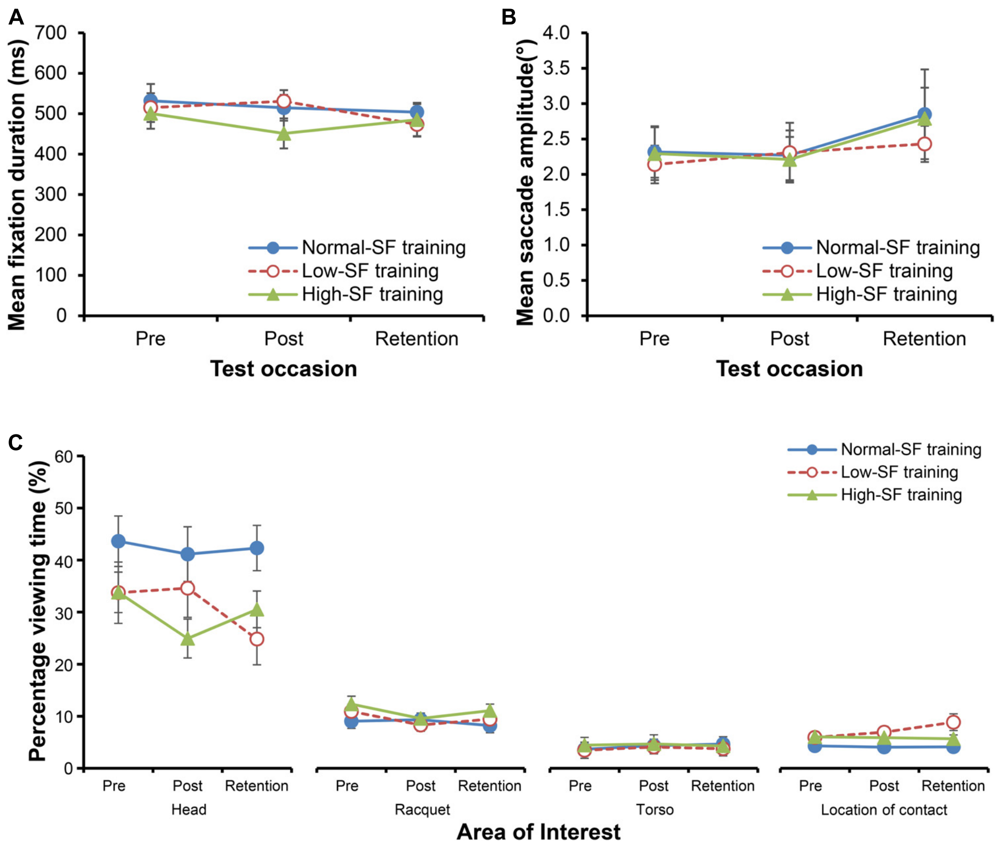

FIGURE 3 | Mean fixation duration **(A)** and mean saccadic amplitude **(B)**. Percentage of total viewing time toward each of four key AoIs for each group **(C)**. To reduce complexity, only the four most frequently fixated AoIs are shown: head, racquet, torso, and location of contact. Error bars indicate the standard error of the mean.

and the retention test ($p = 0.007$, $d = 1.09$), but not in the pre-test ($p = 0.202$, $d = 0.51$). Moreover, there was a borderline interaction between training group and test occasion for the percentage of time spent viewing the *head* of the opponent [$F(4,60) = 2.12$, $p = 0.09$, $\eta_p^2 = 0.124$]. When compared to the normal SF-group, the low-SF group spent significantly less time viewing the head at retention test ($p = 0.007$, $d = 1.13$), but not at pre-test ($p = 0.167$, $d = 0.55$) or at post-test ($p = 0.357$, $d = 0.36$). In contrast, the high-SF group spent less time than the normal-SF group viewing the head at post-test ($p = 0.027$, $d = 1.07$), but not at pre-test ($p = 0.17$, $d = 0.67$) or at retention test ($p = 0.63$, $d = 0.90$).

Performance During Training

Response accuracy progressively increased during the training intervention [**Figure 4A**; main effect for training session, $F(3,90) = 11.95$, $p < 0.001$, $\eta_p^2 = 0.285$]. RA improved significantly from Session 1 to 2 ($p < 0.05$, $d = 0.62$), did not change from Session 2 to 3 ($p = 0.582$, $d = 0.09$), and ultimately improved again from Session 3 to 4 ($p = 0.004$, $d = 0.38$). There was also a significant interaction between training group and training session [$F(6,90) = 2.46$, $p = 0.03$, $\eta_p^2 = 0.141$; no main effect for training group, $F(2,30) = 2.29$, $p = 0.119$, $\eta_p^2 = 0.132$]. The interaction was seemingly due to the low-SF group unexpectedly performing worse than the other groups in Session 3 (*ps* < 0.018, *ds* > 0.96), but not in any of the other sessions (*ps* > 0.082, *ds* < 0.76).

The RT decreased for all training groups during training [**Figure 4B**; main effect for training session, $F(3,90) = 7.73$, $p < 0.001$, $\eta_p^2 = 0.205$]. However, the rate of change in RT did not differ according to the training group [no training group × training session interaction, $F(6,90) = 0.99$, $p = 0.437$, $\eta_p^2 = 0.062$; no main effect for training group, $F(2,30) = 2.35$, $p = 0.113$, $\eta_p^2 = 0.136$].

DISCUSSION

The purpose of this study was to determine whether the ability to anticipate deceptive actions could be enhanced by training that removes superficial visual information. Based on the idea that deceptive intent is conveyed at least in part via superficial (high-SF) information, we hypothesized that low-SF training would educate observers to attend to low rather than high-SF information, and ultimately lead to significant improvements in the ability to anticipate deceptive actions. The findings revealed that a low-SF group who trained viewing only low-SF information were the only training group to improve and retain their ability to anticipate the outcomes of deceptive actions at a level consistently above that of the control group. The high-SF group who viewed only high-SF information improved their performance from pre to post-test, but this improvement was not retained when tested in a 1-week retention test. Moreover, there was some suggestion that the training effect found for the low-SF group could be explained at least in part by a change in visual search behavior, with low-SF training leading to less time spent directing gaze toward high-SF information such as the opponent's face, and more time spent viewing other areas such as the location of racquet-shuttle contact. Ultimately, the results are particularly striking in that the low-SF training led to retained improvements in the ability to anticipate *deceptive* actions, even though participants viewed only veridical (*non-deceptive*) actions during training.

The superior performance of the low-SF group provides further support for the idea that a substantial amount of the deceptive intent is conveyed during motor actions via high-SF information that may distract observers from the low-SF information that seems to be most useful for anticipation. Abernethy et al. (2010a,b) reported a decrease in prediction errors when observers anticipated deceptive actions while watching a *point-light display* rather than video footage of the same action. This result suggests that deceptive intent is contained within high-SF information, and that very simple (low-SF) kinematic information is sufficient for effective anticipation. Further support for the usefulness of low-SF information was provided by Jackson et al. (2009) and Mann et al. (2010c), who each demonstrated that the anticipatory judgments of athletes improved in some cases in the presence of blur. In the present study, we exploited those findings to hypothesize and show that training which taught observers to attend to low-SF information would improve the ability to 'see-through' deceptive intent. The

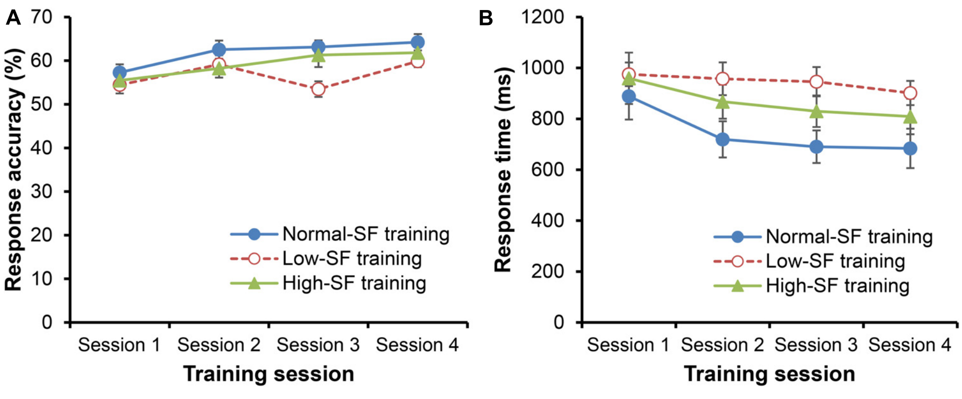

FIGURE 4 | Mean response accuracy **(A)** and response time **(B)** during training intervention. Error bars indicate the standard error of the mean.

superior performance of the low-SF, when compared to the normal-SF group, supports the idea that humans are distracted by high-SF information, and that athletes may not naturally attune directly to the low-SF information that seems to be most useful for anticipation. The findings highlight the need for observers to attend wherever possible to the coarse (low-SF) kinematic information which specifies genuine action outcomes, rather than attending to non-specifying information which is designed to fool or distract the observer.

The low-SF training group viewed low-SF information during training, yet improved and retained their anticipatory skill when tested viewing 'normal-SF' actions that contained both low and high-SF information. Even if the low-SF training was successful in training observers to make use of low-SF information when generating anticipatory judgments, it remained entirely possible that the high-SF information, when made available again in the post and retention-tests, could have been so pervasive that it would have distracted observers from the low-SF information they had learned to use. However, this was not the case. The improvement in anticipatory ability found as a result of training was retained even when viewing normal-SF information in the post-test, showing that the attunement to low-SF information learned during training 'transferred' to the more typical scenario when both low and high-SF information were available.

One of the most surprising outcomes of this study is that observers do not necessarily need to view deceptive actions in order to improve their ability to perceive them, but rather, that the anticipation of deceptive actions can be improved by an intervention which presumably trains observers to rely on the most useful information for anticipating action outcomes. Our study was designed in such a way that observers viewed only non-deceptive actions during training, a choice that was made in order to disambiguate any confounding influence of improved performance that might have been possible if participants became familiar with the deceptive actions. Instead, because deceptive actions were not seen during training, the findings provide some reassurance that the improvements seen when anticipating deceptive actions are the result of a fundamental change in the way that the participants in the low-SF group perceived the actions. An advantage for low-SF training was not found when viewing non-deceptive actions, with the improvement in anticipatory performance for the low-SF group being indistinguishable from that of the high and normal-SF groups when viewing non-deceptive actions in the post-tests. It may have been that the high-SF information that was available when viewing non-deceptive actions did not conflict with the low-SF information which specified the action outcome, and therefore there was no performance disadvantage for the high and normal-SF groups. Yet, when deceptive actions were viewed, it was only the low-SF group who improved and retained their ability to perceive action outcomes beyond that possible for the control group. In that case, their reliance on the highly specifying low-SF information may have made them less-susceptible to the high-SF information that conveys deceptive intent (Abernethy et al., 2010a,b).

The results from the analysis of gaze behavior provide some support for the idea that low-SF training leads to a fundamental change in the way that observers view and anticipate actions. While there was no change in the dynamics or extent of the visual search as a result of low-SF training (see also Ryu et al., 2016), there was evidence to show that the training altered *where* participants directed their gaze. In particular, as a result of training, participants in the low-SF training group decreased the proportion of time they spent viewing the face of their opponent, and increased the proportion of time spent viewing the anticipated location of racquet-shuttle contact. Given that the head is unlikely to be part of the kinematic chain responsible for producing a badminton shot (Abernethy and Russell, 1987), then it stands to reason that information from that location is unlikely to be particularly useful when predicting the outcome of an action (unless the opponent consistently directs their gaze toward the likely direction of the shuttle; Mareschal et al., 2013; Weigelt et al., 2017). Moreover, the information available from the opponent's face can be very compelling and attract attention, often helping the actor to successfully fool or deceive an observer, for instance in the use of head fakes in basketball and soccer (Kunde et al., 2011). Because facial features were not clearly visible when blur was applied during low-SF training (see **Figure 1**), it may be that participants learned to ignore the opponent's head/face, and instead focused their attention toward other more specifying areas of the visual array. Given that the most specifying kinematic information occurs late in the opponent's action, the location of gaze late in the action is crucial. In interceptive tasks, skilled tennis players have been shown to reliably direct their gaze toward the anticipated point of racquet-ball contact immediately before contact (Williams et al., 2002), and in sports such as baseball and cricket, batters direct their gaze toward the anticipated location from which the pitcher/bowler will release the ball (McRobert et al., 2009; Mann et al., 2013; Sarpeshkar et al., 2017). It appears that the participants in the low-SF training group spent more time directing gaze toward the location of racquet-shuttle contact, and less time being distracted by information from their opponent's face.

The results for the high-SF training group were surprising and are also worthy of further consideration. First, the high-SF group experienced a significant improvement in performance from pre to post-test when observing both deceptive and non-deceptive actions. One possible explanation for the improvement in the deceptive trials is that the deceptive intent conveyed via the high-SF information during the pre/post/retention tests might not have been entirely deceptive. That is to say, the high-SF information presented during a deceptive action might not *fully* replicate the high-SF information presented in the non-deceptive action the actor was seeking to replicate/convey. If that were the case, and the high-SF group did during training improve their ability to make judgments on the basis of high-SF information, then it may be that the observers were better able to perceive the attempted deception and to respond accordingly. An alternative explanation could be that as a result of the training, the high-SF group might have improved their ability to discriminate low from high-SF information, and then were able to rely more heavily on the low-SF information during the tests. The second finding of interest is that the improvement in RA from pre to post-test found for the high-SF training group had disappeared only 1 week later when tested at retention. The failure to retain improvements in performance following training is often attributed to the learned skills being acquired in an explicit rather than implicit manner (Maxwell et al., 2001; Masters and Maxwell, 2004). That is to say, if the skill is learned using an explicit approach, during which the learner accumulates declarative knowledge about how they should perform the skill, then the learned skill is more likely to be 'forgotten' over time (Allen and Reber, 1980). It may be that the high-SF training group acquired their skill in a more explicit manner than the low-SF group. The very pervasive nature of the detailed high-SF information may have led the high-SF group to focus explicitly toward specific information in the action sequence and to develop conscious rules about the meaningfulness of the high-SF information. In contrast, the low-SF group did not have access to this detailed information during training and may have instead focused on the coarse kinematic information that humans would typically rely on when judging the movements of others (Troje, 2002). Similarly, it could be that the overt nature of the high-SF information distracted the observer from relying on the low-SF information that better specifies the action outcome, increasing the likelihood that information was processed in a bottom–up rather than top–down fashion (Corbetta and Shulman, 2002; Carrasco, 2011). If true, Attention Control Theory (Eysenck et al., 2007) would suggest that, under anxiety, observers viewing deceptive actions should become more readily deceived, because top–down processing would be impaired and so observers could be more readily distracted by the high-SF information available through bottom-up processing. Accordingly, low-SF training could make observers more resistant to these changes when experiencing anxiety. Future work should seek to test these hypotheses empirically.

It is notable that RA was generally worse during the post and retention-tests for all groups than it was during the training itself, even when viewing the non-deceptive clips that were present during testing and training. We see two key differences that may help to explain the better performance during training. First, participants received feedback during training but not during testing, and the presence of feedback may have led to better performance during training. Second, the deceptive trials were mixed together with the non-deceptive trials in the post and retention tests (but absent during training), and therefore the uncertainty generated by the presence of the deceptive trials may have also reduced performance when viewing the non-deceptive trials (e.g., see Sarpeshkar et al., 2017). There has been growing interest not only in the ability of observers to exploit contextual information to *enhance* anticipatory performance (Abernethy et al., 2001; Cañal-Bruland and Mann, 2015), but also more recently on how the uncertainty generated by an increase in the number of likely outcomes can *decrease* performance (Mann et al., 2014; Sarpeshkar et al., 2017). Future work could look to examine how anticipatory performance changes in accordance with manipulations in the likelihood of a deceptive outcome, and whether blurred training aids in decreasing the degree to which observers are susceptible to the negative influences of contextual information.

It is worth considering whether our results might have been different if participants had viewed non-deceptive *and* deceptive actions during training. First, it seems reasonable to expect that the magnitude of the overall learning effect when compared from pre to post-test would have been greater, because participants would have become more accustomed to dealing with the uncertainty generated by the co-presentation of non-deceptive and deceptive clips (Sarpeshkar et al., 2017). When considering the low-SF training, because the low-SF clips remove the high-SF information that seemingly conveys deceptive intent (Abernethy et al., 2010a,b), then we would not expect any marked improvement in the ability of the low-SF group to anticipate deceptive actions on the basis of the kinematic information beyond that found in this study. However with the benefit of feedback, it could be that the high-SF group when training with both non-deceptive and deceptive actions would have learned which cues they could rely on to specify the actual motion outcome. Specifically, they could learn that the high-SF information is less specifying, and then rely on the low-SF information when it is available in the test. Given that this approach is likely to be quite explicit in nature, if true then we would still expect any gains as a result of high-SF training to be more likely to be lost when tested at retention as a result of 'forgetting' (Masters, 2008).

In this study we have employed a short-term intervention while training inexperienced observers to demonstrate a 'proof-of-concept' for the efficacy of low-SF training. Given the brief nature of the training (360 trials over 3 days), the magnitude of the increase in RA is reasonable ($\approx$10–15%), with significant changes from pre to post-test supported by large effect sizes ($ds > 0.8$). The results do raise the question of whether the training would lead to similar improvements in the performance of more skilled observers (e.g., Hopwood et al., 2011). Skilled observers would be expected to already be more proficient in their ability to anticipate deceptive actions (Jackson et al., 2006), and so it is often considered to be more challenging to improve the already high anticipatory skill of better performers. Nonetheless, a concurrent study by van Biemen et al. (in review) has provided some suggestion that blurred perceptual training might also improve the decision making performance of *skilled* observers. In that study, evidence was found to suggest that the ability of skilled football referees to discriminate deceptive from non-deceptive actions (fouls vs. 'dives' in football) improved as a result of training when viewing blurred actions. Again, further work is warranted to determine the generalisability of these findings to a task where anticipation is required.

Given the recent concerns about the need for the testing and training of anticipation to be performed in conditions which accurately represent the performance environment (Mann et al., 2010a; Pinder et al., 2011; Abernethy et al., 2012; Mann and Savelsbergh, 2015), questions may naturally arise about the generalisability of our findings given that the task was performed when providing a button-press response while viewing video footage on a computer screen. In this study we were largely interested in examining the ability to anticipate deceptive intent, irrespective of whether it is performed by a person who must move to respond (e.g., a rugby defender) or rather must simply provide a perceptual response (e.g., a football referee). When interested in examining tasks where the observer would typically move, compromises are often made to maximize experimental control and convenience (Abernethy et al., 1993). In our case the compromise was largely borne out of necessity: because of the nature of the manipulations of SF, it would not have been possible to present the high-SF information that we used while viewing a live opponent. Manipulations which remove low-SF content act much like an 'edge detector,' and to our knowledge this was only possible using the manipulation of video footage. However, it is much simpler to perform low-SF training in the natural environment: participants can simply wear blurring glasses or contact lenses to achieve a similar effect (Applegate and Applegate, 1992; Mann et al., 2007, 2010b,c), making blur simpler and more applicable than point-light displays which are restricted for use with screen-based stimuli. Given the success of the low-SF training in this study, this now provides the opportunity to empirically (and practically) test the utility of low-SF training in the natural environment to establish whether our findings generalize to tasks where movements are required when responding to opponents *in situ*.

Finally, the findings from this study suggest that it may be possible to improve performance in other tasks where the perception of deception is crucial. Of course there are a range of scenarios from sports in which deception is vital, including one-on-one duals in rugby, tennis, baseball, and cricket. In each of those cases, successful transfer would rely on the findings from the present study, which were found when performing a perceptual task, to extend to tasks where perception and action are coupled. There certainly are though also *perceptual* tasks for which the perception of deception is vital. In addition to sport referees who are often required to discriminate genuine 'fouls' from situations in which an athletes 'fakes' a foul to gain a penalty (Renden et al., 2014), law enforcement officers or customs officials also often need to anticipate the actions of others (Cañal-Bruland, 2017). Another example is in Paralympic classification, where some athletes attempt to exaggerate their level of impairment to gain an advantage by being placed into a class designed for athletes with more severe impairment (Tweedy and Vanlandewijck, 2011; Ravensbergen et al., 2016; Tweedy et al., 2016; Mann and Ravensbergen, 2018). In these situations, the ability to 'see through' deceptive intent is vital, and low-SF training may hold promise as a means of improving the perception of deception if in those tasks success also relies on attunement to basic low-SF information.

CONCLUSION

The findings of this study show that the ability to anticipate deceptive actions can be enhanced by training that removes superficial visual information. The outcomes support the idea that deceptive intent is underpinned by detailed high-SF information, and that attunement to low-SF visual information may prove to be a useful means for observers to become less-susceptible to the information that conveys deceptive intent.

ETHICS STATEMENT

Ethical approval was obtained from the University of Hong Kong Human Research Ethics Committee prior to testing. All participants gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

DR, BA, and DM designed the study. DR and SP acquired the data. DR and DM contributed to the interpretation of the data and drafted the manuscript. BA revised the manuscript.

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An Augmented Perceptual-Cognitive Intervention Using a Pattern Recall Paradigm With Junior Soccer Players

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In sport, perceptual skill training software is intended to assist tactical training in the field. The aim of this field study was to test whether "laboratory-based" pattern recall training would augment tactical skill training performed on the field. Twenty-six soccer players between 14 and 16 years of age from a single team participated in this study and were divided into three groups. The first received field training on a specific tactical skill plus cognitive training sessions on the pattern recall task. The second performed only the field training while the third group served as a control group and had field training on other topics. The task on the pre-, post-, and retention-tests was to recall specific soccer patterns displayed on a computer screen. Results showed significant changes between pre- and post-test performance. There was no significant interaction between groups and tests but the effect size was large. From pre- to retention-test, there was a significant difference between tests and an interaction between groups and tests, but no main effect difference between groups. On the basis of significance testing only retention was affected by the additional training, however, descriptive results and effect sizes from pre- to post-test were as expected and suggested there were learning benefits. Together these results indicate that augmented perceptual-cognitive training might be beneficial, but some limitations in our study design (e.g., missing field test, missing placebo group, etc.) need to be improved in future work.

Keywords: tactics, expertise, field study, video training, talent development

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INTRODUCTION

Starkes and Lindley (1994) considered whether the development of sport expertise could be hastened through the use of video simulations. While this sparked a variety of research that looked to improve performance in the lab, little research has considered whether field training could be augmented by using perceptual-cognitive interventions on a computer (for an exception see Christina et al., 1990). This was the focus of our investigation.

Considerable research attention has been given to understanding the role of video training in facilitating the training of perceptual-cognitive skills (Williams and Grant, 1999). Underpinning our understanding of expert perceptual-cognitive skill in sports is the robust research base emphasizing the malleability of these skills with appropriate training (Williams and Ford, 2008). Differences between expert athletes and lesser skilled performers have been identified in several areas of perceptual skill (for an overview compare Williams et al., 2011;

Williams and Abernethy, 2012). Several studies have shown that skills like decision making (Put et al., 2013) and anticipation (Murgia et al., 2014) can be trained.

Perhaps most relevant for the current investigation, one of the most consistently noted skills has been the ability to recall patterns of domain specific information (cf. Williams and Abernethy, 2012). For example, in team-based interactive sports, experts have been shown to have superior recall of the offensive and defensive structure in their sport than lesser skilled performers (Farrow and Abernethy, 2015). Further, experts' recall performance is only superior in domain specific structured tasks (e.g., Abernethy et al., 1994; Williams et al., 2004). This might be explained by the experts' development of a detailed sport-specific memory of situations and strategies that they experienced during their practice and training (cf. Farrow, 2011). Based on a theoretical foundation from early studies of chess by de Groot (1965) as well as Chase and Simon (1973) and Simon and Chase (1973), expertise differences in pattern recall have been demonstrated in several sports like American football (Garland and Barry, 1991), basketball (Gorman et al., 2012, 2013), field hockey (Starkes, 1987), soccer (Williams et al., 1993; Williams and Davids, 1995; Ward and Williams, 2003), snooker (Abernethy et al., 1994), and volleyball (Borgeaud and Abernethy, 1987). Moreover, the transferability of pattern recall skill has been demonstrated in sports with similar patterns of defense or offense (Smeeton et al., 2004; Abernethy et al., 2005). Researchers have also investigated anticipatory perception in pattern recall tasks, suggesting experts apply an anticipatory encoding of information when solving pattern recall tasks (Gorman et al., 2012, 2013; van Maarseveen et al., 2015) and that this effect also occurs when a series of patterns is used that is shown right before and right after the target image (Gorman et al., 2017).

Despite the consistency of these findings, we know very little about how these skills are trained (Williams and Grant, 1999; Schorer et al., 2015). Previous studies of perceptual training in sport have focused on the influence of different forms of instruction (Smeeton et al., 2005; Abernethy et al., 2012) or feedback (Memmert et al., 2009; Schorer et al., 2010), as well as transfer from the laboratory to field settings (Scott et al., 1998; Williams et al., 2003; van Maarseveen et al., 2016) or from virtual realities to reality (Tirp et al., 2015).

While these studies provide insight into the conditions of perceptual training in the laboratory, they have not evaluated whether perceptual training is useful as an adjunct to normal field training (for exceptions see Christina et al., 1990; Singer et al., 1994; Abernethy et al., 1999; Williams et al., 2002; Gorman and Farrow, 2009). The aim of this study was to determine whether additional pattern recall training off the field is beneficial in combination with "normal" field training for the acquisition and retention of pattern recall skill. Our first hypothesis was that there should be a greater improvement for groups with augmented cognitive training in comparison to only field training and a control group. In our second hypothesis, we assumed the augmented training group would show better retention over time than the other groups. Retention tests are especially important in field studies to demonstrate the efficacy and long-term effects in learning studies (Williams and Grant, 1999; Schorer et al., 2015).

MATERIALS AND METHODS

Participants

Twenty-six youth team male soccer players (mean age = 15.56 years, s = 0.93) participated voluntarily in this study. All played on a single team, in the second highest regional league for their age. All participants were randomly allocated to three different groups, which are described in more detail later. All reported normal or corrected-to-normal vision. Because the players were under age, their parents and the participants provided written informed consent before this study. The study was conducted in accordance with the revised ethical declaration of Helsinki.

Stimuli

For the task, animations presenting different soccer game situations were developed by two experienced coaches (cf. **Figure 1**). While a higher level of fidelity would have been reached by using real videos, they also raise methodological concerns. For example, in real videos the exact position of the presented player is not clear, because the position could be either his or her feet or the stomach or any other defined body part. On tactical boards such as the ones used here, the x- and y-axis position is clearly defined and therefore easy to measure. Moreover, this type of tactical display is very commonly used by coaches. The colored animations were compiled by the program Easy Animations 3.0 and included small yellow and red icons representing the soccer players. The experiment was programmed using Experiment Builder (SR Research) and the animations were presented from an aerial perspective showing one half of a soccer pitch. When the animations begin, the offenders leave the beginning player formation and start moving on the pitch, passing the ball to different players. The defenders shift their positions depending on, and adapting to, the attackers' movements. The animations showed structured attacking situations with the defending team reacting by using typical structured back four defenses. Each scene contained five outfield players per team. The animated scenes had a length of 5 s with the last frame "frozen" for another 5 s followed by a black screen for 2 s. After each animation, a screen presenting the figures and the pitch appeared, which the participants used to position their recalled players. Participants used their forefinger to place the recalled players on the touchscreen (AcerZ5610).

Procedure

Pre-test, Post-test, and Retention-Test

In each test, participants saw 10 evolving tactical animations as described above on a 23-inch touchscreen (Acer Z5610). The participant's task was to replicate the player formation of the last still image of the presented video as precisely as possible. Using their forefinger as the cursor, participants were able to move the various player figures around the pitch. The time between pre- and post-test was 4 weeks with training twice a week. The retention-test was conducted 2 weeks after the post-test.

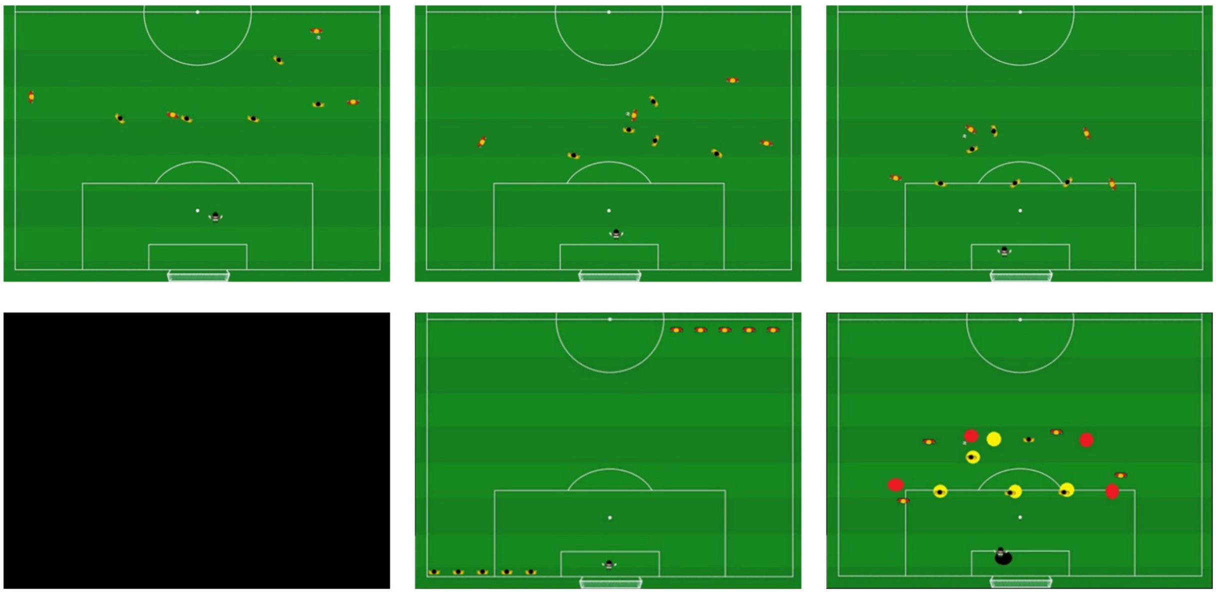

FIGURE 1 | Schematic presentation of the pattern recall task. In row 1, a series of images shows the animations presented to the participants during the task. The last image is an example representing the "frozen" frame at the end of the animation. The black image (row 2, left image) was followed by a recall screen (row 2, middle image). During training players received feedback as demonstrated in row 2, right image.

Field Training

This study was implemented during the normal training of a youth team. Field training consisted of normal elements of training including warm-up, technical drills, and playing football games. During the tactical training all players received instructions by a coach who was unaware of which player was in which group for the training study. The topic of the tactical training on the field was the same as in the stimuli presented in the animations (i.e., the back four defense). Field training was conducted twice per week for 4 weeks and lasted approximately 90 min.

Perceptual-Cognitive Training

Perceptual-cognitive training was also conducted twice a week for 4 weeks. Participants in this group performed training once before and once after the normal field training sessions per week. The task was the same as in the tests with the addition that, after recalling the positions of the players, participants received immediate feedback. Feedback was provided by yellow and red circles indicating the real position of the players in comparison to the recalled positions. Each training session lasted approximately 30 min and in each session, 14 out of 28 situations were randomly selected by the computer and presented in random order for each session and each participant. The scenes used in training were different from the test scenes.

Training Groups

In our study, three different groups participated:

(1) *Cognitive and field training group (n = 10)*. The cognitive and field training groups participated in both forms of training described above.
(2) *Field training group (n = 10)*. This group participated only in the field training.
(3) *Control group (n = 6)*. The control group did not receive any training on this specific tactical situation, however, they participated in different forms of field training.

Statistical Analyses and Dependent Measures

All data were analyzed using SPSS 22.0 and G-Power 3.10 (Faul et al., 2007). For data analysis, the dependent variable was minimized root mean square error (RMSE). Because our task did not assign players to specific positions, we calculated all possible configurations of distances between real and recalled player positions and used minimal distance as the dependent variable. We then ran two hypothesis-driven analyses. First, a mixed-model factorial analyses of variance was done with test (pre- to post-test) as the repeated measure and group as the factorial measure. Second, we conducted the same analysis, but with the repeated measure from pre- to retention-tests. Prior to these analyses, we ran a baseline check. Alpha was set at 0.5 and effect sizes were calculated as f-values (cf. Cohen, 1988). Values of $f = 0.10$ and above were interpreted as small, while values of 0.25 and above indicated a medium effect size and of 0.40 and larger indicated a large effect (Cohen, 1992).

RESULTS

In a first step, pre-test differences between groups were considered. This baseline check revealed no significant differences between groups, $F_{(2,25)} = 1.53$, $p = 0.24$.

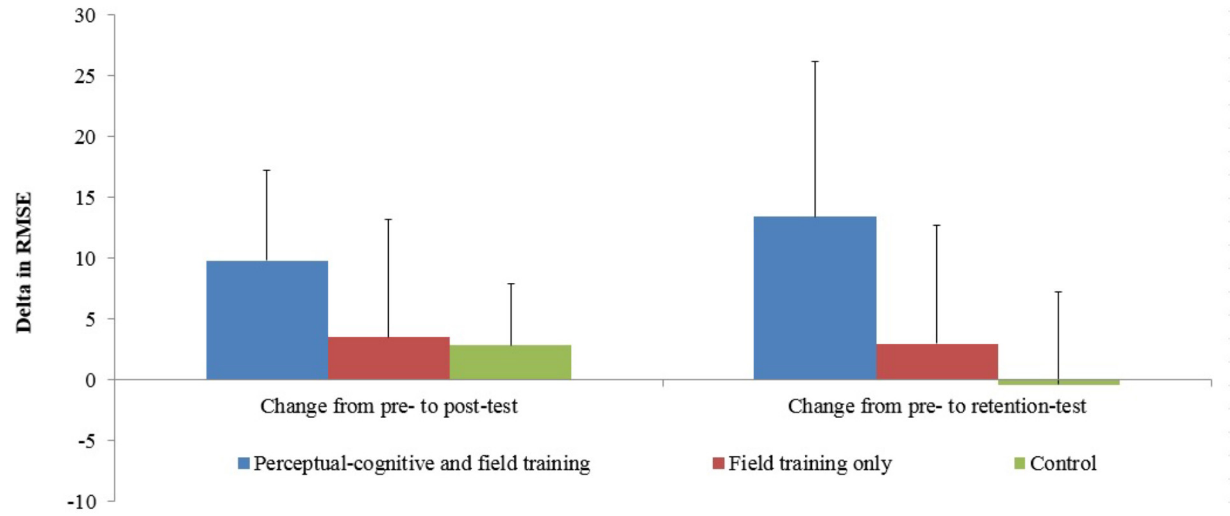

FIGURE 2 | Comparison of changes from pre- to post-test (left bars) and from pre- to retention-test (right bars; bars indicate means while the lines above reflect standard deviations).

TABLE 1 | Comparison of performances in pre-, post-, and retention-tests differentiated by groups (means and SDs in pixels).

	Pre-test	Post-test	Retention-test
Cognitive and field training group	67.54 (10.11)	57.73 (9.49)	54.14 (7.83)
Field training group	62.57 (9.97)	59.07 (9.57)	59.52 (9.69)
Control group	59.17 (8.02)	56.37 (12.08)	59.55 (12.21)

Our first hypothesis proposed a significant interaction between groups and pre- and post-test performance. An analysis of variance with groups as the between subject factor and pre- and post-test as the repeated measure revealed no differences between groups, $F_{(2,23)} = 0.55$, $p = 0.59$, but significant changes between tests, $F_{(1,23)} = 11.03$, $p < 0.01$, $f = 0.68$. Interestingly, the interaction of both factors was not significant, $F_{(2,23)} = 2.07$, $p = 0.15$, $f = 0.42$, but the effect size was large. As can be seen in **Figure 2** and **Table 1**, the cognitive and field training group improved the most followed by the field training group and the control group.

For our second hypothesis, we investigated changes from pre- to retention-test with the same analysis of variance approach. Again, no differences between groups were revealed, $F_{(2,23)} = 0.91$, $p = 0.91$; however, the repeated measure factor test, $F_{(1,23)} = 6.20$, $p = 0.02$, $f = 0.51$, and the interaction of both factors, $F_{(2,23)} = 3.86$, $p = 0.04$, $f = 0.57$, were significant. As can be seen in **Figure 2** and **Table 1**, the highest improvement was for the combined group.

DISCUSSION

In our first hypothesis we assumed a greater improvement in the cognitive and field training group compared to both other groups. While we did not find the expected significant interaction, the descriptive results were in the anticipated direction and the effect size was large. Based on these results, the augmented cognitive training seemed to be beneficial for improving pattern recall skills containing tactical elements. Additionally, the results related to our second hypothesis revealed that it also enabled better retention. Moreover, the long term effect (from pre- to retention-test) – as shown by the significant interaction – was larger than the short-term effect (from pre- to post-test; $f = 0.42$ vs. 0.57). These results indicate that augmented perceptual-cognitive skill training is beneficial for learning in the long-term.

These findings support previous research emphasizing the potential of perceptual cognitive training interventions (Put et al., 2013; Murgia et al., 2014). However, much of the prior work in this area has been done with novel training paradigms that are disconnected from athletes' actual training environments (i.e., how the intervention interacts with an athlete's regular training is unknown). In the current study, we tested an intervention that ran in parallel with athletes' actual on-field training. This allowed us to determine the applicability of a perceptual cognitive intervention as an augmentation to regular training.

While these results provide some promising initial results, several limitations must be noted. First, future work is necessary to verify whether these laboratory results transfer to field performance. This is a consistent limitation of much of the research in this area (for exceptions see Christina et al., 1990; Harle and Vickers, 2001) and while we acknowledge the difficulty of field testing a pattern recall task, future studies should try to implement field tests. A second concern relates to the potential value of a placebo group. Although a placebo group offers a nice method of experimental control, in the current study we had to ensure that all athletes received the same training and dividing the team into yet another group was not feasible. A third concern relates to understanding the precise value of pattern recall to expert perception and anticipation. Looking at the role and mechanisms underpinning recognition of patterns and anticipation of experts, North et al. (2011) demonstrated that anticipation as well as recognition tasks stimulate complex memory structures and representations. Nevertheless, the activated memory representations during recognition tasks differ from the level of cognitive processing during anticipation tasks (North et al., 2009, 2011). Furthermore, Gorman et al. (2015) showed significant differences in visual search strategies in pattern recall and decision-making tasks, suggesting that solving these tasks requires the use of different underlying mechanisms. However, the role and mechanisms underpinning recall of patterns have not been clarified. On the surface, the role of being able to identify complex patterns of domain specific information for individual performance is not immediately clear. It is possible that it plays some role in search and retrieval of domain specific information that facilitates rapid decision-making and/or anticipation, however, further work is necessary to determine the precise role pattern recall plays in expert perceptual-cognitive performance.

This study highlights several areas for further work. First, our sample consisted of good, but not excellent youth players. Future work should examine whether these results apply to players with a higher level of skill and/or age. Second, an intriguing future area would be to test differences in the retention period. While our study had an unfilled retention phase, comparing either field-based or laboratory-based retention periods might provide helpful information for optimizing training plans. This study represents an important step in bridging the gap between laboratory-based perceptual learning studies and applied on-field training of athletes. Clearly more steps are necessary; however, continued research in this area would clarify the value of augmented video training for skill acquisition and expertise development.

ETHICS STATEMENT

We do not have an approval from an ethical committee, because the study was conducted as a master thesis and no approval was needed at the time of conduction.

AUTHOR CONTRIBUTIONS

JS and JH designed the study. LF programmed the test. JH collected the data. JS and JB drafted the first version of this manuscript. JS, LF, MS, and JB revised and discussed all versions of this manuscript. All authors agreed on this latest version of the manuscript.

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The Effect of Blurred Perceptual Training on the Decision Making of Skilled Football Referees

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When judging ambiguous foul situations in football (soccer), referees must attune to the kinematic characteristics inherent in genuine fouls to ensure that they can (i) recognize when a foul has taken place, and (ii) discriminate the presence of deceptive intent on the part of the tackled player. The aim of this study was to determine whether perceptual training that removes superficial visual information would improve the decision-making performance of football referees. Two groups of skilled referees judged ambiguous foul situations on video before and after a training intervention that involved adjudicating foul situations. During the training phase, participants in a blurred-footage training group watched digitally altered, blurred videos that removed superficial visual information, whilst participants in a normal-footage control group viewed the same videos without blur (i.e., with the superficial information present). We hypothesized that blurred-training would train referees to ignore superficial visual information and instead focus on the basic kinematic movements that would better reveal the true nature of the inter-personal interaction. Consistent with this idea, training with blurred footage resulted in a positive change in response accuracy from pre to post-test when compared with normal-footage training. This improvement could not be explained on the basis of changes in response time or bias, but instead reflected a change in the sensitivity to genuine fouls. These findings provide a promising indication of the potential efficacy of blurred-footage training for referees to attune to the kinematic information that characterizes a foul. Blurred training might offer an innovative means of enhancing the decision-making performance of football referees via perceptual training.

Keywords: perceptual training, decision making, referee, football, blur

INTRODUCTION

Football (soccer) referees who adjudicate high-level professional matches are faced with an extraordinarily difficult task. They make an average of 137 decisions about goals, free-kicks, and penalties per 90-min match (Helsen and Bultynck, 2004), all while being scrutinized by players, spectators, and pundits at the match, and potentially by millions of fans watching at home. The most common, and probably most critical decision that referees are faced with are those in which they must differentiate whether a foul has been committed by one player on their opponent, or instead in some cases whether the opponent has taken a "dive" in an attempt to fool the referee into awarding an unjustified foul (Helsen and Bultynck, 2004). In these ambiguous foul situations, the referee is required to "see through" any deceptive intent on the part of the tackled player to judge whether a genuine foul has taken place. The consequences of an incorrect decision can be significant, particularly if a foul is awarded in the team's penalty area, with a penalty shot often resulting in a goal being scored. Data from Top-4 leagues in England show that the outcome of ≈60% of football games are decided by a maximum of one goal difference between the teams (data from top-4 leagues in England; Curley, 2016), making correct decisions vital, and training approaches which minimize errors when adjudicating ambiguous foul situations are clearly desirable (Schweizer et al., 2011; Pizzera and Raab, 2012a).

There are a variety of social contexts in which it is important to be able to perceive deceptive intent (Cañal-Bruland, 2017). Much of the work on deception has its origins in verbal interactions, whereby one person may wish to determine whether another is lying (Ekman et al., 1999; Vrij and Mann, 2004). Research on deception has also been extended to understanding physical interactions, where an observer may seek to anticipate the movement intentions of others. There are a variety of situations in which a person may wish to produce movements that deceive others (e.g., pickpockets, magicians), and this is particularly the case in sports where an advantage can be gained by forcing opponents into misjudging action outcomes, such as one–on–one interactions in rugby, tennis and football. Evidence shows that expert athletes are not only better able to produce deceptive actions, but they also possess a better capability to "see through" this deceptive intent to more accurately anticipate the true action intentions of their opponents (Jackson et al., 2006).

It is not only skilled athletes who possess superiority in their ability to anticipate the deceptive actions of others; skilled sports officials also are better able to discriminate deceptive from non-deceptive actions. For instance, Renden et al. (2014) have shown that football referees have an advantage in their ability to distinguish genuine from deceptive actions when making judgements about ambiguous foul situations in football. In their study, Renden et al. (2014) recruited skilled football referees to make judgements of ambiguous foul situations seen in video footage from actual matches, and compared the judgements of the referees to those of skilled players, wheelchair-bound football fans, and novices. Results revealed that the referees and players outperformed the fans and novices, demonstrating that both groups are better able to discriminate genuine from deceptive fouls in football. The superior performance of the players provided some support for the idea that motor experience through playing the game may have contributed to the superior performance of the players. However, the concurrent superiority of the referees suggested that their perceptual experience in viewing and making decisions in ambiguous foul scenarios was sufficient to support success. This raises the possibility that the visual experience gained via additional perceptual training, which supplements the amount of exposure to these situations, may help to further improve the decision-making ability of referees [see also Luis del Campo et al. (2018)].

The ability to anticipate the outcome of a motor action is underpinned by an ability to interpret the kinematic movements producing that action, particularly when the action contains deceptive intent. Runeson and Frykholm (1983) first demonstrated the role of kinematics in deception. In their experiment, Runeson and Frykholm showed observers recorded videos of an actor lifting a box onto a table. In the videos, the actor was shown as a point-light representation so that the image of the actor was replaced by points of light at each if their key joint centers. Observers were very good at performing the perceptual task, even when the actor attempted to deceive them by pretending that the box was heavier than it really was. Because observers could detect this deception when viewing a point-light representation of the actor, the results suggest that the genuine action intentions are revealed via the basic kinematic movements of the actor. More recently, Abernethy et al. (2010a,b) compared the anticipatory skill of badminton players when watching both videos and point-light displays of an opponent playing deceptive and non-deceptive badminton strokes. The results revealed that deception was effective when players observed the videos of the opponent, but was less effective when viewing the point-light displays. In the point-light displays, observers were better able to see through the deceptive intent of the opponent. On the basis of these findings it was reasoned that deceptive intent must be conveyed largely via superficial (non-kinematic) visual information such as contour, color, and texture that is present in the video, but is not present in point-light display. Genuine intent on the other hand, is largely conveyed through basic kinematic information that is present in the point-light displays. In support, the quality of decisions made when making judgements about moving stimuli has been shown in some situations to improve when superficial visual information is removed via the use of visual blur (Di Lollo and Woods, 1981; Luria and Newacheck, 1992), and in particular when blur is applied while anticipating the actions of others (Jackson et al., 2009; Mann et al., 2010; Ryu et al., 2015, 2016). This suggests that it would be beneficial to learn to ignore superficial (non-kinematic) information when seeking to improve the anticipation of a deceptive movements, and instead to attune to the basic kinematic signature that specifies the movement outcome.

Ryu et al. (2018) have recently demonstrated that perceptual training using a blurred rather than clear image may be advantageous when making judgements about movement outcomes in the presence of deceptive intent. In their study, novice badminton players trained to anticipate the actions of an opponent when viewing video footage that displayed (i) blurred information only, (ii) highly detailed information only, or (iii) normal video footage. When tested following training, the results revealed that those who trained with blurred video footage experienced the greatest improvement in their ability to predict the outcome of deceptive badminton strokes. It was reasoned that the blurred-training group may have better learned to ignore the superficial bodily information, and instead attuned to the underlying kinematic pattern that they had viewed during training, that being the information which best specifies the genuine action outcome of the opponent.

While deception may be specified in many cases by non-kinematic information, there is reason to believe that kinematic information may have an important role to play during ambiguous foul situations when conveying deceptive intent. Morris and Lewis (2010) performed a simple observational comparison of football tackles in which attempts at deception (i.e., dives) clearly were and were not present. Morris and Lewis concluded that the two sets of tackles could be distinguished by differences in kinematics, with diving often characterized by: (i) the presence of the "archer's bow," a form of diving characterized by arms raised and backward, chest thrust out and legs bent at the knees; (ii) a discontinuity between the moment of contact and the supposed effect on the tackled player; (iii) an exaggeration in the effect of the force on the tackled player; and (iv) by spatial misalignment between where contact was made and where the tackled player implied that contact took place. Given that the deceptive intent reported in Morris and Lewis's study was very obvious on the basis of the kinematic differences, the authors speculated that tackled players used highly exaggerated kinematic actions to ensure that observers (including referees) could clearly see the substantial effect of the tackle. This clearly noticeable behavior may be necessary given that the referee often stands a substantial distance away from the incident. Nonetheless, the findings highlight that referees must be attuned to the kinematic characteristics inherent in genuine fouls to ensure that they can (i) recognize when a foul has taken place, and (ii) discriminate the presence of deceptive intent on the part of the tackled player.

The aim of this study was to determine whether perceptual training that removes superficial visual information would improve the decision-making performance of skilled football referees. To do so, skilled referees were allocated to one of two training groups: a blurred-footage training group who adjudicated foul situations when watching video clips that were blurred; and a normal-footage (control) training group who trained viewing the same videos without blur. Based on previous research which has shown the efficacy of perceptual training for improving performance in refereeing (Catteeuw et al., 2010; Schweizer et al., 2011; Pizzera and Raab, 2012a; Put et al., 2013, 2016a,b), we expected both training groups to improve their decision-making accuracy following training. Crucially, we hypothesized that the addition of blur during training would better attune observers to the kinematic information that specifies the genuine movement outcome, resulting in a greater improvement in pre vs. post-test performance for the blurred-footage training group when compared to the normal-footage control group.

MATERIALS AND METHODS

Participants

A total of 22 skilled male referees ($M_{age} \pm SD = 31.3 \pm 8.1$ yrs) from the Dutch National Football Association (KNVB) took part in the experiment ($M_{experience} \pm SD = 13.4 \pm 5.5$ yrs). The referees where either professional or semi-professional, refereeing international ($N = 4$) and/or national in the three highest national Dutch soccer leagues ("Eredivisie," "Jupiler League," and "Tweede divisie"). All referees had adjudicated matches at the national level for at least 1 year ($M \pm SD = 6.9 \pm 4.6$ yrs) and were unfamiliar with video-based perceptual training. They had normal or corrected-to-normal vision. Participants were randomly assigned to one of two training groups (with the allocated group alternating in order of participation): a blurred-footage training group who trained viewing blurred stimuli ($n = 11$; $M_{age} \pm SD = 30.7 \pm 7.3$ yrs; $M_{experience} \pm SD = 13.4 \pm 5.6$ yrs; three internationals), or a normal-footage control group, who trained viewing standard (non-manipulated) video stimuli ($n = 11$; $M_{age} \pm SD = 31.9 \pm 9.1$ yrs; $M_{experience} \pm SD = 13.5 \pm 5.7$ yrs; one international). Participants provided written informed consent to a procedure that conformed to the Declaration of Helsinki and was approved by the Vrije Universiteit Amsterdam Faculty of Human Movement Sciences Ethics committee (approval number VCWE-2016-212).

Study Design

A short-term training study was conducted using a pre-post test design. For practical reasons related to the restricted availability of the referees, training and testing were all conducted on the same day, with the entire procedure taking approximately 45 min for each participant.

Procedure

During the pre-test, participants were asked to judge potential foul situations as a "foul" or "no foul" when viewing video clips displayed on a laptop computer (HP ZBook15, 15.6 inch, 1920 × 1080 pixels). For testing, we used the same clips as Renden et al. (2014), with situations taken from the 2006 FIFA World Cup. Correct responses had been judged by an expert panel of two experienced (Dutch accredited) soccer referees [for details, see original paper of (Renden et al., 2014)]. Participants took part in three practice trials before commencing the pre-test. Following the method of Renden et al., the test consisted of a total of 26 clips: 13 showing fouls and 13 showing no foul. The 50:50 split of fouls vs. no fouls was used to minimize the potential influence of any pre-conceived priors that the referees might have had about the likelihood of a foul taking place. Video clips were presented in a different random order for each participant using OpenSesame software (Mathôt et al., 2012). Each clip commenced with the trial number shown on the screen, followed by a countdown from 3 to 1 to cue the commencement of the clip. Participants were required to decide as quickly and accurately as possible whether the incident seen in the clip should be judged as a "foul" or "no foul" and to press a corresponding key on the laptop keyboard. In order to reflect the need for fast and accurate decisions within a match, participants were required to respond within 3 s of the completion of the clip, otherwise their response was recorded as incorrect. No performance feedback was given during the test. Referees taking part in this study were unfamiliar with videos seen during the test.

During the training phase, participants were required to judge the severity of foul situations while viewing clips shown on the same laptop screen. During training, participants viewed a total of 70 clips, which were taken from the Referee Assistance Programs 2015 and 2016 distributed by the Union of European

Football Associations (UEFA). In advance of testing, participants were asked about their familiarity with the UEFA training program. All declared to be either unfamiliar with the program or admitted not to use the program despite their knowledge of existence of and/or access to the program. Only fouls were shown during training in order to expose participants to the type of kinematic actions that should characterize genuine fouls (Ryu et al., 2018). The task for participants during training was to choose as quickly and accurately as possible whether the situation warranted a red card, yellow card, or no card (foul only). The correct decision for each clip was provided in the program by UEFA, all according to Law 12 of the Game. In this way, the aim was for participants to be trained to better categorize fouls on the basis of the pick-up of the most essential information cues for these decisions. Participants performed three practice trials before the commencement of training. The clips were presented using the same randomized order for each participant. Each clip was preceded by the trial number and a countdown from three to one. Again, there was a time constraint of 3 s to make a decision and, unlike the pre-test, participants received direct feedback on their answer to encourage learning (Schweizer et al., 2011). After the first 35 clips, participants had the choice to take a small break or to continue with the training.

Participants in the blurred-footage training group viewed video clips during training that were digitally altered using the camera blur option in Premier Pro CC software (Adobe Systems Incorporated, San Jose, CA, United States). Each video clip shown during training consisted of television footage that comprised a mixture of wide-field and close-up views of the situation. To achieve a relatively consistent level of blur within the clip, the wide-field parts of the clip were blurred using 7% blur, and the close-up parts of the clip were blurred with 20% blur (**Figure 1**). Those blur levels were chosen on the basis of mutual agreement between the authors during pilot testing where we compared blurred footage with blur used in previous studies (Mann et al., 2007; Bulson et al., 2008, 2015), with the overall aim to achieve a level of blur that would largely remove superficial visual information yet continue to make kinematic information available. Participants in the normal-footage training group viewed the original (unblurred) versions of the same video clips.

The procedure for the post-test was exactly the same as for the pre-test. In the post-test, each participant viewed video clips that they had not seen in the pre-test. The pre and post-test were counterbalanced in such a way that half of the participants viewed one set of 26 clips in the pre-test, and a different set of 26 clips in

FIGURE 1 | Demonstration of the amount of blur used in the training phase when compared to the standard view. Images are screenshots of the videos of the UEFA Referee Assistance Program used in the training. Permission of usage have been obtained by UEFA's Referee Development Department.

the post-test, while the other half of the participants viewed the two sets of clips in the opposite order.

Data Analysis

Response accuracy was the key measure of decision-making performance. Response accuracy was scored on the pre-and post-tests by calculating the percentage of correct responses on each test. To test the hypothesis that blurred-footage training would result in a greater improvement in performance than control training, an independent *t*-test was used to compare the change in response accuracy from pre to post-test between the blurred-footage and normal-footage training groups. Follow-up paired *t*-tests were used to check whether there was a significant change in the performance of each group as a result of training, thus independently comparing the performance of each group to a null effect of zero. Moreover, *t*-testing was performed to check whether the response accuracy of the two groups differed in the pre-test.

We also calculated response time to ensure that any change in response accuracy was not a result of a trade-off between response accuracy and time. Response time was determined by calculating the time in milliseconds from the completion of the clip until the keyboard response was registered. An independent samples *t*-test was used to compare the change in response time from pre to post-test between the two groups to check whether response times changed as a result of training.

Signal detection analysis was used to check whether any changes in response accuracy following training could be attributable to changes in sensitivity or response bias (Cañal-Bruland and Schmidt, 2009; Bruce et al., 2012). This was particularly important because training consisted of only foul situations, so it was possible that participants could increase their bias to judge ambiguous foul situations as fouls following training. For signal detection analysis, responses were labeled as hits when participants correctly identified a foul (the "signal"), a miss when participants incorrectly judged a foul situation as no-foul, a correct-rejection when a no-foul clip was correctly judged as no-foul, and a false alarm when a no-foul clip was judged as a foul. To account for situations where the hit or false alarm rates could equal zero for a single participant, for the purposes of calculating hit and false alarm rates a log-linear approach was used (Stanislaw and Todorov, 1999), where 0.5 was added to each participant's number of hits and false alarms, and one added to their number of signal and signal-absent trials. Sensitivity (d') was defined as the ability to distinguish fouls from no-fouls and was calculated by subtracting the inverse of the standard normal cumulative distribution of the false alarm rate from that of the hit rate (Stanislaw and Todorov, 1999). Response bias (β) was defined as the tendency to favor either a foul or no-foul judgement, and was calculated by the formula $e^{0.5^{*}(z(FA)\wedge 2-z(H)\wedge 2)}$, where FA is the false alarm rate, and H is the hit rate (Stanislaw and Todorov, 1999). Independent *t*-tests were used to check whether any change in the sensitivity and response bias as a result of training differed between the two groups. Data were tested for normality using the Shapiro–Wilk test; the Mann–Whitney U test was used instead of the *t*-test in any cases where the assumption of normality was violated. Effect sizes were calculated using Cohen's d and expressed as a small (± 0.10), medium (± 0.30), or large effect (± 0.50) (Field, 2009). To evaluate the precision of the effect size, 95% confidence intervals were calculated for each effect size (95% CI_{ES}) following the formulae of Nakagawa and Cuthill (2007). Alpha was set at 0.05 for all testing, with all analyses conducted using SPSS Statistics 22.

RESULTS

Tests for normality showed that all data for the control group were normally distributed, including the measures of response accuracy [pre-test; $D(11) = 0.94$, $p = 0.56$, post-test; $D(11) = 0.86$, $p = 0.051$, difference; $D(11) = 0.92$, $p = 0.31$], response time [pre-test; $D(11) = 0.96$, $p = 0.70$, post-test; $D(11) = 0.93$, $p = 0.44$, difference; $D(11) = 0.92$, $p = 0.32$], sensitivity [difference; $D(11) = 0.95$, $p = 0.61$] and bias [pre-test; $D(11) = 0.96$, $p = 0.79$, post-test; $D(11) = 0.96$, $p = 0.82$, difference; $D(11) = 0.86$, $p = 0.05$]. The data of the training group were normally distributed for response accuracy [pre-test; $D(11) = 0.89$, $p = 0.10$, post-test; $D(11) = 0.90$, $p = 0.17$, difference; $D(11) = 0.88$, $p = 0.10$], response time [pre-test; $D(11) = 0.87$, $p = 0.07$, post-test; $D(11) = 0.85$, $p = 0.05$, difference; $D(11) = 0.92$, $p = 0.28$] and bias [pre-test; $D(11) = 0.86$, $p = 0.06$, post-test; $D(11) = 0.95$, $p = 0.61$]. Therefore parametric testing was used for these variables. The data for the difference in sensitivity [$D(11) = 0.85$, $p = 0.04$] and the difference in bias [$D(11) = 0.84$, $p = 0.03$] from pre- to post-test were not normally distributed. For these variables, non-parametric Mann–Whitney U tests were used.

The blurred-footage training group's change in response accuracy from pre to post-test was significantly greater than that for the normal-footage training group (**Figure 2**), planned *t*-test (one-tailed), $t(20) = -1.012$, $p = 0.029$, $\beta = 0.487$ [blurred-footage vs. normal-footage training group $(M \pm SD) = 3.9 \pm 8.3\%$ vs. $-4.5 \pm 11.0\%$], large effect size (Cohen's $d = 0.86$), 95% $CI_{ES} = 0.45–1.27$. Follow-up *t*-tests showed that the blurred-footage training group experienced a borderline increase in response accuracy as a result of training, $t(10) = -0.773$, $p = 0.07$, $\beta = 0.288$ one-tailed [pre vs. post-test $(M \pm SD) = 75.9 \pm 4.3\%$ vs. $79.7 \pm 8.5\%$], with a medium effect size ($d = 0.47$, 95% $CI_{ES} = -0.26–1.20$), whereas the normal-footage training group experienced a borderline decrease in performance, $t(10) = 0.685$, $p = 0.10$ one-tailed, $t(10) = 1.370$, $p = 0.20$, $\beta = 0.237$ two-tailed [pre vs. post-test $(M \pm SD) = 77.3 \pm 8.9\%$ vs. $72.7 \pm 7.0\%$], with again a medium effect size ($d = 0.41$, 95% $CI_{ES} = -0.42–1.24$). There was no difference in response accuracy between the blurred-footage and normal-footage training groups at pre-test, $t(20) = 0.473$, $p = 0.64$, $d = 0.20$, 95% $CI_{ES} = -0.18–0.58$).

The difference between the two groups in the change in response accuracy following training could not be explained by changes in response times. A *t*-test comparing the change in response time from pre to post-test for the two groups showed that there was no significant difference between the blurred-footage and normal-footage training groups, $t(20) = 0.617$, $p = 0.54$, $\beta = 0.090$ two-tailed, $d = 0.26$, 95%

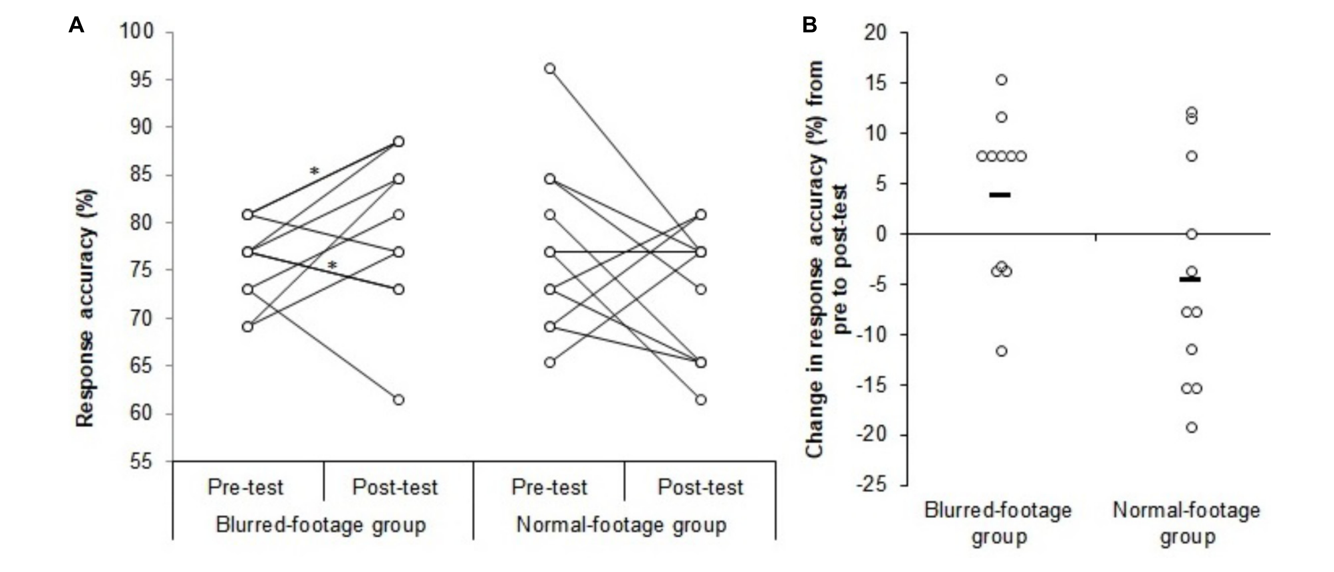

FIGURE 2 | Change in decision-making performance from pre to post-test as a result of training for the blurred-footage and normal-footage training groups. Panel **A** shows each individual participant's response accuracy in the pre and post-test, and panel **B** shows each individual's *change* in response accuracy from pre to post-test. The black bars represent the means, the asterix (*) indicates two participants having exact the same pre-test and post-test scores.

CI_{ES} = −0.12–0.64 [blurred-footage vs. normal-footage training group *(M ± SD)* = −56 ± 126 ms vs. −4 ± 248 ms). Neither of the groups experienced a significant change in response time from pre to post test, blurred-footage group, $t(10) = 1.462$, $p = 0.17$ two-tailed, $d = 0.44$, 95% CI_{ES} = 0.16–0.72 [pre vs. post-test *(M ± SD)* = 842 ± 366 ms vs. 786 ± 356 ms], normal-footage group, $t(10) = 0.051$, $p = 0.96$ two-tailed, $d = 0.02$, 95% CI_{ES} = −0.44–0.48 [pre vs. post-test *(M ± SD)* = 833 ± 304 ms vs. 829 ± 327 ms).

Signal detection analysis revealed that the differences in the behavior of the two groups could be explained by changes in their sensitivity to genuine fouls rather than a bias to expect fouls. A non-parametric Mann–Whitney test revealed a significant difference in the change in sensitivity for the two groups following training (**Figure 3A**), $U = 25.00$, $z = -2.33$, $p = 0.02$, $d = 1.15$, 95% CI_{ES} = 0.71–1.59 [blurred-footage vs. normal-footage training group *(M ± SD)* = 0.30 ± 0.63 vs. −0.37 ± 0.66]. This result showed that the ability to identify genuine fouls increased for the blurred-footage group when compared to the control (normal-footage) group. The analysis of response bias showed that there was no difference in the change in bias between the groups as a result of training (**Figure 3B**), $U = 49.00$, $z = -0.76$, $p = 0.450$, $d = 0.33$, 95% CI_{ES} = −0.05–0.71 [blurred-footage vs. normal footage group *(M ± SD)* = −0.12 ± 0.71 vs. −0.09 ± 0.38]. A response bias of $\beta = 1$ would indicate that referees favored neither a "foul" or "no-foul" call. The results showed that the response bias of the referees never varied significantly from $\beta = 1$ irrespective of the test, blurred-footage training pre-test, $t(10) = -0.097$, $p = 0.92$, $d = 0.022$, 95% CI_{ES} = −0.35–0.40 ($M \pm SD$ = 0.99 ± 0.45), blurred-footage training post-test, $t(10) = -0.92$, $p = 0.38$, $d = 0.28$, 95% CI_{ES} = −0.10–0.66 ($M \pm SD$ = 0.90 ± 0.36), normal-footage training pre-test, $t(10) = 0.017$, $p = 0.87$, $d = 0.053$, 95% CI_{ES} = −0.32–0.43 ($M \pm SD$ = 1.03 ± 0.57), normal-footage training post-test, $t(10) = -0.57$, $p = 0.58$, $d = 0.18$, 95% CI_{ES} = −0.20–0.56 ($M \pm SD$ = 0.91 ± 0.50). These results confirmed that the change in behavior of the groups following training cannot be explained by a change in any bias to favor a "foul" or "no foul" call.

DISCUSSION

The aim of this study was to determine whether perceptual training that removed superficial visual information would be effective for improving the decision-making performance of skilled football referees. When adjudicating ambiguous foul situations, referees must contend with the potentially deceptive actions of players who seek to fool them into awarding an unjustified foul. We hypothesized that blurred-footage training which removed superficial information would help referees to attune to the kinematic information associated with a genuine foul, leading to a significant improvement in decision-making performance. The results revealed that referees who performed a short period of training watching blurred footage experienced a significantly larger improvement in decision-making performance than referees who performed the same training without blur. The difference between the groups could not be explained on the basis of changes in response time or bias, but instead reflect a change in the sensitivity to genuine fouls. What is most remarkable is that the findings were uncovered in skilled referees, many of whom already perform at the highest level within their national competition. The findings suggest that the attunement to the putative kinematic information inherent within motor actions may hold promise as an effective means

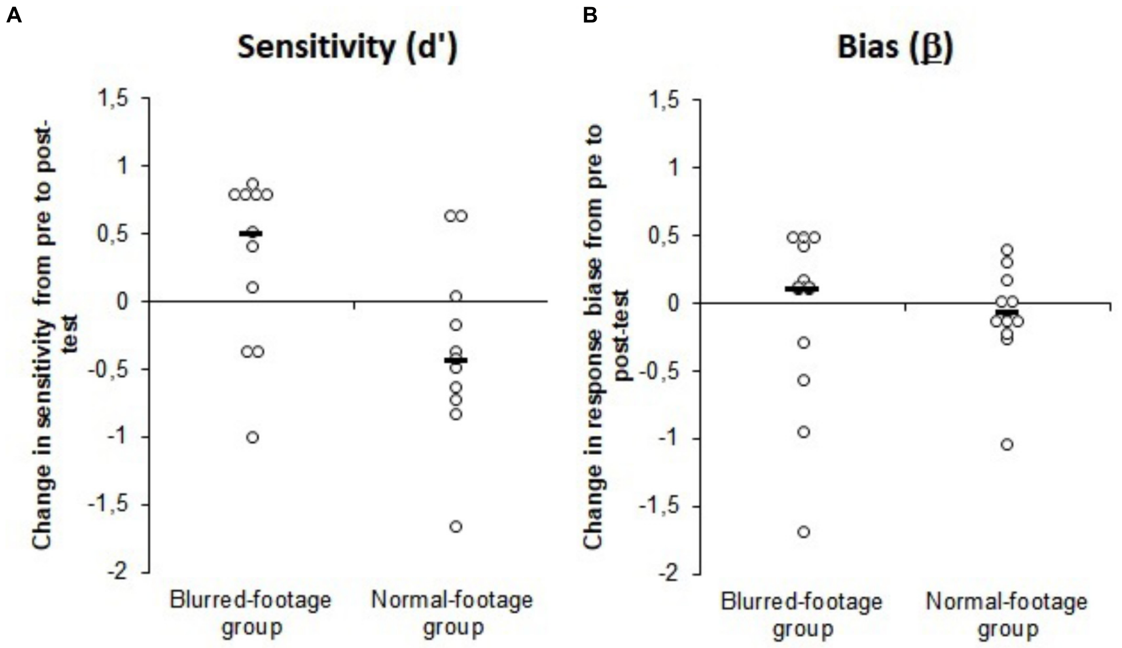

FIGURE 3 | Change in **(A)** sensitivity and **(B)** response bias from pre to post-test as a result of training for the blurred-footage and normal-footage training groups. The black bars represent the means.

of improving the quality of decision making of officials in sport.

The results of this study are consistent with previous work which shows that the discrimination of deceptive from non-deceptive actions can be enhanced via attunement to the kinematic information inherent in an action sequence (Ryu et al., 2018). Previously, the suggestion has been that deceptive intent when performing motor actions is conveyed largely via very detailed non-kinematic information such as facial expressions and gaze direction (Abernethy et al., 2010a,b). In the case of a "dive" in football, it has instead been suggested that deceptive intent is largely conveyed via alterations in kinematics such as those resulting in the "archers bow" (Williams et al., 2006; Morris and Lewis, 2010; Lopes et al., 2014). Given that, in the case of adjudicating fouls, there are kinematic differences that characterize dives from fouls, then it stood to reason that blurred perceptual training could help referees to become more sensitive to the underlying kinematics and thereby to use that information to distinguish dives from fouls. The exposure to genuine fouls during blurred training may have helped referees attune to the kinematic signature that specifies when a player is fouled, helping the referees to better identify deceptive kinematic information when a player attempted a dive.

The decision whether an action is a foul or not is a very complex one (Johnson, 2006), with success in the task relying heavily on the visual and/or motor experience of the referee (Renden et al., 2014). Evidence demonstrates that perceptual training designed to improve the quality and/or volume of visual experience can positively contribute to the decision making performance of a referee (Catteeuw et al., 2010; Schweizer et al., 2011; Pizzera and Raab, 2012b; Put et al., 2013, 2016a,b). Therefore, we had a reasonable expectation that both of our training groups would improve their decision-making performance from pre to post-test. Evidently though, this was not the case. Specifically, the performance of the control group tended to decrease from pre to post test. Although this change fell short of significance ($p = 0.10$ using a conservative one-tailed t-test, $d = 0.41$ $\beta = 0.237$), the finding does justify further scrutiny. Given the wealth of previous studies which show video-based perceptual training to be an effective means of improving performance (Abernethy et al., 2012; Ryu et al., 2012; Put et al., 2013), it seems unlikely that the control video-based training in our study genuinely decreased the decision-making performance of the referees. Moreover, the inclusion of a corresponding control (e.g., placebo) group would have been necessary to disambiguate this conclusion from any effects of fatigue or boredom. The control training group was incorporated in our study to control for effects of learning and/or fatigue when evaluating the performance of the blurred-footage group, and it could be that the decrease in performance from pre to post-test can be better explained on the basis of fatigue and/or boredom. Fatigue does seem unlikely though given that our skilled referees are accustomed to long periods of decision making under cognitive and physical duress (a match lasts 90 min vs. 45 min for our procedure). Boredom could represent a viable explanation for our findings, particularly if participants in the control group experienced *more* boredom than those in the blurred-footage training group. Future work should look to include manipulation checks for cognitive engagement and/or boredom and to compare that across the intervention groups. To address another possible explanation, we applied signal detection analysis to determine whether any change in the type of responses made by the control group could be explained by a bias to judge a foul or not. Results revealed that there was no bias from either of the groups to judge a foul or not, and no significant difference in the change in the bias from pre to post-test between the two groups. Instead, the changes in response accuracy from pre to post-test were reflected by a change in the sensitivity to genuine fouls. The slight (non-significant) reduction in the response accuracy of the control group may be best attributed at this stage to chance. Follow-up and replication studies should reveal whether the slight decrease in performance for the control group can be replicated or is best attributed to chance.

Given, though, the poor post-test performance of the control group, it is important to consider whether the blurred-footage training group did experience their own change in decision-making performance as a result of training. The results show a ≈4% increase in decision-making performance for the blurred-footage training group, even after only approximately 20 mins of training (from 75.9 to 79.9%). On the basis of the planned expectation that the blurred-footage training group would improve their performance following training, we conducted a one-tailed t-test to test the significance of the change, with the effect falling just short of significance (p = 0.07, β = 0.288), though with a moderate measure of effect size (d = 0.47). These results do provide some tentative support for the potential efficacy of blur training as a means of improving the decision-making performance of football referees, though clearly further work is required to verify the findings, especially in the translation to on field decision making. Nonetheless to translate our findings, referees have been shown to make an average of 137 decisions per match, with approximately 60 of those related to foul situations (Helsen and Bultynck, 2004). An improvement of 4% would therefore equate to approximately 2.4 more correct foul-decisions per match. Since free kicks and penalties account for approximately 47.6% of all set play goals (∼25% of all goals) (Mitrotasios and Armatas, 2014), an increase in correct foul-decisions could have a significant impact on the outcome of a match.

A relatively unique aspect of this study is that training was conducted using skilled rather than novice participants. Most studies of perceptual training recruit novice participants (for an exception, see Hopwood et al., 2011), presumably to provide easy access to participants and to maximize the chance of finding a learning effect. The skilled referees who we tested in our study already possessed a high level of expertise in decision making, and so we ran the risk of not finding a training effect due to ceiling levels of performance (evidently this wasn't a problem, with ≈75% pre-test response accuracy). Accordingly it is entirely possible that we have underestimated the size of any training effect when compared to most previous studies. Indeed the effect size we found for our blurred-footage training group (d = 0.47) is less than that found in comparable studies of perceptual training [d = 0.9–1.5; (Schweizer et al., 2011; Put et al., 2013; Ryu et al., 2018)], though those studies did typically test lesser-skilled rather than skilled participants and/or used longer periods of training.

It can of course be challenging to access a sufficient number of skilled participants for lengthy periods of time, and in this study we conducted the training over a period of time that was much shorter than that used in previous studies. The relatively brief access also meant that our participant numbers were limited (n = 11 per group); that we were not able to conduct a retention test of response accuracy as is customary in most training studies; and we did not conduct an on-field test of skill transfer. Clearly these improvements to the experimental design are desirable, and we hope that the relatively promising results found in this and other studies (e.g., Ryu et al., 2018) will lead to future work that addresses these shortcomings. In particular, future work should include a higher participant number to increase power and can look to establish what might be the optimal level of blur for training; the efficacy of longer training interventions ideally incorporating multiple training sessions; the retention of skill over a longer time-period; and the transfer of skill to check whether referees improve the quality of their on-field decision making (e.g., Put et al., 2013).

In the field of perceptual training in sport, there has been some general concern about the efficacy of training approaches which seek to train on-field skill using video-based stimuli (Starkes and Lindley, 1994; Dicks et al., 2015). In particular, there is concern that video-based training typically requires participants to produce verbal or button-press responses rather than producing genuine movement responses which replicate those that would typically be performed on-field (i.e., perception is decoupled from action). However, football refereeing represents a perceptual-cognitive task in which perception and action are largely decoupled, with referees required to make decisions which do not require a direct movement response. In this sense, video-based designs which decouple perception from action are more likely to be appropriate for testing and training referees than they might be for most athletes. In support, video-based training has previous been shown to improve the on-field performance of football referees (Put et al., 2013), providing confidence that video training is appropriate for our task.

CONCLUSION

The results of this study show that blurred-footage training which removes superficial visual information may hold promise as a means of improving the ability of sport officials to discriminate "fouls" from "dives" when deciding whether to award a foul in ambiguous foul situations. It appears that the blurred intervention may have helped to train even skilled referees to attune to the kinematic information which characterizes a foul situation. Given Put et al.'s (2013) finding that web-based perceptual training can improve skill and enhance on-field decision making, the findings offer a potentially innovative means of enhancing the gains possible via perceptual training in refereeing. Future work should seek to establish whether there is an optimal level of blur for training along with whether a training schedule exists that maximizes benefits as a result of training.

DATA AVAILABILITY STATEMENT

The de-identified data are available from the corresponding author.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the national Code of Ethics for Research in the Social and Behavioural Sciences, The Scientific and Ethical Review Board (VCWE). The protocol was approved by the Vrije Universiteit Amsterdam Faculty of Human Movement Sciences Ethics committee (approval number VCWE-2016-212). All subjects gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

TvB, JK, and DM contributed to the conception and design of the study. TvB, PR, JK, and DM designed the experiments. TvB performed the measurements, processed the experimental data and wrote the first draft of the manuscript. TvB and DM and performed the statistical analyses. DM was involved in supervising the work and wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Can Slow-Motion Footage of Forehand Strokes Be Used to Immediately Improve Anticipatory Judgments in Tennis?

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Slow-motion footage of sports actions is widely used as a visual learning tool in observing the dynamic motor behaviors of athletes. Recent studies on action observation have reported that extending the observation time in slow-motion footage provides benefits of understanding the intention of an opponent's action, at least when observing rapid movements. As such, the use of slow-motion footage may have the potential to improve the anticipatory judgments of an opponent's action outcome without training (or feedback). To verify this possibility, we examined the effects of the replay speed of slow-motion footage on the anticipatory judgments of shot directions and recognition of kinematic positions of opponents' forehand strokes in tennis. Nine skilled and nine novice tennis players were asked to anticipate the direction of their opponent's shots (left or right) and then attempted to recognize proximal (trunk center) and distal (ball) kinematic positions. Computer graphic animations of forehand strokes were used as visual stimuli, which were presented at four different replay speeds (normal, three-quarter, half, and quarter speeds). We failed to show the immediate effect of the use of slow-motion footage on the anticipatory performance of the skilled and novice players, although the anticipatory performance of the skilled players was superior to that of the novice players. Instead, we found an effect of the use of slow-motion footage in terms of promoting recognition of important kinematic cues (trunk center) for effective anticipation by skilled players. Moreover, no significant correlations were observed between the anticipatory judgments and motion recognition in all experimental conditions. These results suggest that even if the use of slow-motion footage enhances the recognition of key kinematic cues, it may not immediately improve anticipatory judgments in tennis.

Keywords: anticipation, motion recognition, computer graphics, expertise, sport

INTRODUCTION

Slow-motion footage of sports actions is widely used as a visual learning tool in observing complex and quick motor behaviors by athletes, such as a golfer's swing movement and a tennis player's forehand stroke (Williams et al., 2002; Wilson, 2008). Recent studies (Moriuchi et al., 2014; Moriuchi et al., 2017) on action observation have reported that extension of the observation time in slow-motion footage provides benefits of understanding the intention of an opponent's action, at least when observing rapid movements. Moriuchi et al. (2014) examined how speeds of observed actions affected the excitability of the primary motor cortex (M1). The size of motor-evoked potentials of the hand muscles was induced by transcranial magnetic stimulation (TMS) when participants observed a video footage of an individual catching a ball at three different replay speeds (normal, half, and quarter speeds). The results showed that the excitability of the M1 was higher when the observed action was at low-speed replays (half and quarter speeds) than at normal-speed replays. More recently, Moriuchi et al. (2017) reported that the same effects were confirmed only when viewing the low-speed replay video of rapid movements (i.e., catching a ball); such effects were not confirmed when viewing slow movements (i.e., reaching for and lifting a ball). The authors explained that the benefit of using slow-motion footage is likely to be obtained only for rapid movements, in which the components of observed actions would not be visible at normal speed. In other words, there seems to be no benefit in using slow-motion footage for slow movements, for which observers could recognize the components of actions even at normal speed. As such, the use of slow-motion footage should lead to the activation of the action observation network (AON), allowing understanding of an opponent's action intention (Rizzolatti et al., 2001) when applied to rapid movements.

The present study was designed to investigate whether the use of slow-motion footage of forehand strokes can immediately improve anticipatory judgments of shot directions and recognition of kinematic positions of opponents' forehand strokes in tennis. The ability to anticipate the direction of an opponent's forthcoming shots is important to return a shot successfully in racket sports, such as badminton and tennis. The forehand stroke in tennis is a rapid movement; therefore, the use of slow-motion footage should lead to the activation of the AON. Considering that skilled anticipatory judgments are underpinned by the detection of key kinematic cues from an opponent's movements (Jones and Miles, 1978; Shim et al., 2005; Abernethy and Zawi, 2007; Jackson and Mogan, 2007; Williams et al., 2009; Ida et al., 2011a,b; Fukuhara et al., 2017), the prolonged time afforded to detect key kinematic cues from an opponent's movements would lead to better anticipatory performance.

To date, no study has investigated the effects of the use of slow-motion footage on anticipatory judgments in racket sports. Moreover, two studies did not support the effectiveness of the use of slow-motion footage on anticipatory judgments in other types of rapid movements (Lorains et al., 2013; Uchida et al., 2014). Uchida et al. (2014) showed that in the anticipation task of free throw shot success in basketball, the anticipation accuracy of experienced players decreased when they viewed the slow-speed motion condition (half speed). The authors suggested that the reason for the decrement in anticipatory performance with the use of the slow-speed video was derived from the "mismatch" between the temporal information acquired through experience and the stimulus's temporal information (Barclay et al., 1978). Lorains et al. (2013) also found no improvement in a video-based decision-making task in Australian football under the slow-speed motion condition (three-quarter speed).

Herein, we examined the anticipatory judgments of shot directions and recognition of opponents' kinematic positions (errors between subjective evaluation findings and measured values) when skilled and novice tennis players viewed slow-motion footage of tennis forehand strokes at four different replay speeds (normal, three-quarter, half, and quarter speeds). Based on the findings of the two studies that did not support the effectiveness of the use of slow-motion footage (Lorains et al., 2013; Uchida et al., 2014), we speculated that the replay speed could affect the benefit of the use of slow-motion footage. Therefore, we adopted four replay speeds, two of which were the same as those in the studies of Uchida et al. (2014) and Lorains et al. (2013).

We also evaluated the recognition of kinematic positions using the visual analog scale (VAS). We speculated that the benefit of using slow-motion footage may come in part from the prolonged time available for detecting key kinematic cues from an opponent's movements. If this is the case, then the recognition of the opponent's kinematic position would also be improved when slow-speed footage is used. Therefore, we tested this possibility with this recognition performance.

We hypothesized that the correct responses and recognition errors in both skilled and novice players would be improved with the decline in replay speeds. Moreover, if enhancing the recognition of key kinematic cues improves anticipatory judgment, then it was hypothesized that there would be a strong correlation between both performances. We also hypothesized that skilled players would outperform their novice counterparts in anticipating shot directions based on the findings of previous studies regarding anticipation in tennis (Shim et al., 2005; Williams et al., 2009; Fukuhara et al., 2017).

MATERIALS AND METHODS

Participants

Nine skilled tennis players (M_{age} = 19.8 ± 1.5 years, 12.2 ± 2.2 years of tennis experience) and 9 novice counterparts (M_{age} = 22.2 ± 4.7 years) participated in this study. Skilled players were on a university tennis team that had played in national tournaments. Additionally, this team had won in all-Japan intercollegiate tournaments in 2016. Novices had played tennis at least once in physical education class but did not play regularly. The experimental protocol was approved by the institutional ethics committee of Tokyo Metropolitan University (authorization number H27–36). The tenets of the Declaration of Helsinki were followed. All participants gave written informed consent prior to participation. None of the participants had previous experience with the experimental task or procedure.

Visual Stimuli

We adopted computer graphic (CG) animations as visual stimuli to accurately evaluate recognition errors between the VAS scores and the original coordinate position output from motion capture data. We used CG animations of forehand shots to test the evaluation validity for anticipatory judgment of shot direction (Fukuhara et al., 2009; Fukuhara et al., 2017). First, forehand stroke shots by a professional tennis player (22 years old, 11 years of tennis experience, and ranked in the top 30 in Japan) were recorded on the tennis court using three-dimensional motion capture cameras (Hawk system, Motion Analysis Inc.). The motion capture system included eight cameras with a sampling rate of 200 Hz and tracked forty-one passive retro-reflective markers. The tennis player was filmed standing at the middle of the baseline on the court (i.e., center mark position) and was asked to hit the ball with maximum effort toward two square targets on the opposite side of the court. The two target areas (1.5 m × 1.5 m) were set on the left side of the court (i.e., inside-out stroke) and on the right side of the court (i.e., cross-court stroke). A total of 12 successful shots, 6 inside-out, and 6 cross-court strokes, were used for motion capture data in CG animations. The positions of 21 anatomical landmarks on the body and 5 locations on the racket and ball were tracked during each trial (see details in Fukuhara et al., 2017).

Second, a CG tennis avatar (e.g., Ida et al., 2012; Fukuhara et al., 2017) was constructed from the motion capture data using character animation software (MotionBuilder 2013, Autodesk Inc.). The character modeling and AVI exporting were conducted with 3DCG software (Maya 2013, Autodesk Inc.). Moreover, a black background image that is traditionally used in biological motion perception studies was included in the CG animations (Johansson, 1973). The viewpoint was matched to the viewing angle of a receiver positioned at the midpoint of the service line on the tennis court. A tennis net was also inserted into the CG animations as a perceptual judgment criterion for the recognition task of the kinematic position. Here, we set a center strap in the net as a criterion point in the display. Additionally, the net mesh was deleted to avoid using another judgment criterion.

Third, the CG animations were set to four replay speeds to investigate the perceptual effects of the use of slow-motion footage: normal speed and three slow-speed motion conditions (three-quarter, half, and quarter speeds); the criterion used was previously described in a study on action observation with TMS (Moriuchi et al., 2014) and two studies on sports (Lorains et al., 2013; Uchida et al., 2014). Moreover, the length of the CG animations was set to 1,800 ms from the ready position to one frame (30 ms) before the moment of racket and ball contact. This occlusion point was adopted to avoid learning effects through feedback information because the moment of racket and ball contact slightly includes ball flight information after contact (Jackson and Mogan, 2007; Fukuhara et al., 2009).The replay duration for each of the four clips was 1,800, 2,400, 3,600, and 7,200 ms. In total, we created 48 video clips for analysis: 12 shots × 4 types of replay speeds.

Procedure and Apparatus

Participants sat on a chair with their heads fixed on a chin support. The visual stimuli were presented on a 27-inch display monitor (GW2270HM-UN, BenQ, Taiwan; 1920 × 1080 resolution) connected to a laptop computer (ProBook450G2, HP, United States), and positioned at 0.5 m in front of participants. The vertical visual angle was approximately 20 degrees. Presentation software (E-prime 2.0, Psychological Software Tools Inc., United States) was used for visual stimuli and collection of participant responses.

Two perceptual judgment tasks are shown in **Figure 1**. We decided to conduct these separately in this experiment to prevent a dual task involving attention to both tasks at the same time. An anticipatory judgment task was performed as the first block, and the recognition task of kinematic position was then performed as the second block. A total session was approximately 60 min (i.e., 30-min anticipatory judgment task, 30-min recognition task) in duration.

Anticipatory Judgment Task

The participants were instructed to watch the visual stimulus presented and to anticipate the shot direction (left or right) (**Figure 1A**). We did not set a time constraint for responding but asked the participants to respond as soon as the stimulus was occluded by clicking the corresponding mouse buttons for the left and right targets. Prior to testing, the participants completed eight practice trials (four left and four right shot trials, which were randomly presented) to familiarize themselves with the task procedure. The practice trials included four different replay speeds. For the testing session, the participants completed 48 trials, and the stimuli were randomized.

Recognition Task of Kinematic Position

Participants were instructed to evaluate the kinematic positions of the trunk-center and ball in the CG avatar immediately after observing the presented visual stimuli (**Figure 1B**). The visual stimuli were the same as those in the anticipatory judgment task, and the evaluation of position was performed only in the transverse direction (parallel to the net). The recognition of kinematic position was rated on the VAS by moving a computer mouse pointer over a slider bar, from -50 (left, equivalent to -1.45 m in real scale) to + 50 (right, + 1.45 m) in reference to the center position, i.e., a center strap (VAS = 0 ± 0 m). Participants first evaluated the position of the trunk-center and then the position of the ball.

Prior to testing, the participants completed eight practice trials (four left and four right shot trials, which were randomly presented) to familiarize themselves with the task procedure. The practice trials also included four different replay speeds. For the testing session, the participants also completed 48 trials, and the stimuli were randomized.

Data Analysis

Correct Responses

The dependent variable was the percentage of correct responses for shot directions at each replay speed. All variables were

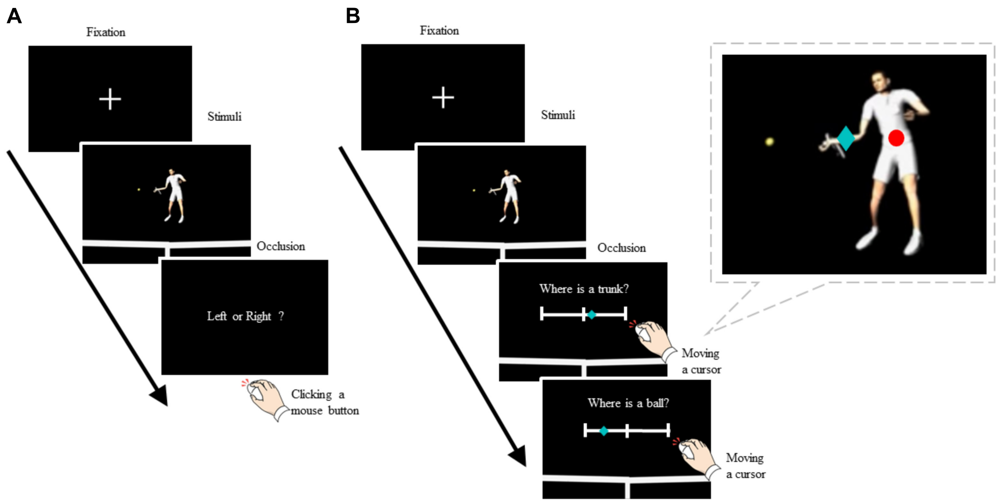

FIGURE 1 | Experimental Settings. **(A)** Anticipatory judgment task. Participants were asked to click a mouse button with the right index finger (left side) or a middle finger (right side) to indicate the anticipated direction of the ball. **(B)** Recognition task of kinematic position. Participants were asked to evaluate the kinematic positions of trunk-center and ball in the CG avatar by moving a cursor with an optical mouse on a visual analog scale (VAS) as a reference to the center position, i.e., a center strap (VAS = 0 ± 0 m). The recognition errors were computed as the absolute value of the distance between the VAS score evaluated by the participants (transformed into the coordinate position in real scale, green rhombus) and the original coordinate position output from the motion capture data (red circle). A score change of 1 in the VAS score was equivalent to 2.9 cm in a real scale.

converted to arcsine transformation to satisfy the normal distribution assumption. We evaluated data using a two-way factorial analysis of variance (ANOVA), with the two groups (skilled and novice) used as between-participants factors, and four replay speeds (normal-, three-quarters-, half-, and quarter-speed) as the within-participants factors. To investigate whether the percentage of correct responses exceeded a 50% guess level (chance level), one-sample *t*-tests were also performed to evaluate the percentage of correct responses in each experimental condition.

Recognition Errors

The dependent variable was the recognition error (cm) for two kinematic positions of the trunk-center and ball in the CG avatar at each replay speed. Fukuhara et al. (2017) examined kinematic cues for effective anticipation of shot directions by skilled tennis players using manipulation of graphical information richness in a CG avatar. Results suggested that skilled players used the movements of proximal (i.e., trunk, hips, and shoulders) and distal (i.e., racket-arm and ball) body parts to anticipate the direction of forthcoming shots, while novice players mainly focused on the movement of distal body parts (Ward et al., 2002; Huys et al., 2009; Williams et al., 2009). Based on these finding, we selected the trunk-center and ball as the evaluation items in a recognition task of kinematic position.

The VAS score ranging from -50 to +50 was equivalent to 2.90 m (from −1.45 m to +1.45 m) in the transverse direction; thus, a score change of 1 in the VAS was equivalent to a difference of 2.90 m/100 = 2.9 cm in real scale. The recognition errors were computed as the absolute value of the distance between the transformed VAS position and the original kinematic position obtained as the coordinate value of motion capture data (see **Figure 1B**). In each kinematic position (trunk-center and ball), two-way ANOVA was performed, with the 2 groups (skilled and novice) used as between-participants factors, and four replay speeds (normal-, three-quarters-, half-, and quarter-speed) as within-participants factors.

Correlation Between Correct Responses and Recognition Errors

Pearson's correlation coefficient was computed between correct responses and recognition errors for two kinematic positions (trunk-center and ball) for each of the four replay speeds (normal-, three-quarters-, half-, and quarter-speed) in two group (skilled and novice) to investigate whether recognition of kinematic position has an influence on anticipatory judgments.

Bonferroni's *post hoc* test for multiple comparisons was used for further analysis. Partial eta-squared (ηp^2) values provided a measure of effect size. In all analyses, the significance level was set at $\alpha = 0.05$.

RESULTS

Correct Responses

The mean percentages of correct responses for skilled and novice groups are shown in **Figure 2**. The correct responses in the skilled group were significantly over chance levels of 50% (all $p < 0.05$), while the novice group was also significantly superior to chance levels (all $p < 0.05$), with the exception of the half-speed condition ($p = 0.11$).

Two-way ANOVA revealed a significant main effect for group [$F(1,16) = 6.37$, $p < 0.05$, $\eta_p^2 = 0.29$]: skilled players ($M = 69.68\%$, $SD = 12.14$) showed more accurate performance than their novice

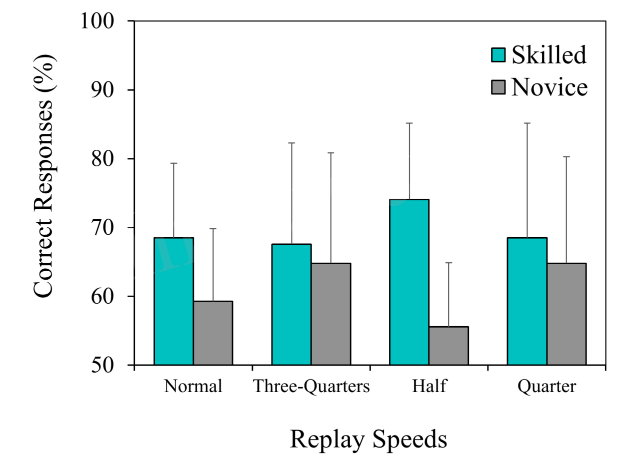

FIGURE 2 | The mean accuracy score (skilled and novice groups) for each of the four replay conditions, with the chance level set at 50%.

counterparts (M = 61.11%, SD = 13.21). However, the main effect for replay speeds [F (3,48) = 0.28, p = 0.84, η_p^2 = 0.02] and the group × replay speed interactions [F (3,48) = 1.42, p = 0.25, η_p^2 = 0.08] were not significant.

Recognition Errors

The mean percentages of recognition errors under each experimental condition for the skilled and novice groups are shown in **Figure 3**. A two-way ANOVA for the trunk-center condition (**Figure 3A**) identified a significant main effect for the replay speeds [F (3,48) = 3.41, $p < 0.05$, η_p^2 = 0.18], but *post-hoc* analyses indicated that there were no significant differences. The main effect of group was significant [F (1,16) = 4.02, $p < 0.05$, η_p^2 = 0.21]. *Post hoc* analysis indicated that recognition errors (16.85 cm) in the skilled group were smaller than those of their novice counterparts (26.43 cm) ($p < 0.05$). A group × speed interaction was significant [F (3,48) = 3.21, $p < 0.05$, η_p^2 = 0.17], indicating that the recognition errors of trunk-center in the skilled group for the quarter-speed condition were smaller than for all other speed conditions (all $p < 0.05$), while the novice group did not show any significant differences for replay speed. For the quarter-speed condition, skilled players were significantly more accurate than their novice counterparts ($p < 0.05$). On the other hand, a two-way ANOVA for the ball condition (**Figure 3B**) showed no significant main effect for group [F (1,16) = 0.02, p = 0.96, η_p^2 = 0.01] and replay speeds [F (3,48) = 0.55, p = 0.65, η_p^2 = 0.03]. There was no significant interaction for group × replay speeds (F (3, 48) = 0.57, p = 0.87, η_p^2 = 0.03).

Correlations Between Correct Responses and Recognition Errors

In all experimental conditions, no significant correlation was observed between the two dependent variables (see **Supplementary Table 1** in the **Supplementary Materials**).

DISCUSSION

The present study investigated the effects on anticipatory judgment of shot directions and recognition of opponents' kinematic positions (trunk center and ball) when skilled and novice tennis players viewed CG tennis shots at four different replay speeds (normal, quarter-half, half, and quarter speeds). We failed to show an immediate effect of the use of slow-motion footage on the anticipatory judgments of both the skilled and novice players. The correct responses in both skilled and novice players did not improve as the replay speeds decreased. In contrast to the results of the anticipatory judgments, we found reduced recognition errors regarding the trunk center position in the skilled players. The recognition errors in the trunk center position significantly improved in the slowest replay condition (quarter speed) compared with the other speed conditions. In the same condition, the skilled players more accurately recognized the trunk center position than their novice counterparts. Moreover, no significant correlation was observed between the anticipatory judgments and motion

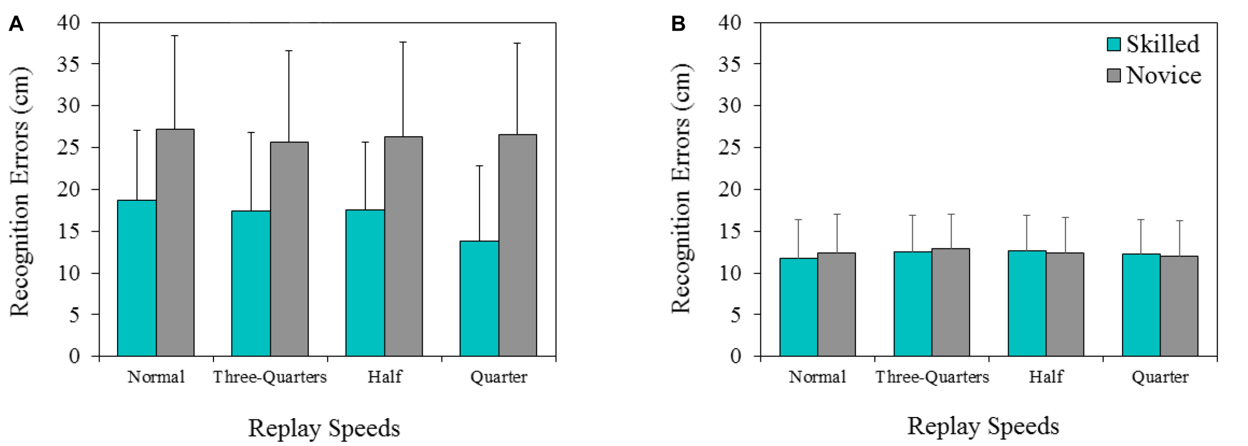

FIGURE 3 | The mean error score (skilled and novice groups) for two evaluation positions **(A)**: trunk-center and **(B)**: ball) for each of the four replay conditions.

recognition in all experimental conditions. These results showed that extension of the observation time with slow-motion footage provided an added benefit of immediately enhancing the motion recognition by skilled players but did not improve the participants' anticipatory judgments.

Before discussing the main finding regarding the immediate effects of using slow-motion footage, it is necessary to confirm whether our unique CG animations were valid in investigating anticipatory skills in tennis. The results showed that (i) the correct responses of both skilled and novice players were superior to chance levels of 50% (except for the novice players at the half-speed condition), and (ii) the anticipatory performance of the skilled players was superior to that of their novice counterparts. These results indicate that skilled players can pick up key kinematic cues from the CG avatar for effective anticipation when compared with their novice counterparts. These results are comparable with those of previous studies that used videos (Williams et al., 2002; Jackson and Mogan, 2007), point-light or stick figure displays (Ward et al., 2002; Huys et al., 2009; Williams et al., 2009), and CG animations (Fukuhara et al., 2009; Ida et al., 2012; Fukuhara et al., 2017). From these findings, we can safely say that our CG animations have sufficient quality for evaluating anticipatory skills in tennis.

The present findings did not support our hypothesis that the correct responses in both skilled and novice players would be improved with the decline in replay speeds, given that the forehand stroke in tennis is a rapid movement. This finding is inconsistent with previous findings, which showed that a slow-speed replay of observed actions (particularly rapid movements) enhanced the understanding of an opponent's action intention when compared with a normal-speed replay (Moriuchi et al., 2014; Moriuchi et al., 2017). Moriuchi et al. (2017) have reported that the M1 excitability was higher only when observing low-speed replay videos of rapid movements than when observing normal-speed replay videos; however, the effect was not confirmed when viewing slow movements. The authors explained that the discrepancy between the two movement tasks was attributed to whether participants were able to acquire new information on kinematic elements that cannot be observed at normal speed; if individuals can recognize the kinematic elements at normal speed, the benefit of using slow-motion footage is not evident. In the present study, the one-sample *t*-test showed that both skilled and novice players were able to pick up kinematic cues from the CG avatar for anticipation of shot directions even under the normal-speed condition. Based on these findings, the failure to show the benefit of using slow-motion footage in the present study can be explained by the participants' ability to recognize their opponents' forehand stroke at normal speed.

The present findings are consistent with those of a previous study, which showed that there were no improvements in a video-based decision-making task in Australian football under the slow-speed condition (Lorains et al., 2013). Lorains et al. (2013) have clarified that the decision-making of elite footballers was more accurate in the fast-speed video (1.5-times faster speed) than in the normal- and slow- (0.75 times) speed videos. The authors suggested that the time pressure in the speeded video may allow elite footballers to perform more automatic processing required in an actual game situation. Considering this, skilled anticipation may not be sufficiently aided by the use of slow-motion footage without severe time constraints (i.e., time pressure).

In contrast to the findings of the anticipatory judgments, the present findings partially supported our hypothesis that the recognition errors in both skilled and novice players would be improved with the decline in replay speeds. We found that slow-motion footage has a perceptual feature that immediately enhances the motion recognition of the trunk position by skilled players. Previous studies on tennis (Huys et al., 2009; Williams et al., 2009) have reported that skilled tennis players used the movements of the proximal (i.e., trunk, hips, and shoulders) and distal (i.e., racket-arm and ball) body parts of an opponent to anticipate shot directions, whereas novice players mainly focused on distal body information. More recently, Fukuhara et al. (2017) have suggested that the role of using proximal body information among skilled players may be to anticipate subsequent movements of distal body parts. Such visual attention was also reported in another study (Piras et al., 2015) that investigated microsaccades when elite table tennis players anticipated shot directions. Moreover, in the present study, the recognition errors by the novice players were not significantly different among the four replay conditions; this indicated that the use of slow-motion footage did not provide an added benefit of immediately enhancing the recognition of the opponents' kinematic position among the novice players. Considering these findings, the skilled players, but not the novice players, may have qualitatively developed a specific motion recognition ability to recognize the movements of proximal body parts accurately.

Contrary to our expectation, there were no correlations between the anticipatory judgments and recognition of kinematic positions in all experimental conditions. The enhancement of position recognition induced with the use of slow-motion footage had no influence on the anticipatory judgment. This finding indicates that even if recognition of a specific kinematic feature (i.e., position or orientation of the trunk) is facilitated by the use of slow-motion footage, such information pick-up might not be effective for successful anticipation.

This study has some limitations. First, we investigated and classified nine elite college tennis players (members of the champion teams of Japan intercollege tournaments in 2016) into the skilled group; there were nine players in each of the skilled and novice groups. However, the number of participants was relatively smaller than those in previous studies on racket sports (Lorains et al., 2013; Schweizer and Furley, 2016). Thus, it is necessary to examine this issue further using larger sample sizes.

Second, the present study aimed to conduct the anticipatory judgment task and the recognition task separately. This may be one reason why there were no significant correlations between the anticipatory judgments and the recognition of kinematic positions. The reason for separating the two tasks was to prevent a dual task involving paying attention to both tasks at the same time. However, by separating both tasks, we might not directly evaluate the recognition of the kinematic positions during anticipation of the shot directions. Future studies are needed to investigate whether there is a relationship between the two dependent values when the tasks are performed simultaneously.

Third, the research method regarding the recognition task of kinematic positions may have affected our results. The participants evaluated the two kinematic positions (trunk center and ball) only on the horizontal axis of the display. However, some anticipation studies on tennis have reported that skilled tennis players used not only the movements of the trunk but also those of other proximal body parts (e.g., shoulders, hips, and legs) for anticipating shot directions (Huys et al., 2009; Williams et al., 2009). Considering this, the results of the present study might reflect only a part of the motion recognition ability of skilled players. In future studies, it is necessary to use a novel evaluation method that can assess high-resolution spatial information, such as touch panel computer (two-dimensional space) or virtual reality environment (three-dimensional space). If such evaluation methods are established, we would be able to investigate the degree to which skilled players accurately recognize the entire body movements of an opponent in detail.

CONCLUSION

The aim of the present study was to clarify whether the use of slow-motion footage of forehand strokes can immediately improve anticipatory judgments of shot directions and recognition of kinematic positions in tennis. We failed to show the immediate effects of the use of slow-motion footage on the anticipatory judgments of the skilled and novice players. Instead, we found that slow-motion footage has a perceptual feature that immediately enhances the fine-tuning of recognition of the trunk position by skilled players. Moreover, no significant correlation was observed between the anticipatory judgments and motion recognition in all experimental conditions. From these results, we concluded that even if the recognition of opponents' kinematic cues is facilitated by the use of slow-motion footage, such information pick-up might not be effective for immediately improving the anticipatory judgments in tennis.

AUTHOR CONTRIBUTIONS

KF and TM designed and conducted an experiments. KF wrote the manuscript. TO, BS, and MI helped planning our experimental paradigm. TH and HI supervised this study.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.01830/full#supplementary-material

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Exploring the Effectiveness of Immersive Video for Training Decision-Making Capability in Elite, Youth Basketball Players

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Decision-making is an essential capability for success in team sport athletes. Good decision-making is underpinned by perceptual-cognitive skills that allow athletes to assess the environment and choose the correct choice from a number of alternatives. Previous research has demonstrated that decision-making can be trained "off-line" by exposing athletes to gameplay scenarios and having them make decisions based on the information presented to them. These scenarios are typically presented on television monitors or using life-size projections but recent advances in immersive video capabilities provide opportunities to improve the fidelity of training by presenting a realistic, 360° view of the competition environment. The purpose of this study was to assess the effectiveness of immersive video training and whether training would improve decision-making performance in elite, youth basketball players (male and female). A training group completed 10 or 12 immersive video (360° video presented in a head-mounted display) training sessions in which they viewed and responded to gameplay scenarios across 3-weeks while the control group only participated in their usual training routine. Performance was assessed on an immersive video test and during small-sided games (SSG). The male training group had a large, non-significant improvement on immersive test score (+4.0 points) and in the SSG (+5.8 points) compared to the male control group (+0.3 points and +1.0 points, respectively). While both the female control group (+9.7 points) and training group (7.4 points) had large improvements in the immersive training test, only the female control improved their performance in the SSG (+6.9 points). Despite the mixed findings, there may be benefit for using immersive video for training decision-making skill in team sports. The implications of these findings (e.g., gender of the actors used to create stimuli, variety of scenarios presented) and the limitations of the experiment are discussed.

Keywords: skill acquisition, expertise, decision-making, perceptual-cognitive training, immersive video, team sports, basketball

INTRODUCTION

Good decision-makers are highly sought after in team sports yet a precise characterization of what makes a good decision-maker in a particular sport is rather elusive. Decision-making is defined as the process of choosing one option from a group of alternatives (Bar-Eli et al., 2011) and effective decision-making can be the difference between success and failure in team sports. In the expertise literature it is well established that elite decision-makers, while often indistinguishable from other performers on physical attributes, possess superior perceptual cognitive skills compared to their near-elite and novice counterparts (Mann et al., 2007). Elite decision-makers have better pattern recognition and recall skills (Gorman et al., 2012), anticipation (Müller and Abernethy, 2012), different visual search strategies (Klostermann et al., 2018), and knowledge structures (Sutton and McIlwain, 2015) which underpin their superior decision-making capabilities. Given that these perceptual cognitive skills discriminate between elite, near-elite, and novice performers it could be assumed that these skills can be trained and this training would then transfer into improved on-field performance (Abernethy and Wood, 2001). The purpose of this experiment was to explore whether new technology that allows for the capture of immersive video could be used to train decision-making in elite, youth basketball players.

Decision-making in sport has typically been assessed and trained using simulations of sport-related scenarios presented to participants using television/computer monitors (e.g., Lorains et al., 2013) or through projection of life-size images (e.g., Bruce et al., 2012). While the size of the image has no influence on the decision making performance of athletes (Spittle et al., 2010), these studies have consistently shown differences in decision-making skill between experts and novices in sports such as: netball (Bruce et al., 2012), baseball (Paull and Glencross, 1997), soccer (Vaeyens et al., 2007), and basketball (Ryu et al., 2013). More importantly, there is growing evidence that perceptual-cognitive training can be used to improve the performance of athletes in competition (Williams et al., 2003; Gabbett et al., 2007). In basketball, the effects of perceptual-cognitive training for improving decision-making have been equivocal. Starkes and Lindley (1994) showed that perceptual-cognitive training could be used to improve response time and accuracy in youth, elite basketball players. While they didn't find any transfer of training to on-court performance, it could be argued that the transfer test used – having players view live game scenarios from the stands – did not faithfully recreate the demands of a basketball game. More recently, Gorman and Farrow (2009) found no benefits for perceptual-cognitive training or transfer of training in skilled basketball players although there was a trend for players who underwent training to improve their performance on the video-based test.

Despite the lack of evidence to support the efficacy of perceptual-cognitive training in basketball, this mode of training can be an effective means of improving athlete performance across a range of skills (Larkin et al., 2015). According to the Modified Perceptual Training Framework (MPTF; Hadlow et al., 2018), the efficacy of any perceptual training tool can be assessed by examining the targeted perceptual function (e.g., basic ocular function vs. decision-making), how closely the stimuli resembles and behaves like stimuli from the competition environment, and whether the response required mimics the demands placed on performers in the competition. The emergence of technology that improves the fidelity of the simulations being presented to athletes offers promising opportunities for the development of future training approaches (Craig, 2013). For example, advances in virtual reality (VR) have already demonstrated the added benefit of having athletes perform in an interactive, virtual environment compared to video images (Vignais et al., 2015). Because this type of training targets high-order processes, presents sport-specific stimuli, and requires sport-specific responses, the MPTF would predict benefits from training would transfer to on-field performance. A recent study by Gray (2017) highlighted the benefit of VR training in baseball; players who underwent an adaptive virtual training program improved their performance on a batting test and in competition.

While VR training is certainly a promising avenue for improving sports performance, it is currently not practical for many sports teams. Hardware to support VR training (e.g., Oculus Rift, HTC Vive) is more affordable but the specialist software to support training programs (i.e., sport-specific scenarios that the performer interacts with) requires resources (i.e., programming and development) that may be beyond the means of many organizations. A possible solution could be the use of immersive video that maintains some of the benefits of VR but is not as resource intensive. Commercially available 360° video cameras and head-mounted displays (e.g., Google Cardboard, Samsung Gear VR) now permit the relatively easy creation of immersive video content. For example, a 360° camera could be used to capture sport-specific scenarios from a first-person perspective and these could be played back on the mobile phone of the athlete. The MPTF would predict that this type of training would produce better transfer than viewing scenarios on a monitor/projector screen because of the increased response correspondence. Rather than viewing from a static point-of-view, the performer now has the ability to control the viewing orientation. Given that the head is an important component of the gaze control system (along with the eyes and body; Vickers, 2007) this additional level of interaction may improve performance outcomes over traditional training approaches which only permit a single perspective.

Opportunities to create more realistic and interactive perceptual-cognitive training environments are becoming increasingly accessible with the development of technology. While previous research using video monitors has been shown to be effective for improving performance, little is known about whether emerging technology is as effective. The purpose of this study was to explore whether immersive video could be used to improve the decision-making performance of elite, youth basketball players and whether training using immersive video would transfer to improved passing performance in small-sided games. We hypothesized that players who underwent immersive video training would improve their test scores and performance in small-sided games relative to a control who participated in regular training only.

MATERIALS AND METHODS

Participants

Twenty ($n = 20$; 10 male, 10 female, age: 17.0 ± 0.6 years) elite, youth basketball players (positions: 6 guards, 6 wings, 8 bigs) volunteered to participate in the experiment. All players were members of the National Under-19 Basketball Australia Centre of Excellence basketball program at the time of testing and had represented their country at an international competition. One participant was unable to participate in the experiment due to an injury and another was unable to complete any of the testing due to motion sickness induced by wearing the head-mounted display (the participant indicated a history of hyper-susceptibility to motion sickness). This left the final number of participants at 18 (9 female, 9 male). Due to coaches requests for players to complete the training the final group composition was 11 training (5 males, 6 females) and 7 control (3 female, 4 male). This study was carried out with the recommendations of the National Health and Medical Research Council's Statement on Human Experimentation and Supplementary Notes, NHMRC Australian Health Ethics Committee. The protocol was approved by the Australian Institute of Sport Ethics Committee. All participants or their guardians gave written informed consent in accordance with the Declaration of Helsinki.

Apparatus

Immersive Video Capture

Immersive videos for testing and training were created by filming basketball game play scenarios using a 360° video recording system on the court. The recording system consisted of six action cameras (GoPro Hero 4 Black, GoPro, Inc.) mounted on a camera rig (Freedom 360 Classic Mount; Freedom360, LLC) that had each camera facing a different direction. The camera rig was attached to a microphone boom stand (Manfrotto 420B Combi Boom Stand, Manfrotto) and mounted on a dolly (Manfrotto 127 Portable Dolly, Manfrotto). This allowed for the camera to be held just over the player's heads while the scenarios were being filmed and to move with them. The perspective captured in the videos was from a first-person viewpoint; if the participant looked down in the video they could see the player in control of the ball. During testing and training, however, looking down would prevent the participant from viewing the unfolding scenario in front of them and none of the participants adopted this strategy during testing. Prior to filming all of the cameras were set to record and an audio cue (a clap captured on all six cameras) was used for later synchronization.

Scenario Filming

Filming was done during a 3-h session on a regulation basketball court (with shot clock) in a stadium setting. Ten players from the men's basketball team (two were participants in the study, however, filming occurred 3 months prior to testing and performance on the test was at or below the group average which suggests that there was a significant wash-out period between filming and testing) were used as actors in the filming session. They were dressed in their game uniforms and half the players wore the home uniform (yellow) and the other half wore the away uniform (green). Prior to filming players were informed about the goals of the session and given the opportunity to practice how each scenario would proceed. The scenarios were created by one of the co-authors (MK; who was an assistant coach with the men's program) and agreed upon by two other members of the coaching staff). A total 56 scenarios were created for filming and these included variations of 6 different base formations that were used by the team. Each scenario was designed to include ball movement prior to a designated decision-maker receiving the ball and a clear option for a pass (i.e., there was an open teammate). We included a pre-defined option to ensure that players involved in the filming had a clear goal. To avoid making scenarios too position-specific, a wide variety of scenarios for post players and guards, as well as generic passing decisions that could occur across multiple positions were included. Prior to filming each scenario both teams were told what the desired outcome was and how they were to respond to the ball movement. They were then given the opportunity to simulate the play once before filming commenced. For filming the players were told to play at full speed as though they were in a competitive game. A camera operator moved the camera based on the designated decision-maker's movements and a "spotter" viewed the entire sequence to ensure that the camera was over the players head while filming. If there were errors in ball movement or the camera operator could not keep the camera over the designated decision-maker's head during filming, the scenario was repeated. At least two good takes (as noted by the spotter) were captured for each scenario.

Immersive Video Creation

Video footage from the six action cameras was synchronized in software (PluralEyes 4.1, Red Giant, LLC) and exported into a video stitching program (Autopano Video, Kolor). The software stitched the videos together and created a single 360° video that could be played back in a head-mounted display. Once the videos were created they were inspected for quality to ensure that the camera remained over the designated decision maker's head to create a first-person perspective and that the correct decision was made. One of the coaches also viewed the clips to ensure they accurately captured the required movements for a given scenario. A total of fifty-six unique immersive video clips were created for inclusion into the study for testing and training (see **Figure 1B** for an example).

Testing Apparatus

A selection of fifteen clips was selected to be used exclusively in testing sessions (i.e., they were not presented during the training intervention). A minimum of two clips from each of the six broad categories of scenarios was included. For the testing sessions, video clips were presented through a tethered head-mounted display (HMD; Oculus Rift SDK, Oculus). This allowed the researchers to monitor through an attached display and record the responses of the participants (see **Figure 1A**). The HMD was connected to a computer (Mac Pro, Apple, Inc.) running the immersive video clips through a 360° video player (Kolor Eyes, Kolor). While wearing the HMD, the orientation of the video presented would change in response to head rotations of the player but did not respond to the movements (i.e., translations)

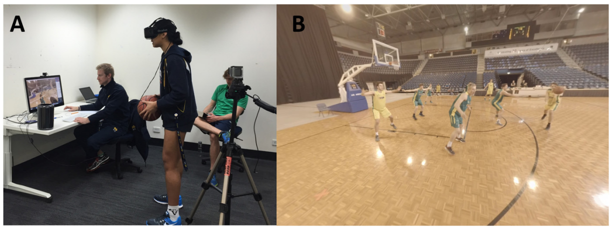

FIGURE 1 | Example of the testing apparatus **(A)** and the players view in the HMD **(B)**.

of the player's body otherwise (i.e., moving the head would cause the scene to rotate but any other actions had no effect). A video camera (GoPro Hero 4 Black, GoPro) was positioned to capture the actions and audio from the player wearing the headset and the orientation of the video presented on the computer screen.

Training Apparatus

Immersive video clips not used in the testing session (41 clips) were used for the training intervention. For the training sessions players viewed 360° video footage via a mobile HMD (Samsung Gear VR, Samsung) presented on a mobile phone (Samsung S6). To ensure consistency between the testing display and the training display, the videos were presented at the same resolution. While this prevented data collection during training (i.e., during testing sessions the only difference was that the researchers could view the player's head orientation) it allowed sessions to be conducted at the basketball court prior to normal practices. The footage was presented using a custom designed video player. The video player used a text script that contained the name of the clip, the start time of the clip, the decision time (i.e., when the decision-maker passed the ball), and the end time. Using this information, the video player would present the video at the designated start time. The participant could then orient themselves to the information available within the scenario and then press a button on the side of the HMD to start the video. The video would play until the point of the decision when the video would pause and the participant would be asked to make a decision. Then they would press the button on the side of HMD again at which point the next scenario would be presented (note: in the training sessions, the videos ended at the point of decision and no additional information or feedback was provided).

Small-Sided Games (SSG)

To determine whether transfer of training occurred, SSG were used to assess player's on-court performance. For the SSG, players were split into two teams of four players each (4 vs. 4) and competed on half a basketball court. The structure of the games was two 5-min halves and otherwise played according to the official FIBA 3 vs. 3 game rules[1]. SSG were video recorded and the footage was analyzed using SportsCode Elite (Hudl). On every occasion that a player had possession their performance was assessed against the categories shown in **Table 1**. Each category was weighted according to its value toward a positive outcome (e.g., scoring a basket) or negative outcome (e.g., contested shot). Player performance was coded and the points from each category added together to give a total score after each SSG for each player. This method was used by the team to assess player performance during games and allowed for easier comparisons to other performances.

TABLE 1 | Decision-making categories for assessing performance during the SSG.

Category	Description	Points
Successful pass	A pass that arrives at the intended teammate	1
Hockey assist	A pass that leads to an assist (e.g., the next pass results in an assist) or causes defensive perturbations. A pass from the inside out (kickout passes), an extra pass to an open player or a pass into an inside player are examples of hockey assists.	2
Assist	A pass that directly leads to the team mate scoring	3
Open shot	The decision to recognize the opponent is more than 2 m away and one is in a position to score	3
Contested shot	The decision to shoot despite an opponent being close	−1
Deflected pass/bobble	A pass that is deflected or is not delivered accurately to a team mate	−1
Passing turnover	A pass that is stolen by the opposition or thrown out of bounds	−2
Dribble turnover	When the opponent gains possession while the attacker is trying to dribble the ball	−2

Procedures

After providing informed consent in the week prior to undergoing the testing and training intervention, participant's on-court performance was assessed in two SSG conducted 48–72 h apart. In the following week, all participants completed an immersive pre-test session in the laboratory. The laboratory was an open space with a computer desk and video camera that permitted movement within the length of the tether to the HMD (4 m). For testing, the procedures and task were explained to the participant and then they were fitted with the HMD. The instructions for the participant were to: imagine they were in the shoes of the player in the clip, view the scenario as it played out on the footage, and make any decision (e.g., shoot, pass, dribble, etc.) that they liked when the ball came to them. If the clip stopped, then they were to make a decision as quickly as possible. After the instructions, they were then presented with five practice clips (selected from the training footage) to familiarize themselves with the procedure. Each scenario started with the clip paused and the participant was instructed to look around to orient themselves to the location of the other players and the ball. When they felt they were ready, they were asked to say "go" and one of the researchers started the video. Participants were asked to verbalize their decision as soon as they could and were given a ball to simulate their decision (e.g., if they decided to pass they would act

[1]http://www.fiba.basketball/3x3/rules

as if they were intending to pass the ball in a particular direction – although the ball was not actually passed – if they decided to shoot they would mimic a shooting action). Once the practice clips were completed, participants were asked if they had any questions regarding the procedure and the instructions were provided again for reinforcement prior to presentation of the test videos. The test itself consisted of 15 unique clips presented in a randomized order for each participant. During the test participants were prompted with instructions if they were indecisive or failed to act out their decision. The test took 15 min to complete.

The training intervention started the week after the initial testing session. For the training intervention, participants were assigned to either the control group or training group. Both groups took part in their normal practice routine but the control group only participated in the SSG and testing sessions. In addition to this, the intervention group viewed 15 randomly selected immersive videos prior to their regular training through a HMD. Training was conducted on-court and the task and instructions were identical to that of the testing session. Each training session took 5 min to complete and was supervised by one of the researchers to ensure compliance with instructions. Due to scheduling constraints the female participants completed 10 training sessions over 3 weeks while the male participants completed 12 training sessions (number of sessions completed was used as a covariate in the analysis). The week after training completed, all participants completed an immersive test using the same videos as in the pre-test and competed in 1 or 2 SSG (due to injury issues and competition schedules the female participants only completed a single SSG). At the completion of the study, participants in the training group were also given a short survey that allowed them to provide feedback on the immersive videos and the training intervention.

Dependent Variables

Immersive Test Performance

Player decisions were scored based on criteria established in consultation with three coaches from the Basketball Australia Centre of Excellence program. Coaches viewed the clips as many times as they liked and ranked their top 3 decisions (coaches were told they could choose any basketball-related decision and they were not limited to making passing decisions); each decision was then given a score between 1 and 3 with 3 being their preferred decision (Lorains et al., 2014). Despite designing the clips so there was a free player in each scenario (in accordance with the definition of decision making presented in the introduction), the open player was not always judged to be the best option by the coaches (as was expected). To account for this inconsistency, we summed the ranking between coaches to weight decisions where there was higher levels of agreement. For example, if all three coaches chose the same decision as their first preference it would be worth 9-points in the test and if one coached ranked a decision first and the other two ranked it third it would be worth 5-points in the test. Using this weighted system of scoring, a wide number of potential decisions were identified and the maximum score any player could get on the immersive test was 109-points.

SSG Performance

A total score was determined by tallying individual player results from each of the categories shown in **Table 1** (i.e., the cumulative total of all the player's decisions were tallied to provide a total score that could be positive or negative). Individual categories were also compared prior to and after the intervention.

Analysis

Immersive test results and SSG performance variables (total score, eight individual categories) were analyzed separately using linear mixed modeling. In the model, the group (training, control), test (pre, post), and gender (male, female) were used as fixed factors, test was a repeated measure, number of training sessions and participant were used as random factors. The fit of the model was adjusted by inclusion of random intercepts and slopes and changing the variance structure. Goodness of fit between models was compared using the Akaike Information Criterion. Due to the exploratory nature of the study we performed *post hoc* tests for significant and non-significant effects using a Bonferroni correction and Cohen's d was used to determine effect sizes (0.2 = small, 0.5 = medium, 0.8 = large). The data for total score ($w = 0.967$, $p = 0.351$) and SSG ($w = 0.988$, $p = 0.850$) were normally distributed).

RESULTS

Immersive Test

The three-way interaction of group x test x gender was not significant (p = 0.275). Performance on the test is shown in **Figure 2A** and **Table 2**. For females, both the control ($p = 0.007$, $d = 2.71$) and training ($p = 0.004$, $d = 1.79$) groups had large, significant improvements. For males, the control group did not improve ($p = 0.929$, $d = 0.06$) while the training group had a large but non-significant improvement ($p = 0.127$, $d = 0.80$).

Small-Sided Games

For total SSG score, the three-way interaction of group x test x gender was significant ($p = 0.032$). Performance in the SSG for each group and gender is shown in **Figure 2B** and **Table 2**. Follow-up tests did not reveal any significant differences. For females in the control group there was a large, non-significant improvement ($p = 0.262$, $d = 1.31$) in performance from the pre-test to the post-test while the female training group did not change ($p = 0.855$, $d = 0.06$). For males, there was no change in performance for the control group ($p = 0.528$, $d = 0.14$) while the training group had a medium-to-large, non-significant improvement in performance ($p = 0.080$, $d = 0.74$).

Individual variables from the SSG were compared and the results are shown in **Table 2**. For number of successful passes ($p = 0.274$), assists ($p = 0.987$), hockey assists ($p = 0.910$), contested shots ($p = 0.713$), deflected passes ($p = 0.371$), passing turnovers ($p = 0.635$), and dribbling turnovers ($p = 0.056$) there was no significant interaction of group x test x gender. For open shots, the three-way interaction was significant ($p = 0.003$). While *post hoc* tests did not reveal any significant differences, the female

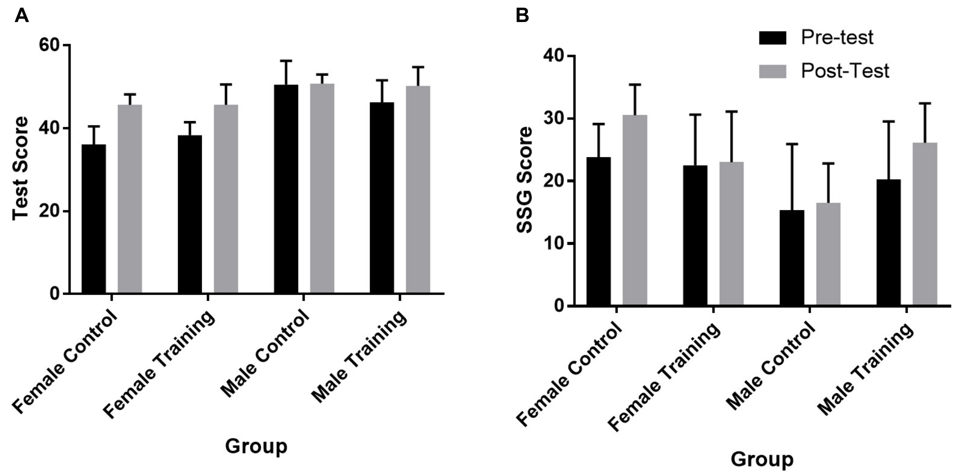

FIGURE 2 | Comparison of pre-test and post-test scores for male and female control and training groups in the immersive video test **(A)** and in the small-sided games **(B)**. (Note: Errors bars represent SD).

control group ($d = 1.36$) and male training group ($d = 0.85$) both had large increases in the number of open shots taken.

DISCUSSION

Sports teams are always looking for a competitive advantage and, in team sports, improved decision-making is viewed as an asset for athletes. In this study we sought to determine whether immersive video training could be effective for improving decision-making performance in elite, youth basketball players. Although we predicted that the training groups would show improvements in test and small-sided game performance, the results from our study were equivocal. When athletes were assessed on their decision-making performance, there were no differences in performance between the pre-test and post-test. Given the exploratory nature of the study and the fact that this was an applied study (i.e., coaches were interested in within-group changes), we analyzed the group differences and found that both the female control and training group and male training group had large improvements in decision-making performance on the immersive test (although the males improvement was non-significant). More importantly, we found a medium-to-large, non-significant improvement in overall performance during a SSG for the male training group and, rather unexpectedly, in the female control group – although there were limitations to the design which will be discussed later. Overall, there were some issues that may have affected the results but there was no detriments in performance as a result of using immersive video and, given the potential value of training observed, we would recommend using immersive video as a perceptual training tool although additional research is necessary to better understand how it compares to other training modalities.

One of the most striking findings is how differently males and females responded to the testing and training. While the male training group's results were generally in line with expectations, the response of the female control was unexpected. Because the male control group did not show the same pattern of change as the female control group this could rule out test familiarity as a confounding factor. The simplest explanation may be that the training did not benefit females. There were, however, other design issues that may have influenced the results. First, there were only three participants in the female control group (vs. six in the training group) which limits the amount of data available for comparison. Second, the females only completed one SSG for the post-test which increases the likelihood that their performance during the SSG would be influenced by performance variables that may have temporally inflated their scores (Magill and Anderson, 2017). Third, the amount of training differed between groups; although the dose-response relationship is not well understood in perceptual-cognitive training (Larkin et al., 2015), it is possible, but not likely, that the two extra training sessions would have benefitted the male training group (although this doesn't account for the improvements in the female control group). The content of the stimuli may have impacted the results as well. The footage used for testing and training was created using scenarios from the male's team playbook and using male participants. Research into observational learning, based on social cognitive theory (Bandura, 1989), suggests that the similarity of a model to the participant (e.g., gender) can influence self-efficacy (George et al., 1992; Weeks et al., 2005) and motor performance (Meaney et al., 2005). Although this study did not assess observational learning, it is possible that using male actors in the stimuli may not have promoted the same level engagement and learning in female participants and future research may benefit from using actors of the same gender.

Feedback from the athletes was overwhelmingly positive. All of the athletes felt that the training was beneficial for improving their performance on-court with several commenting that the training "helped with court vision and being able to see options on offense" and "noticing where defenders were moving." When asked about what they enjoyed about the training approximately half of the athletes commented on the realism of

TABLE 2 | Pre-test and post-test scores (mean ± SD) for the immersive test, total SSG score, and each individual variable from the SSG with a comparison of values (*p*-value) and effect size (d).

Variable	Gender	Group	Pre-test	Post-test	*P*-value	Effect size (d)
Immersive test score	Female	Control	36.0 ± 4.4	45.7 ± 2.5	0.007	2.71
		Training	38.3 ± 3.1	45.7 ± 4.9	0.004	1.79
	Male	Control	50.5 ± 5.8	50.8 ± 2.2	0.929	0.06
		Training	46.2 ± 5.4	50.2 ± 4.5	0.127	0.80
Total SSG score	Female	Control	23.8 ± 5.3	30.5 ± 4.9	0.262	1.31
		Training	22.5 ± 8.1	23.0 ± 8.1	0.855	0.06
	Male	Control	15.3 ± 10.6	16.5 ± 6.3	0.528	0.14
		Training	20.2 ± 9.3	26.1 ± 6.3	0.080	0.74
Successful pass	Female	Control	8.8 ± 4.1	6.0 ± 0.0	0.320	0.97
		Training	8.9 ± 4.6	9.3 ± 2.7	0.642	0.11
	Male	Control	4.7 ± 2.1	6.3 ± 3.3	0.173	0.58
		Training	4.1 ± 2.9	6.1 ± 5.9	0.218	0.43
Assist	Female	Control	1.8 ± 1.3	2.0 ± 1.4	0.858	0.15
		Training	1.8 ± 1.4	1.7 ± 1.6	0.862	0.07
	Male	Control	1.3 ± 1.4	2.1 ± 1.2	0.415	0.61
		Training	1.7 ± 1.6	1.5 ± 1.4	0.632	0.13
Hockey assist	Female	Control	1.7 ± 1.4	1.5 ± 0.7	0.726	0.18
		Training	1.7 ± 1.7	2.3 ± 2.0	0.216	0.32
	Male	Control	2.0 ± 2.2	0.9 ± 1.4	0.663	0.60
		Training	1.4 ± 1.7	1.8 ± 1.7	0.239	0.24
Open shot	Female	Control	3.7 ± 2.4	6.0 ± 0.0	0.104	1.36
		Training	3.1 ± 1.5	2.8 ± 1.0	0.777	0.24
	Male	Control	2.6 ± 1.7	2.1 ± 1.6	0.684	0.30
		Training	3.6 ± 2.6	5.8 ± 2.6	0.075	0.85
Contested shot	Female	Control	1.7 ± 2.1	0.5 ± 0.7	0.443	0.77
		Training	1.1 ± 1.1	2.2 ± 1.6	0.225	0.80
	Male	Control	2.7 ± 3.1	1.0 ± 0.8	0.050	0.75
		Training	1.1 ± 1.4	2.1 ± 1.7	0.340	0.64
Deflected pass/bobble	Female	Control	0.8 ± 1.2	0.0 ± 0.0	0.225	0.94
		Training	1.1 ± 0.9	0.7 ± 0.8	0.334	0.47
	Male	Control	0.3 ± 0.5	0.5 ± 0.8	0.575	0.30
		Training	0.7 ± 0.9	0.4 ± 0.7	0.493	0.37
Passing turnover	Female	Control	1.0 ± 0.6	1.0 ± 1.4	1.000	0.00
		Training	0.9 ± 1.2	0.8 ± 1.6	0.720	0.07
	Male	Control	0.7 ± 0.8	1.3 ± 1.3	0.286	0.56
		Training	0.3 ± 0.5	1.1 ± 0.8	0.130	1.20
Dribble turnover	Female	Control	0.2 ± 0.4	–	N/A	N/A
		Training	0.3 ± 0.5	–	N/A	N/A
	Male	Control	0.7 ± 0.6	0.1 ± 0.4	0.044	1.18
		Training	0.0 ± 0.0	0.3 ± 0.5	0.282	0.85

the scenarios, including comments such as: "it was really cool how real it felt" and "it felt like we were in the arena." The added fidelity of the immersive videos (e.g., full environment, ability to control head orientation) may have been beneficial although it has been suggested that the realism of an immersive environment is less important when compared to whether or not an it maintains behavioral realism (Craig, 2013). In terms of aspects of the training that could be improved, approximately two-thirds felt that increasing the number/variety of scenarios and using scenarios with different visuals features (e.g., different environments, teams, etc.) would make the training more engaging. There may be skill learning advantages to increasing the variety of scenarios as well due to the contextual interference effect (Porter and Magill, 2010). The results from the immersive test were somewhat surprising given the variety of responses received from players (and coach raters) on the same scenarios. All of the scenarios were designed to have a clear passing option but the decisions generated by players included dribbling, shooting, and holding the ball. There is evidence that viewing perspective can influence decision making (Mann et al., 2009) and it is possible that performing in an immersive environment with a first person perspective influences the options each scenario affords a player because they are able to scale their choices based on their individual action capabilities.

Although the results are encouraging, this study was not without its limitations which highlights the difficulty of working in an applied environment. The participants were the top youth players in Australia which is beneficial but also means that the sample size is going to be small. While this may cause issues with statistical power, it does need to be acknowledged that this is a limited population and a lot of insight can be gained from using these small, highly skilled groups. For example, we could expect improvements in lesser skilled groups because the landscape for improvement is much greater. Because this research was conducted in a high-performance program, there were constraints on player scheduling that needed to be worked around which is why we were not able to complete the same amount of testing and training with each group. It also limited the amount of time athletes could devote to additional training; it would be useful to determine the appropriate dose-response relationship to provide recommendations regarding the minimum amount of training needed to observe an effect. Methods of analysis need to be used (e.g., linear modeling) that take into account the likelihood that there is going to be uneven groups, and missing data due to factors like player injuries. A retention test was also not conducted under these circumstances which does not allow for statements on the long-term learning effects of the intervention and future research should include additional measures over time. From a theoretical (Craig, 2013; Hadlow et al., 2018) and design standpoint, giving the players the opportunity to interact with the immersive environment would be useful because, as the MPTF would predict, this may lead to better transfer. As previous researchers have suggested, simply providing a verbalization of the outcome and the use of a simulated movement may not have captured the full capabilities of the participants (Araújo et al., 2010; Dicks et al., 2010). Increasing the interactivity of the scenarios would require additional resources and could be beyond the capability of sporting organizations who might want to use the technology already available. Finally, the effectiveness of immersive training was not compared against any other modalities (e.g., videos presented on a monitor) so, at this stage, it is not possible to comment on the relative effectiveness of this type of training. It is possible that, relative to other training, there may be no added benefit to using immersive video training and future research should compare different approaches.

In summary, there were a number of encouraging findings in this study (e.g., improved on-court performance for trained males) along with some unexpected results (e.g., on-court improvements in the female control group). The study demonstrated that perceptual-cognitive training tools do not necessarily need to be completely representative (Davids et al., 2006) to benefit in game performance and coaches and practitioners should use a framework such as the MPTF (Hadlow et al., 2018) to understand potential trade-offs in transfer when assessing the merits of any particular training tool. Immersive training could be used for player rehabilitation and during travel to keep players cognitively engaged when they are unable to perform physically. Through the discussion a number of issues have been highlighted for future research to consider when using immersive video as a perceptual-cognitive training tool. Despite these limitations, the findings suggest that there is a potential benefit for using immersive training and it may be a practical tool that sporting organizations can implement at a relatively low cost. Given that players had positive experiences with training, enjoyed engaging with this type of presentation and there were no detrimental effects of participating in training, it is certainly worthwhile considering expanding its usage in the daily training environment.

IMPLICATIONS

There were a number of practical takeaways from this research that are highlighted below:

- For development of training programs using immersive video, it is important to ensure there is enough variety in scenarios (e.g., quantity and type of decisions) to maintain player engagement. Given the accessibility and ease-of-use of technology for creating immersive content it could be quite feasible to regularly update stimuli.
- Stimuli should be created that are specific to the group engaging with the training program (e.g., female athletes should view footage of female athletes within the training footage).
- The options generated by participants in immersive environments may vary from expectations given the first-person perspective. If the goal is to target a specific aspect of decision-making skill (e.g., passing) then scenarios should be carefully designed that afford passing options over other decisions.

AUTHOR CONTRIBUTIONS

DP was involved in study conception and design, scenario filming, data collection and processing, analysis, and manuscript preparation. MK was involved in study conception and design, scenario creation and filming, data collection and processing, and manuscript preparation. SH was involved in scenario filming and stimulus creation, data collection and processing, and manuscript preparation.

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REVIEW
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Evaluating Weaknesses of "Perceptual-Cognitive Training" and "Brain Training" Methods in Sport: An Ecological Dynamics Critique

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The recent upsurge in "brain training and perceptual-cognitive training," proposing to improve isolated processes, such as brain function, visual perception, and decision-making, has created significant interest in elite sports practitioners, seeking to create an "edge" for athletes. The claims of these related "performance-enhancing industries" can be considered together as part of a *process training approach* proposing enhanced cognitive and perceptual skills and brain capacity to support performance in everyday life activities, including sport. For example, the "process training industry" promotes the idea that playing games not only makes you a better player but also makes you smarter, more alert, and a faster learner. In this position paper, we critically evaluate the effectiveness of both types of process training programmes in generalizing transfer to sport performance. These issues are addressed in three stages. First, we evaluate empirical evidence in support of perceptual-cognitive process training and its application to enhancing sport performance. Second, we critically review putative modularized mechanisms underpinning this kind of training, addressing limitations and subsequent problems. Specifically, we consider merits of this highly specific form of training, which focuses on training of isolated processes such as cognitive processes (attention, memory, thinking) and visual perception processes, separately from performance behaviors and actions. We conclude that these approaches may, at best, provide some "general transfer" of underlying processes to specific sport environments, but lack "specificity of transfer" to contextualize actual performance behaviors. A major weakness of process training methods is their focus on enhancing the performance in body "modules" (e.g., eye, brain, memory, anticipatory sub-systems). What is lacking is evidence on *how* these isolated components are modified and subsequently interact with other process "modules," which are considered to underlie sport performance. Finally, we propose how an ecological dynamics approach, aligned with an embodied framework of cognition undermines the rationale that modularized processes can enhance performance in competitive sport. An ecological dynamics perspective proposes that the body is a complex adaptive system, interacting with performance environments in a functionally integrated manner, emphasizing that the inter-relation between motor processes, cognitive and perceptual functions, and the constraints of a sport task is best understood at the performer-environment scale of analysis.

Keywords: perceptual-cognitive training, brain training, motor learning, neuroplasticity, ecological dynamics, sport performance

INTRODUCTION

There has been a recent upsurge in the "process training industry," proposing how to improve isolated processes such as perceptual and cognitive capacities, like vision, attention, creative thinking, memory, "ultra-fast" decision-making, in order to improve performance at work, in tests and examinations, and sport. In related vein, a "brain training industry" also promotes the idea that, for example, playing digital games not only makes you better at playing these games but also makes you smarter, more alert, and helps you to learn faster. Brain training software presents neuroscience research about neuroplasticity to support the efficiency of their programs in training brain processes which are claimed to underpin performance effectiveness in many specific performance domains, including sport. Taken together, the claims of the perceptual-cognitive training and brain enhancing programs can be addressed under the rubric of "process training" industries. Their claims have created significant interest in elite sports practitioners, seeking to enhance athletic performance and create an "edge" for athletes. Process training industries claim that they can develop core abilities that underpin perceptual and cognitive skills and brain function beyond a particular sport. But does process training really improve perceptual-cognitive abilities and brain processes in a way transferable to sport tasks performance? Can this kind of training be used as a shortcut to enhance sport performance? In this position paper, we show how an ecological dynamics rationale can undermine the significance of these industry claims, focusing on the weakness of the supportive evidence on specificity of transfer of training.

While practice is essential to improving sports performance, the search for the so-called one-percenters is commonly promoted by leading sport scientists and practitioners who are seeking to create an "edge" or "marginal gains" for elite athletes. To that end, athletes spend significant periods in "off-field" training activities to enhance perceptual skills such as improving their visual search for information, maintaining attentional focus, and improving memory through cognitive skills training to build "knowledge" in support of their on-field performance. There are commercial interests driving the industrial scale of the financial value and promotion of these training devices/programmes in sport. Systematic reviews, such as that of Harris et al. (2018) clearly point to the industry worth billions of dollars behind the use of a range of different "process training devices/programmes" in sport. Their analysis shows that this "methodological approach" in sport has all the hallmark characteristics of an "industry." Furthermore, these commercial interests are supported by the lucrative publication of popular science books, which have not necessarily been subject to rigorous peer review that academic literature has to undergo. Large swathes of the digital and conventional media provide broad support for the, sometimes, spurious claims of the process training industry (see Moreau et al., 2018).

Key questions for sport practitioners include: Is spending this amount of money justified? and What added value do these approaches purport to bring to performance? In this position paper, we address these questions and examine the evidence in support of these industry claims. We provide an ecological dynamics rationale to explain the limitations of the preferred modularized approach to training processes of perception and cognition and brain functions for understanding effects on sport performance. To address these issues, we first evaluate current approaches and evidence that support perceptual-cognitive training and its application in sport. We question the mechanisms purported to underpin process training and their limitations. A key focus is efficacy of theories of transfer, additive models, and evidence from neuroscience on brain plasticity (a key tenet for those advocating efficacy of "brain training"). In evaluating perceptual training effects, to exemplify our arguments, we provide an in-depth critical review of the evidence from the perspective of Quiet Eye, which could be considered as part of vision training programmes. We conclude by presenting an ecological dynamics rationale that proposes a context-dependent perspective on the role of cognition, perception, and action, highlighting that the human performer is a complex adaptive system, which interacts with performance environments in a functionally integrated manner.

A commonality in training programs for brain and perceptual-cognitive processes is that, currently, both industries tend to adopt a "modularized" approach. The assumption is that isolated processes (i.e., modules) in the brain and perceptual-cognitive functions can be trained separately from action in a performance context. Post-training, it is assumed that the enhanced process can be integrated back into the whole system with resultant performance duly enhanced. Indeed some proponents define CT as the act of improving what are termed "core cognitive processes," which they assume to underlie sport performance (e.g., Walton et al., 2018). Substantial evidence for this claim is lacking, along with a rigorous definition of what is meant by the term "core cognitive processes."

These assumptions in contemporary sport practice are based on the default approach of indirect perception underpinning sport psychologists' attempts to describe and develop specific processes, such as perception, anticipation, attention, memory, and decision-making, by exposing performers to selectively adapt and modify displays such as still images, short video clips, and snapshots of performance environments (Araújo et al., 2017). This methodology is exemplified by schematic presentations of the position of chess pieces on a board (Chase and Simon, 1973), the co-positioning of players in two basketball teams or the serve actions of tennis players hitting topspin, slice, or flat serves (for a review, see Williams et al., 1999; Starkes et al., 2001). It does not seem to be considered important that an "action response" might constitute a button press in the studies evaluated (Walton et al., 2018). The assumption seems to be that any response will suffice to test effects of cognitive training on behavior, and it is unsurprising that a major outcome of current evaluations is a call for further investigation.

The assumptions underpinning the default approach in the literature supporting process training are not supported by other theoretical rationales, such as that of ecological dynamics (Araújo et al., 2017). In contrast, the ecological dynamics approach considers perceptual, cognition, and action sub-systems to be deeply intertwined in their activity, functioning as continuously integrated and highly coupled systems. Theoretically, it is not coherent and of little value to use a modularized approach and decouple processes of perception, cognition, and action to train them in isolation. Further, ecological dynamics is deeply concerned with knowledge and considers intentions and cognition to play an important role in theoretical explanations of human behavior (Davids et al., 2001a,b; Davids and Araújo, 2010a; Araújo et al., 2017). Determining how effective the indirect methods of developing underlying mechanisms of sports expertise is the key issue addressed in this paper. How can we enhance the cognition, perceptions, and actions through indirect means to support skilled performance that emerges through direct learning for athletes to become perceptually attuned to relevant properties of the environment? Here, we propose that effective interventions can be achieved by basing learning design on a view of knowledge, cognition, and intentions as deeply integrated and intertwined. Intentions, perception, and action interact to mutually constrain performance in practice and competition, and this key point needs to underpin the design of performance enrichment programs which target PC processes.

Training programs, based on indirect methods to build "knowledge about" the environment, enhance knowledge that can be used to describe (verbally or pictorially) performance. In contrast, the more direct "knowledge of" the environment (see Araújo et al., 2009; Araújo and Davids, 2011) supports how an individual interacts with a performance environment, intentionally, perceptually, and motorically, in picking up and utilizing *affordances* from the performance environment (defined as *opportunities for action* in ecological psychology). Gibson (1966, 1979) has suggested that *knowledge of* the environment is expressed by action and implies direct perception (i.e., the environment informs about what it is without the need of a mental—indirect—attribution of meaning) and direct experiences with specific environments. Adaptive behavior emerges as a continuous cycle where performers can prospectively control their actions by detecting information (Araújo et al., 2018). Consequently, ecological psychologists suggest that direct learning (Jacobs and Michaels, 2007) to develop "knowledge of" the environment is achieved by "doing." Direct epistemological contact with an environment facilitates knowing how to achieve a task goal because it involves learning to detect and attune to key perceptual variables that regulate performance behaviors. Direct perception differs from indirect perception in its insistence of the mental integration of action, cognition, and perception through *active performance* to underpin human behavior. Ecological psychologists agree that knowledge could be obtained *via* mediated or indirect perception (Gibson, 1979) as a way of developing knowledge "second hand." Essentially, the indirect acquisition of knowledge about the environment *via* a *passive* "classroom" approach, advocated and adopted in many contemporary approaches to sport psychology, is aligned with historical accounts of learning per se (i.e., *formal discipline theory*). Indirect knowledge about the environment involves shared knowledge about a performance environment mediated by language, symbols, pictures, displays, and verbal instructions (Araújo and Davids, 2011). The role of indirect forms of knowledge is to direct awareness and previous experiences for channeling a future "direct" experience with a specific environment (Reed, 1991). Here, we argue that, if enrichment programs are going to succeed in enhancing sport performance, they need to be predicated on the deeply intertwined relations between cognition (in the form of knowledge of the environment), actions, and perception, to pick up and utilize affordances during learning and performance.

These ideas are somewhat aligned with those in an embodied framework of cognition (e.g., Moreau et al., 2015) outlining the inter-relations between motor and cognitive processes, emphasizing that motor (cognitive) system involvement depends on specific cognitive (motor) interactions with a performance environment.

Some Questions Over the Methods of the Process Training Industry

The recent upsurge in brain training programmes *via* computer "testing" has led to a multi-million GB pound industry (Owen et al., 2010), with proponents claiming improvements across the board in terms of cognitive functions for older people, preschoolers, and for those who play videogames, over those that do not. Brain training is appealing for consumers as it can be used outside of formal education and skill learning programmes, potentially marketing continuing cognitive development to a wider population. Despite the popularity, there remain some key questions that need to be addressed in future research.

What Are the Supportive Theory-Practice Links to Sustain General Ideas of Process Training?

Traditionally, perceptual-cognitive skills have been defined as the ability to identify and process environmental information, and integrate them with pre-existing knowledge and motor capabilities, to select and execute adequate actions (e.g., Marteniuk, 1976). In the 1960s and 1970s, there was an enormous amount of experimentation on "preprogramming" movements, muscle commands, the structure of motor programmes, central representations, attention and conscious control, movement execution in the absence of feedback, and invariant properties of abstract representations stored somewhere in the brain. This research led to disparate views of motor programmes in the literature, from an abstract, symbolic representation to a grouping of neuronal cells functioning in the vertebrate motor system The notion that skilled performance can be enhanced by storing motor programmes in the brain has had considerable influence on approaches to performance analysis and training in the sports sciences. For example, more recently, Summers and Anson (2009) revisited the notion of a motor programme, proposing that it was one of the most robust and durable phenomena in the motor control literature. An implicit assumption has been that skilled performance in sport is characterized by motor system invariance. This notion has led sports biomechanists to pursue the identification of an "ideal" movement template considered as a criterion of expert performance and acquired through numerous trial repetitions (e.g., Brisson and Alain, 1996). The implication is that motor programmes can be internalized in central nervous system structures of athletes with specific practice of a target movement assumed to be optimal with respect to time and learning (Gentile, 1972; Schöllhorn et al., 2006). Motor programmes reflect a traditional bias in psychology towards seeking personal attributions in explanations of human behavior and the neglect of situational attributions. This inherent bias in traditional psychology is exemplified by an overemphasis on the acquisition of *enriched internal states* in the brain (predicated on perceptual and cognitive skills) for explaining behavior regulation (Dunwoody, 2006; see also Davids and Araújo, 2010a,b; Araújo and Davids, 2011). The concept of *organismic asymmetry* refers to a predisposition to attribute behavior regulation solely to personal characteristics internalized in the brain by individuals through learning and practice, underplaying the role of the environment in transactions to support behavioral adaptation. Organismic asymmetry in traditional psychological theories reflects a preference for internal mechanisms, such as mental representations, to explain how the processes of perception, action, and cognition may be regulated. Dunwoody (2006) has expanded upon Brunswik's (1955) criticisms of cognitive psychology explanations of behavior being biased away from person-environment interactions, as the basis of an "organismic asymmetry." These theoretical biases and assumptions are harmonious with goals and aims of process training programmes based on learning to acquire a complex integrated representation of a movement in achieving expert performance in sport (Schmidt and Wrisberg, 2008).

Furthermore, some psychological theories have argued that it is the underlying cognitive control structures supporting performance that distinguish highly skilled individuals from their less-skilled counterparts (Abernethy et al., 2007). There is relevant research on the possible effectiveness of cognitive training in sport (Brown and Fletcher, 2017), specifically in interventions focusing on training perceptual-cognitive (P-C) skills such as pattern recognition, anticipation, decision-making, and quiet-eye (Farrow, 2013). Perceptual training programmes have been suggested as an additional aid to enhance performance preparation across all skill levels but are considered particularly useful for elite level performers who are time poor and have to conserve physical (energy) resources (Farrow, 2013) or avoid problems of overtraining and potential overuse injuries. However, while elite sports organizations may justify adopting such methods, it is somewhat surprising that few studies have examined the efficacy of such training programmes (Farrow, 2013). The same fundamental question underlies all process training programmes (i.e., the same concerns arise over general training programmes for enhancing brain processes and developing generic cognitive abilities): Do these programmes really improve cognitive abilities, perceptual skills, and/or brain processes in a way that is transferable to sport performance? Can this kind of training be used as a shortcut to enhance sport performance or are their perceived effects illusory?

Unsurprisingly, the majority of P-C training programmes have adopted similar methods to those used by researchers in measuring expertise, methods which have evolved in concert with emergent technologies. A clear tendency has been to use sports-specific content as a central feature of such training, as opposed to generalized training approaches, deemed as being ineffective (Abernethy and Wood, 2001). For example, early studies of expertise used static images of typical performance situations to examine cognitive and perceptual abilities of athletes, such as pattern recognition and recall skills (e.g., Chase and Simon, 1973; Allard and Starkes, 1980). Some researchers began to use temporal and spatial occlusion methods by requiring performers to watch dynamic video clips of "actions" of cricket bowlers, basketballers, footballers, squash, or badminton players, for example, in seeking to identify the information that novices and experts use to guide processes such as anticipation and decision-making. Many of these studies have recently been viewed as having a number of significant limitations including the use of small 2D screens, making information difficult to interpret; a lack of first person perspectives; and a putative "correct answer" associated with verbal or written responses instead of sport actions (van der Kamp et al., 2008).

How Strong Is Evidence for Some Claims of the Brain Training Industry?

Despite a large number of publications reporting tests of the effects of brain training interventions, evidence that training with commercial brain training software can enhance cognition, outside the laboratory tests is limited and inconsistent for performance in general (Simons et al., 2016) as well as in sport (Walton et al., 2018). For example, Owen et al. (2010) reported data from a six-week study in which 11,430 participants were trained online on cognitive tasks focusing on improving reasoning, memory, planning, visuospatial skills, and attention. Improvements were only registered in the cognitive tasks that were trained online. There was no evidence for transfer effects to untrained related tasks, even those considered to be "cognitively" closely related. Overall, it seems that practicing a cognitive task in brain training programs results in consistent improvements in performance *on that particular task* (near transfer). The available evidence that such training generalizes to other related tasks or to nondigital, ecological performance (far transfer) is not compelling (Simons et al., 2016).

Evidence on the limitations of brain training may not come as a surprise, given the plethora of research that has examined the underlying psychological processes underpinning expert sport performance, which involves a simultaneous participation of motor and cognitive processes (Williams and Ericsson, 2005).

What Does the Perceptual-Cognitive Training Industry Claim?

A systematic review by Harris et al. (2018) located 43 studies purporting to examine the beneficial effects of use of Commercial Cognitive Training devices on sport performance. Their search yielded only a single study that examined the most important issue of transfer effects to sport performance. Unsurprisingly, they concluded that there was limited evidence for transfer effects to sport performance. They attributed the lack of support for beneficial effects of perceptual-cognitive training to the current lack of studies seeking to provide evidence for these effects. There are two problems with this conclusion. First, it does not take into account that there may be many studies of perceptual-cognitive process training, which have not been submitted for publication because researchers did not find the expected benefits. This is a limitation that quantitative reviews always need to acknowledge, known as publication bias. Second, it is possible that the lack of beneficial effects may have been compounded by a lack of a substantive theoretical rationale implemented in research designs for how process training may yield benefits to performers. This is a weakness of contemporary research that we seek to address *via* this position statement.

What Can the Process Training Industry Learn From Research Seeking to Integrate Perception and Action in Sport Performance?

A key criticism of process training methods is that they do not allow participants to access both the dorsal and ventral visual cortical systems used in actual performances (van der Kamp et al., 2008). Developing technologies have enabled researchers more recently to undertake "*in situ*" studies of perception and action by using equipment like liquid occlusion goggles to enable more representative perception-action couplings to emerge during performance of a sport action. Ensuing data has revealed that requiring performers to utilize action-regulating perceptual information and demonstrate greater fidelity in perception-action responses may be more effective in highlighting expertise differences between athletes (e.g., Mann et al., 2010). Similar findings have been reported in eye tracking studies to assess visual search strategies. For example, goalkeepers were shown to alter their visual search patterns with respect to a "stimulus" presented and the action response required (Dicks et al., 2010; Dicks et al., 2017; Navia et al., 2017). Interestingly, the study by Dicks et al. (2010) demonstrated that the initiation of an action response by football goalkeepers facing penalties was mediated by their action capabilities. Goalkeepers who could dive "faster" were able to sample more of the penalty taker's unfolding kick than those who moved more slowly. Pinder et al. (2011a,b) found that video training involving simulated cricket batting against a video-projected bowler on a "life-size" screen was partially representative of the fidelity of batting actions used against an actual bowler. When batting against the projected image, batters coupled the backswing of the bat and initial step, when preparing to get into position to hit the ball. However, the initiation of the downswing and swing velocity was different under the two conditions.

To enhance a tight coupling of perception and action systems during training in cricket, an ecological dynamics rationale proposes that batters need to couple the act of swinging a bat to hit a ball during actual flight, not an indirect image of a ball in flight simulated on a 2-dimensional video screen. The key issue is that the relevant affordances used by batters under the two conditions are different and quite specific. The implication is that extended practice in both different practice conditions is likely to lead to learners becoming more successful in batting *under those specific conditions*. The important question for cricket coaches (and of course skill acquisition theorists who advise them on learning design) is as follows: Which practice simulation is more closely related to the affordances available in cricket batting performance? To develop effective perception-action couplings in a time-efficient manner, the theoretical implication is that batters need to face real bowlers in practice, which would allow the batters to pick up and use affordances from the bowlers' actions in delivering the ball (and earlier). To address issues faced by limited video training or use of ball projection machines, where no advanced information is available from opponents such as baseball pitchers or cricket bowlers, technologies such as ProBatter^{TM} have emerged, which seek to strengthen the links between perception and action. This has the potential to be a useful compromise, based on a powerful theoretical rationale in ecological dynamics, linking video images of a bowler's actions with a ball projection machine. However, challenges emerge for participants when perceptual information provided in a video image is not representative of that provided by a bowler. In cricket bowling, bowlers change their bowling actions or their grips on the ball to deceive batters, imparting different spins, or to create swerve in ball flight. At present, projected ball flight with such technology does not reflect these important variations in flight. What you see is what you do not get. Additionally, the ball is projected through one hole and a batter can quickly become attuned to the information from the projection machine and learn to simply watch the projection hole only. Additionally, this fixed release point also limits the ability of the batter to determine the bounce point of the ball as a function of the angle of the bowler's arm at ball release. The impact of practicing with these technological limitations on skill performance was demonstrated in a recent investigation combining video technology and a ball projection machine. Catching performance was negatively impacted with even a minor de-synchronization of perceptual images presented and flight characteristics of a ball projected by a machine (Stone et al., 2014).

Data such as these have important implications for those interested in designing and implementing perceptual training programmes. The evidence over the last 15 years from numerous reviews (e.g., Williams and Ward, 2007; Causer et al., 2012; Travassos et al., 2013; Vine et al., 2014; Broadbent et al., 2015; Slimani et al., 2016) is clear on the usefulness of P-C training. However, there is a major problem to be resolved. While P-C programmes "provide an idealized method for developing anticipation and decision-making judgments in athletes" (Broadbent et al., 2015, p. 329), the degree to which they transfer to competitive performance needs much more work. That is, transfer tests to competitive performance in sport settings are highly important and need to be implemented more frequently than they currently are in existing research (see also Harris et al., 2018). Overall, the current evidence is that P-C training effects remain specific to the confines of the training context: participants seem to improve at the training task. However, their effectiveness when transferred to sport performance is strongly mediated by the degree to which the training environment is *representative* of a performance environment and the *fidelity* of the actions required as a response (Travassos et al., 2013). To that end, a number of researchers have called for a more systematic programme of research to examine the nature and content of perceptual training approaches and their relationship with the skill of the user/learner (Farrow, 2013). Similarly, others have highlighted the need for such studies to be based on a strong theoretical framework that captures the complexity of cognition, perception, and action in sport performance and the nature of transfer from practice to performance (Seifert et al., 2013; Chow et al., in press).

Can We Be Sure That Research Findings on Use of P-C Skills Observed in Skilled Sport Performers Are Relevant for Training of Sub-elite Individuals?

One of the limitations of perceptual training programmes is that they often adopt a "one-size-fits all" approach in implying that the information used to anticipate and act in research studies is thought to be commonly used by all sport performers, regardless of skill level (Farrow, 2013). A good example where this approach has been adopted is in the research on Quiet Eye, which has recently seen a significant level of interest from researchers interested in P-C training but is now also attracting significant criticisms. The Quiet Eye (QE) phenomenon provides insights into gaze behaviors and their utility for decision-making and action in sport contexts (e.g., Vickers, 1996). QE, a consistent perceptual-cognitive measure investigated in sports research (cf. Mann et al., 2007; Baker and Wattie, 2016), is defined as the final fixation towards a specific location or object within 3* of visual angle or less for a minimum of 100 ms (Vickers, 2016) and has been described as process training (Wilson and Vine, 2018). The onset of QE occurs just before the critical movement of the action, while the offset occurs when the final fixation deviates from the located target for more than 100 ms (Panchuk and Vickers, 2006; Vickers, 2016). QE is proposed as one of the key determining factors associated with expert decision-making in sport, declared as *the* "perception-action variable" (Vickers, 2007; Causer et al., 2011). Rienhoff et al. (2016) meta-analysis located 581 published papers on QE research, evident of a significant amount of research activity over the years, which is almost exclusively situated within a linear cause-and-effect methodological landscape, based within a program dedicated to identifying a sole point of engagement with information within the perceptual field, typical of traditional decision-making studies (Glimcher, 2005; Chemero and Heyser, 2009). Further, it remains unclear why research on QE has been dominated by assumptions and terminology associated with an *information-processing* perspective towards cognition in sports performers (Michaels and Beek, 1995; Rienhoff et al., 2016). Regardless of this theoretical imbalance, some studies have utilized QE as a tool for perceptual training in sport. For example, QE training interventions have been used in attempts to train visual search strategies of nonexperts in similar tasks performed by expert counterparts. For example, Harle and Vickers (2001) study demonstrated the potential of QE-based training interventions, with significant improvements reported during free throw simulations, and notable fidelity of transfer into games (see also Causer et al., 2011).

While on the face of it, these data imply relevance of QE values which are universal for sport performers regardless of skill level, there have been numerous concerns raised over the legitimacy of QE training interventions. As Causer (2016, p2.) suggested in his commentary to Vickers (2016), "there are limited acquisition trials, short retention periods and multiple training interventions." It is clear from the literature that the design of training interventions and research methods associated with them has been underdeveloped. For example, often trials are isolated incidents of performance, with the tasks being nonrepresentative of the constraints that exist in performance settings (Rienhoff et al., 2016). The lack of representative design is even more concerning when addressing dynamic team sports where there are numerous evolving landscapes governed by spatial and temporal constraints. The generalizability of findings in such studies to expert performance is currently limited. Additionally, while it may be argued that there may exist some task- and expertise-dependent features of QE, the central premise of QE training is the search for a *putative optimal behavior*, with QE times typically being averaged out across trials and participants (Dicks et al., 2017a). However, evidence is emerging that variability in gaze patterns in learning and performance are task- and individual-specific as are many movement behaviors. This observation highlights the fallacy of attempting to replicate a *universal optimal gaze pattern* to sit alongside optimal universal movement patterns (Dicks et al., 2017a).

In summary, research has shown inconclusive results for effects of brain training (Simons et al., 2016; Mirifar et al., 2017) and P-C training programmes and many questions remain. Nevertheless, more important to the understanding of sport performance, this process-oriented research has neglected the role of the body and environment in performance (Ring et al., 2015). The analysis of many P-C interventions, including QE training programmes, suffers the same methodological issues inherent in brain training studies: no pre-test baseline, no control group, lack of random assignment, passive control group, small samples, and lack of blinding when using subjective outcome measures (Simons et al., 2016; Walton et al., 2018). While these methodological weaknesses may be more apparent in brain training studies compared to P-C research, published evidence rarely shows zero effects of training interventions (null hypothesis is supported), implying universal benefits of these process training programmes. Further research is needed to understand whether the apparently universally successful outcomes of process training studies may actually be more indicative of Psychology's problem with replication and publication bias more generally.

In order to consider how we can best develop P-C skills in performers, we need to undertake a critical review of the mechanisms and theory underpinning the current approaches used. We undertake this task next with a focus on Additive Models, the role of transfer, and the evaluation of the neuroscience underpinning P-C programmes.

ADDITIVE MODELS OF LEARNING

To examine efficacy of cognitive training programmes, such as generic computer-based brain training programmes or perceptual training programmes, we need to consider the rationale or theoretical beliefs about learning behind such approaches and then consider the empirical evidence. The basic assumption of this neurocomputational approach is that brain functions process input information and produce behavioral outputs like a computer (Anson et al., 2005). This approach favors the acquisition of knowledge indirectly through the enrichment of representations of the world in the brain. Therefore, a common approach adopted by applied sport psychologists is to provide knowledge about performance in the classroom or laboratory, before later (hopefully) applying it (Andersen, 2000; Weinberg and Gould, 2011). This approach is implicitly based on ideas from *formal discipline theory*, which has been the basis of education systems for centuries (Simons et al., 2016). This theory suggests that the mind consists of capacities (e.g., concentration, reasoning ability, memory) that can be improved through exercise, with the brain being just like a muscle that can be trained (Barnett and Ceci, 2002; Taatgen, 2013; Simons et al., 2016). Hence, each capacity can be developed generally, and in isolation from action in a performance environment, before being applied or transferred into practice in step-like sequences (Taatgen, 2013).

Despite empirical evidence suggesting that the development of a more generic knowledge base is limited, the additive, modular, step-like approach to learning key cognitive capacities supporting performance is strongly embedded in applied sport psychology. For example, Williams (1986; 2010) proposed a four-step model of integrating sport psychology techniques such as goal setting or relaxation into performance. Similar programmes were promoted by sport psychologists working for the National Coaching Foundation in the UK in the early 1980s. For example, it was believed that athletes could improve their concentration by utilizing "concentration grids" where they could find and cross off numbers 1–100 in a 10 × 10 numbered square (see https://cgridid.com/2017/04/03/concentration-grid-for-coaches-and-sports-psychologyperformance-professionals/ for a contemporary version) or learn progressive muscular relaxation techniques *via* an audiotape.

Despite recent potential advances in theoretical approaches to develop a more connected approach to movement analysis with "parts" being seen as more connected than in a traditional motor programming model (e.g. Hossner et al., 2015), in reality, the additive model is still strongly represented in practice design, for example, in the common part-whole approach to learning. In this approach, practitioners break a task down into its subcomponents to reputedly make learning easier. Decomposing a task into parts is purported to help develop greater performance consistency and stability (Handford, 2006). A proposed theoretical premise of this approach is motor programming (e.g. Schmidt, 1975), which, despite the emergence of contemporary neural computation theories of brain and behavior remains a prevailing theoretical model in motor control and learning (e.g., Shea and Wulf, 2005; Schmidt and Wrisberg, 2008; Summers and Anson, 2009). Hence, advocates of such approaches suggest that tasks composed of serially organized motor programmes are best suited to part-whole learning (Schmidt and Young, 1986). For example, tennis serving is proposed as a task where there is "clear evidence that practicing the subtasks in isolation can transfer to the total task" (Seymour, 1954 cited by Schmidt and Young, 1986, p. 23). Apparently, this is not surprising as the subtasks are essentially independent activities with little difference when performing them apart or whole. Accordingly, tennis serving is made up of two separate motor programmes (i.e., the ball-toss backswing as the first programme and the programme which produces the hit) that run sequentially (Schmidt and Young, 1986). However, there is limited neuroscientific evidence in support of this explanation, with empirical research questioning the efficacy of additive approaches in skill acquisition. A number of studies have shown that breaking actions down to improve modules or subphases does not lead to transfer when performing the whole task. For example, in tasks such as tennis or volleyball serving, coaching manuals have followed the model of part-whole learning emphasizing that a consistent ball toss is crucial to the success of the serve (Davids et al., 2001a). Coaching practice, therefore, focuses on developing a stereotyped toss action in isolation from the "hit." Commonly, coaches put a small hoop or draw a chalk circle on the court surface and require players to throw the ball up to land inside the hoop. Only when consistency is achieved do coaches "add in" the hitting component. However, evidence shows that even expert tennis and volleyball players do not actually achieve invariant positioning in the vertical, forward-back, and side-to-side toss of the ball. Handford (2006) observed senior international volleyball players and found that the only invariant feature of their serves was the vertical component of the toss, with the forward-back and side-to-side dimension showing high levels of variability. It seems that servers aim to create temporal stability between the time of peak height of the ball toss and the time required for the forward swing of the hand to contact the ball. In a study to compare ball toss characteristics in part and whole tasks, the variability of the peak height of ball toss, when undertaking part practice, and the mean value for peak height was much greater than when the whole task was performed (Handford, 2006). Decomposing the task led to movement patterns that were dysfunctional for performance, and the key to skill acquisition was to learn to couple perception and action (interrupted by part training methodology). Other evidence questioning the usefulness of decomposing complex motor skills into smaller parts in actions that require individuals to couple their movements to the environment to achieve task goals exists in research on locomotor pointing tasks such as long jumping or cricket bowling. A nested task attached to the end of a run-up like jumping, or throwing an implement or ball, emphasizes the importance of the run-up to achieve a functional position to successfully complete the added task. Unfortunately, this emphasis has led to some coaches focusing on developing a stereotyped run-up. For example, in the long jump, athletes are asked to practice "run-throughs" without the need for jumping. However, empirical evidence has highlighted differences in gait regulation strategies when there is a requirement to jump rather than simply run through the pit (Glize and Laurent, 1997). Motor programming models of skill performance have had a significant impact on coaching of run-ups. For example, the belief that run-ups can be simply "run-off" with no need to engage with the environment is seen in the advice of former fast-bowling great and coaching guru, Dennis Lillee (Lillee and Brayshaw, 1977). Lillee suggests that the bowler who is having no-ball problems should simply put down a marker on the outfield, close his (or her) eyes, and run-up to "bowl" and mark the point at which the ball is delivered. After a few trials, the bowler will "know" the ideal run-up length, which should be measured and transferred to the game. Consequently, it is now common to observe cricket bowlers calibrate their run-ups with a tape measure. However, empirical evidence again rejects the idea of stereotyping of foot placement, reporting refined adaptations of gait, regulated by informational constraints of the environment, most commonly picked up by vision (de Rugy et al., 2002). In fact, continuous perception-action coupling during human locomotor pointing (i.e., running to place a foot on a target) has been demonstrated by athletes who make adjustments to their foot positioning as and when needed throughout the entire run-up (Renshaw and Davids, 2004). Continuous gait adjustments were found to be based on perception of the athletes' current versus requisite positioning of the foot in relation to a target (Renshaw and Davids, 2004). Some expert coaches are aware of this concept and have noted that the ability to perceive the difference between current and ideal footfall positioning evolves through practice and experience and is part of the skill set of elite athletes (Greenwood et al., 2012).

In summary, evidence in support of additive models is somewhat flawed, and even studies of what might be viewed as highly "repeatable techniques," such as running (Kiely, 2017), have highlighted that even when expert runners run at steady paces, movement patterns continuously vary. In fact, a key property of human movement systems, degeneracy (i.e., the emergent organization of the movement system in many different ways to achieve the same outcome), promotes efficiency and robustness in performance. When systems display increased stability and reduced complexity, for example, due to wear and tear due to chronic injury, misuse, or disuse, it can lead to performance decrements and further injuries (Kiely, 2017).

TRANSFER

In elite sport, where time is precious, planned activities need to be empirically supported by evidence. An essential question for sport psychologists working with sports organizations is Do indirect methods of learning transfer to actual task performance? Practitioners and sport psychologists need to have confidence that prior experiences will prepare participants for novel situations and that practicing one task will improve performance of a related task. The rest of this paper will focus on the question of how much trust can be placed on perceptual-cognitive research and training activities undertaken *via* computer training or in laboratories or classrooms. How effective are these methods in contributing to improve cognition, perception, and action in performance settings? Here, we focus on the key issue: transfer.

The concept of transfer is central to the discussion of effectiveness of perceptual-cognitive training programmes in enhancing sport performance. Transfer of learning has been defined as "the gain (or loss) in the capability for responding in one task (termed the criterion task) as a function of practice or experience in some other task(s)" (Schmidt and Young, 1986, p. 2). Despite the prevalence of ideas from *formal discipline theory* in contemporary sport psychology, opposition to these ideas was initially raised by Thorndike (1922). Thorndike proposed the identical elements theory of transfer which argued that to transfer, elements of the practice task must be tightly coupled to the properties (stimuli, tasks and responses) in the performance task (Simons et al., 2016). Hence, only tasks with near transfer (i.e., those tasks which share common features) are likely to result in effective transfer, while far transfer (i.e., tasks/domains with significantly different common elements) is less likely to be effective. More recent models of skills acquisition have attempted to overcome the problems of explaining far transfer as per Thorndike's theory by proposing models of skill acquisition such as the ACT production system (Newell, 1980; Anderson, 1982). Production models suggest that an initial stage of skill learning is characterized by the development of a declarative knowledge base (where a person initially learns only the "facts" about the skill), which is converted into procedural knowledge (Anderson, 1982). The procedural knowledge (or production phase) uses the declarative knowledge interpretively, with an initial composition of elements that takes sequential elements and collapses them into single complex production units (i.e., chunking-Chase and Simon, 1973). The procedural phase involves application of knowledge learned, meaning that nondomain-specific knowledge can be applied to perform in a specific domain, supporting behaviors appropriate to that domain (Anderson, 1982). While the ACT model was updated with proposed neuroscientific support in 2004 (Anderson et al., 2004), to our knowledge there has yet to be a sustained attempt to integrate the model into a practice programme in sport for training brain or P-C processes. It is apparent that, in production models, knowledge necessary for a particular task is encoded in a set of internalized rules in a "condition-action" paradigm (Taatgen, 2013). The result is that production models seek to explain how far transfer may occur by suggesting that the declarative knowledge base acts as the main source of transfer (Taatgen, 2013), suggesting the efficacy of domain-general cognitive abilities (Sala and Gobet, 2017).

But, a key issue is how to separate specific elements from general items in order to maximize transfer (Taatgen, 2013). What components are "near" and "far" in this model of transfer? There are other limitations in production models for explaining transfer, for example, What is the starting point of knowledge? Cognitive models therefore suffer from the problem of prior knowledge in some form (Taatgen, 2013). Finally, enhancement should not be mistaken with transfer (Moreau and Conway, 2014); enhancement is demonstrated when an experimental condition shows significant improvement in any kind of measurement task relative to the control condition; this is not the same as responding in one task (sport) as a function of practice in some other task (brain training task).

In summary, there is significant empirical evidence that practice only generally improves performance for a practiced task, or nearly identical ones, and does not greatly enhance other related skills. Generic noncontextual interventions may have limited value (Simons et al., 2016). The current view on transfer can be considered in terms of a continuum spectrum; the bigger the similarity between tasks, the bigger the transfer (Barnett and Ceci, 2002).

EVIDENCE FROM NEUROSCIENCE RELEVANT TO PROCESS TRAINING

Given the arguments on transfer, it is clear that brain training programmes typically focus on performance during relatively general tasks (promoting at best far or general transfer). In line with the general discipline theory of learning, advocates for brain training claim that learning these skills by, for example, playing computer-based games will make them "smarter, more alert, and able to learn faster and better" (Lindenberger et al., 2017). That is, they will lead to the development of a more general range of skills in a wide range of contexts. However, while evidence is lacking for these claims (e.g., Sala et al., 2017), advocates for cognitive training programmes have turned to the science of neural plasticity to support their claims (Simons et al., 2016). Understanding how brain training might work requires a compelling theoretical rationale for explaining how and why processes in brain development and, in particular, the role of brain plasticity in adaptive learning. Without a comprehensive explanation one is left with an operational description of brain processes as modular which are assumed to be trainable in isolation. So what does the science actually tell us? Plasticity is defined as "the brain's capacity to respond to experiences with structural changes that alter the behavioral repertoire" (Lindenberger et al., 2017, p. 261). It is a key feature of learning, remembering, and adapting to changing conditions of the body and the environment (Power and Schlaggar, 2017). When learning a new skill, studies of brain development have demonstrated that the mechanisms of plasticity can be modeled as a two-phase process, with an overproduction phase preceding a pruning phase (Lindenberger et al., 2017). The increase in the number of synapses at the beginning of the plastic episode corresponds with an initial exploration phase as the learner searches for a functional task solution (Chow et al., 2015). Once found, stabilization occurs, with connections that "work" being selected and nonfunctional neural patterns decaying. Consequently, changes in brain gray matter volume are specific to the experiences undertaken with the brain exhibiting "dramatic, larger scale changes in organization in response to experience" (Power and Schlaggar, 2017, p. 4). This point has important implications for learning and practice design highlighting the need for careful thought to promote functional neural organization. For example, neuroimaging of musicians who play stringed instruments revealed larger than normal sensory activation in the cortex for the fingers specifically involved in string manipulation (i.e., the left digits), but not for the thumb (which is not used) (Power and Schlaggar, 2017).

Until recently, brain plasticity was viewed as being particular prominent for brief critical periods or "windows of opportunity" early in life. The long-held view of critical windows has been challenged by recent advances in understanding brain development, which has revealed that brain plasticity occurs throughout the lifespan. This "new" understanding has led to great interest in potential interventions that could reverse age-related decrements in cognitive functioning (Power and Schlaggar, 2017).

There is potential to exploit inherent neuroplasticity for those interested in brain training, such as sport practitioners and psychologists working with adults who may wish to change dysfunctional movement patterns (e.g., an errant golf swing or basketball shooting technique). Could a deep, stable attractor (i.e., pattern) be linked to mechanisms of brain plasticity and to the closing off of critical periods? Changing action when a movement pattern is well established is notoriously difficult and perhaps relates to the idea of the closing off of critical periods which may involve the physical stabilization of synapses and network structure by myelin (a fatty substance wrapped around the axons of neuron, providing insulation and increasing the speed of neural conduction). Given the formation of new neural connections is metabolically costly (Lindenberger et al., 2017), closing off critical periods would make sense. A potentially useful strategy may be to exploit established attractors such as walking patterns (for different forms of bipedal locomotion) or well-learned implement swinging actions to explore other object-striking tasks. Perturbing a stable attractor could be viewed of sufficient importance and have some evolutionary (in performance terms) value. Consider, for example, the challenge of neural reorganization after a stroke, when previously functional behaviors can become dysfunctional, the brain undergoes a dynamic process of reorganization and repair and behavior remodeling shaped by new experiences (Jones, 2017). Motor impairments *invite* adaptations for motor system with different characteristics, a process considered as "skill re-acquisition." When previous ways of performing an action no longer work (due to impairment, conditions, or chronic injury), the process of adaptation involves skill refinement (including perception, action, and cognition), which is practice dependent. It quickly becomes apparent that there is no typical way of performing an action because of the personal constraints that each individual needs to satisfy during movement performance. For this reason, rehabilitation programmes need to focus on functionality, defined as successful task completion by each individual, depending on the uniqueness of his/her personal constraints (e.g., intact limbs, muscle wastage or damage, degradation of the nervous system through conditions like peripheral neuropathy, level of perceptual or cognitive impairment). Nervous system regenerative processes occur over long time spans (months or longer) but are particularly dynamic early (days to weeks) after a stroke (Jones, 2017), providing a critical window for skill reacquisition. It would appear that neurobiological reorganization mirrors early learning experiences with initial overproduction followed by pruning. There is a possibility that research findings on neural reorganization in stroke patients may have potential implications for practitioners who wish to change perception-action skills in unimpaired participants. Just like in a stroke, a breakdown in performance as a result of a disruption to existing functional patterns or connections within the CNS *demands* system reorganization in an attempt to develop functional behavior solutions to achieve desired outcomes (Alexandrov et al., 1993; Järvilehto, 2001). However, these experiences may compete with one another in shaping neural reorganization patterns, as in learning a novel task in unimpaired individuals (see Jones, 2017). The interaction between cognitions, perceptions, and actions to regain functionality is highlighted in these cases as system reorganization or skill reacquisition.

The previous sections have highlighted the limitations of current methodologies and mechanisms purported to support effects of P-C training on behavior change and refinement. Throughout, it is clear that a single focus on developing cognitive skills and knowledge situated inside the heads of individuals has led to interventions that are failing to achieve their goals, i.e., transfer of learned P-C skills is weak. There is a need for research and practice to be underpinned by a theoretical model that sets processes of cognition, perception, and action in an embodied world. Here, we propose that the transactional meta-theory of ecological dynamics is a candidate framework, emphasizing the continuous emerging relations between each individual and the environment during behavior, which can meet this requirement.

AN ECOLOGICAL DYNAMICS APPROACH TO EVALUATING RELATIVE MERITS OF PROCESS TRAINING PROGRAMS

Ecological dynamics can help in guiding researchers in gaining a deeper understanding of merits of perceptual-cognitive training, including "brain training" (Davids and Araújo, 2016). Ecological dynamics elucidates understanding of how perception, action, and cognition emerge from interacting constraints of performer, task, and environment (not solely from the individual, nor from component parts, like the brain). It focuses on the role of adaptive variability in skilled individuals perceiving affordances in performance environments (Araújo et al., 2017). For example, How is useful information revealed as such for an individual performing a given task? How can relevant contextual information be distinguished from irrelevant information, *before* the detected information is "transmitted" to the brain, as proposed in theories emphasizing the role of perceptual-cognitive processes? This is an important question because explanations of brain training effects rely, traditionally, on assumptions that the brain processes (detects, attends to, learns, or memorizes) "relevant" information. Information from a sport context will then "feed" neural networks, allowing brain structures to organize (programme) a motor response. But, how are "brain training" games designed to distinguish distracting informational sources in competition from those which are simply raising alertness for each individual?

From a neurocomputational view, the putative role of the brain is to attribute meaning to stimuli, process internal representations, and select an already programmed response. The problem is that the starting point is missing in a brain-centered explanatory framework: How is an action that helps the body to search for relevant information "programmed by the brain"? A process-oriented, representational explanation to this question requires a "loan on intelligence" (Dennett, 1991). One possible answer to such a challenging question implies a clear understanding of the role of constraints and task information in explaining how intertwined processes of perception, cognition, and action channel goal achievement in athletes (Araújo et al., 2017). And, this explanation cannot be confined to how task constraints and information are represented in the brain, because this will always postpone the answer to the question (require a loan on intelligence) concerning how these task constraints and information sources were selected in the first place.

An ecological dynamics framework that formally includes both the individual (body and brain) and the environment (task constraints) does not centralize the brain and its training as the sole explanation for expert performance, as implied in "brain training" claims. The view that visual information from monitors is sufficient to train the brain is too restricted from an ecological dynamics viewpoint. This advocates that there are more constraints than eye movements, brain waves, and button pressing in explaining and training for expert performance in sports (Davids et al., 2015). This is one reason why it may be timely for perceptual-cognitive training in general, and brain training research in particular, to focus on the role of interacting constraints. An interacting constraints model can be used to theoretically inform experiments and practice on behaviors and brain function. To explain that an expert performer is already "in the right place at the right time" and "reads the game well," an ecological dynamics perspective can address how the brain needs to be understood beyond an "organismically biased" perspective (Davids and Araújo, 2010b). The separation of organism and environment leads to theorizing in which the most significant explanatory factors in behavior are located within the organism. The upshot is that causes for behavioral disturbances are equated with perturbations in brain function (e.g., Yarrow et al., 2009). This reductionist explanation of sport performance, as solely dependent on "brain" processes, seems to endorse psychological attributes (representations, programmes, schemas, scripts) as specific anatomical substrates, rather than emerging from continuous interactions of the *individual-environment system*. Analysis of a "brain-centered" perspective reveals a belief that the brain perceives, executes, conceives, represents, and constructs an action and not the organism-environment system. For this reason, some neuroscientists have argued that sport performance represents a valuable natural context for their research to address (Walsh, 2014). However, it is the whole individual, rather than separate anatomical parts of his/her body, who perceives and acts during dynamical interactions with sport environments (Araújo and Kirlik, 2008). Performance is not possessed by the brain of the performer, but rather it can be captured as a dynamically varying relationship that has emerged between the constraints imposed by the environment and the capabilities of a performer (Araújo and Davids, 2011).

From an ecological dynamics perspective, current research on brain training and neurofeedback raises questions such as: How does a given value of quiet eye relate to emergent coordination tendencies of an individual athlete as he or she attempts to satisfy changing task constraints? How do skilled performers adapt and vary brain wave parameters during performance to support coordination of their actions with important environmental events, objects, surfaces, and significant others? Rather than looking for optimal values of brain waves or quiet eye, it would be more important to look for "critical threshold bandwidths" which could be functionally distinctive according to task and individual constraints, within and between expertise levels, while studying emergent actions in sport performance (Davids and Araújo, 2016).

From an ecological dynamics approach, behavior can be understood as self-organized, in contrast to organization being imposed from inside (e.g., the brain) or outside (e.g., the instructions of a videogame). Performance is not prescribed by internal or external structures, yet within existing constraints, there are typically a limited number of stable solutions that can achieve a desired outcome (Araújo et al., 2017). From an athlete's point of view, the task is to exploit physical (e.g., rule-determined playing area characteristics) and informational (e.g., movements of other players) constraints to stabilize performance behaviors. Constraints have the effect of reducing the number of configurations available to an athlete at any instance, signifying that, in a performance environment, behavior patterns emerge under constraints as less functional states of organization are dissipated. Athletes can exploit this tendency to enhance their adaptability and even to maintain performance stability under perturbations from the environment. Importantly, changes in performance constraints can lead a system towards bifurcation points where choices emerge as more specific task information becomes available, constraining the environment-athlete system to switch to a more functional path of behavior (Araújo et al., 2006). Of significance for this discussion, neuroplastic changes induced by sport practice are more long-lasting when practice is self-motivated rather than forced by a decontextualized imposed task (Farmer et al., 2004).

In ecological dynamics, all parts of the system (brain, body, and environment) are dynamically integrated during action regulation (see also Moreau and Conway, 2014, Moreau et al., 2015). As a starting point, the concepts of affordances, self-organization, and emergent behaviors make it likely to expect that there may be functional variability in brain functioning characteristics (within critical bandwidths) among athletes as they perceive affordances under different task constraints. Seeking optimal values of brain processes, due to training with digital devices, is rather limited to more general effects with currently unknown transfer effects to performance environments.

CONCLUSIONS

Elite sports organizations often spend significant time and money on off-field activities designed to build knowledge and train processes to give them the extra "one percent" and a "crucial edge" on their rivals. How effective and efficient is the use of valuable resources on process training activities in elite sport? Do these process training programmes work and, if so, how can we make them even better?

In this paper, we argued that the term "process training" captures activities and methodologies, which are predicated on assumptions that perceptual and cognitive systems and brain processes can be trained in isolation from the informational constraints of competitive performance environments. For this reason, process training, in general, can be critically evaluated for its effectiveness and efficient use of time and money in achieving performance outcomes. Current research suggests that process training has little evidence to support effectiveness and efficiency with respect to performance behaviors (e.g., see Harris et al., 2018).

Compelling evidence exists that the dominant process training methodologies tend to be operationally defined on the basis of an assumption of modularized subsystems and lack a clear theoretical rationale to underpin their effective *implementation* in elite training programs. These suggestions are in line with arguments of Simons et al. (2016, p. 161), when discussing the value of brain training. They suggested that "in order to provide effective guidance…we need assessments of the effectiveness of the training itself, but we also need studies assessing the comparative effectiveness of interventions that do work. Moreover, we need to consider the opportunity costs [including time demands] and the generalizability of those interventions. At present, none of those further analyses are possible given the published literature." They further added that "cognitive-intervention research needs more complete translational theories that meaningfully connect lab based measures to objective measures of everyday performance (p. 161)".

In this position paper, we considered theory and evidence to determine the effectiveness of current indirect methods of developing the underlying neuropsychological mechanisms of sports expertise. We highlighted the focus of P-C training on modular cognitive and perceptual structures in the majority of studies, discussing insights on limitations of P-C training. In line with ideas of Broadbent et al. (2015), we concluded that the current evidence that P-C training methods leads to effective transfer to performance is limited and requires more work. A key proposal here is that any P-C training programme claimed to have a positive impact on performance must be *representative* of performance environments, resulting in *fidelity* of response actions (Travassos et al., 2013). Current P-C training is hamstrung by the decision of sport psychologists to underpin interventions with traditional cognitive and experimental psychological process-oriented perspectives. This theoretical rationale leads to a biased modularized focus on the organism and a glaring neglect of environmental constraints on behavior (Araújo and Davids, 2011). The biased emphasis on acquisition of enriched internal representations typically fails to acknowledge (and embrace) the dynamic interdependence of knowledge, emotions, and intentions at the heart of mutually constraining perception-action couplings that underpin performance. A problem is the advocacy of key concepts and ideas of formal discipline theory where psychological process modules are trained (like muscles) in isolation before being applied in practice. We discussed the relatively weak empirical evidence that supports this approach. We exemplified this lack of empirical support by focusing on part-whole learning in the context of Schmidt's (1975) schema theory and Thorndike's (1922) identical elements theory and contemporary iterations such as Anderson's (1982) ACT theory. We concluded that there are limitations in production models for explaining transfer, for example, by highlighting that performance enhancement should not be mistaken for transfer (Moreau and Conway, 2014). The latter may only be demonstrated when significant improvement in one task (sport) can be shown to be a function of practice in some other task (brain training task), which is currently lacking in evidence.

The putative mechanisms underpinning P-C training requires researchers to evaluate evidence of neuroplasticity and brain development. In this respect, it is important to note how current thinking has moved away from critical periods or windows of opportunity to develop P-C skills to a more lifelong view of neuroplasticity. Overall, the neuroscience evidence in support of P-C training is harmonious with experimental findings from P-C studies showing that functional neural connectivity is specific to the experiences undertaken. The result is that changes in the brain exhibit "dramatic, larger scale changes in organization in response to experience" (Power and Schlaggar, 2017).

So how can current research help us enhance P-C training programmes? Here, we proposed that adopting an ecological dynamics perspective may help researchers to frame interventions to enhance understanding of continuous, complex interactions between individual and team P-C skills from a brain-body-environment relationship (Gibson, 1979; Chemero, 2003; Kiverstein and Miller, 2015). Central to this approach is a focus on ensuring that individual-environment mutuality sits at the heart of any intervention design. Sampling of the environment (e.g., Brunswik, 1956; Pinder et al., 2011a), when designing interventions to enhance P-C skills, has been largely neglected. Consequently, it has yet to be established *if* or *how* perceptual mechanisms such as QE can inform the design of practice environments for the purpose of skill development. Ecological dynamics and its emphasis on the integrative, inter-connected relationship between cognitions, emotions, intentions, and emergent perception-action couplings posit a complementary role for indirect and direct methods of learning P-C skills. Adopting such integrative approaches moves the field beyond the unhelpful cognitive versus ecological debate and takes an embodied view of cognition allowing researchers and practitioners to begin to design-in factors such as context specific knowledge and their link to intentions, perceptions, and actions.

In summary, we have attempted to draw on theoretical insights that can better articulate cognition, perception, and action as it relates to the dynamic performance environment inhabited by experts, rather than the stale and contrived research "tests" performed in computers in laboratories. There are clear epistemological and methodological conflicts here that require a reimagined breadth of methodology for P-C training to be utilized beyond the pages of academic journals. Research methodologies must cater for the ambiguity of multiple acting constraints upon the performance environment. A research approach grounded in the theory of ED has the potential to provide a powerful theoretical rationale for how to develop P-C and brain processes in expert performers by designing dynamic training tasks which call for intertwined cognition, perception, and actions. This focus will ensure that performers can develop adaptive variability demonstrated by skilled individuals when perceiving affordances in performance environments (Araújo et al., 2017). Accordingly, P-C training should be understood as a process by which athletes become attuned to action-specifying sources of information. Future studies in P-C training need to be grounded in a theoretical model whose methodologies support tasks with representative design, furthering the coupling of perceptual attunement and skill acquisition.

AUTHOR CONTRIBUTIONS

IR co-created the paper and led the writing of the paper. KD and DA co-created the paper and made a significant contribution to the writing. AL contributed to the sections on P-C training. WR, DN, and BF contributed to the section on Quiet Eye and the summary.

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