Topical Review of Perceptual-Cognitive Skills, Methods, and Skill-Based Comparisons in Interceptive Sports

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Abstract

Perceptual-cognitive (PC) skills and abilities are keys to success in interceptive sports. The interest in identifying which skills and abilities underpin success and hence should be selected and developed is likely going to grow as technologies for skill testing and training continue to advance. Many different methods and measures have been applied to the study of PC skills in the research laboratory and in the field and research findings across studies have often been inconsistent. In this paper we provide definitional clarity regarding whether a skill is primarily visual-attentional (ranging from fundamental/low-level skills to high-level skills) or cognitive. We review those skills which have been studied using sport-specific stimuli or tests, such as postural cue anticipation in baseball, as well as those that are mostly devoid of sport context, considered general skills, such as dynamic visual acuity. In addition to detailing the PC skills and associated methods, we provide an accompanying table of published research since 1995, highlighting studies (for various skills and sports) which have and have not differentiated across skill groups. **Significance:** We give a comprehensive picture of PC skills which could contribute to performance in interceptive sports. Both visual skills that are low-level and unlikely influenced by experience, as well as higher-level cognitive-attentional skills are considered; informing practitioners for identification and training and alerting researchers to gaps in the literature.

Topical review of perceptual-cognitive skills, methods, and skill-based comparisons in interceptive sports

Researchers in sport have for many years attempted to identify skills or abilities that discriminate exceptional, top athletes from less skilled athletes, which has culminated in various popular-press books exemplifying this research.[1,2] Identification of skills has typically been achieved through cross-sectional comparisons of various skill groups, to explain how and why exceptional performance is achieved.[3–5] Considerable emphasis has been placed on identifying physical and physiological attributes which distinguish across athlete groups,[6–8] whereas fewer studies have focused on perceptual and cognitive abilities, such as the ability to perceive and track a moving ball with the eyes, to focus attention, or to anticipate an opponent's next move. Because all sports require athletes to process sensory information, allocate attention and make decisions about when or where to act, perceptual-cognitive skills are critical for superior athletic performance. Although recent advancements in technology have increased research on perceptual-cognitive skills over the past few decades,[9–11] the field lacks clear definitions as to what perceptual-cognitive skills are, how they should be classified and measured, and which ones have distinguished across athlete groups and are worthy of further study. In this review, we focus on methods for assessing perceptual-cognitive skills in interceptive sports to provide definitional clarity and guidance, assisting the reader in adopting the most suitable technique and gauging the level of evidence of a given sport-specific or general skill as a test, descriptor or predictor of skill in sports.

Being able to locate, track and respond to advance information from an opponent or ball flight, under time constraints, is a critical component of many sports. Interceptive or partner sports primarily involve the coordinative interaction between the body or an object held by the body (e.g., bat) and an object in the environment, typically a ball.[12] In interceptive sports, athletes must deploy and switch attention appropriately, for example, from the point of ball release to the point of bounce or interception. Our definition of interceptive sports is based on situations typically involving the interplay between two people, such as a bowler and batter. Examples of interceptive sports are baseball, cricket (batting and close-range catching), and tennis. For some sports (e.g., volleyball and soccer), interception is a subset skill of the sport where interpersonal interactions additionally require game reading skills and the need to respond to multiple stimuli, so we do not include these dynamic team sports in this review. Due primarily to space limitations and the fact that there has recently been a review of visual skills in combat sports athletes,[13] we also do not consider these person-to-person sports in this review. However, we do include the isolated component skill of goal tending and thus include research from soccer, handball and hockey based on goaltenders responding to penalty shots.

What are Perceptual-Cognitive Skills?

Perceptual-cognitive skills describe capacities related to the perception of sensory information in the environment; including detection, discrimination, identification, recognition, and classification. These skills are also related to the evaluation and integration of sensory information with existing knowledge, resulting in appropriate interactions with the environment.[14,15] In most sports, perceptual skills are centered on vision. Other senses, such as hearing and touch, can contribute to sports performance, but few studies exist on skill-level differences in these other senses. In the context of sport, perceptual-cognitive skills are highly embodied, such that what we see and what we think are tightly bound to how we move.[16] Therefore, although we refer to these skills above as perceptual-cognitive, this descriptor is not meant to ignore or relegate the relations these skills have to the motor system, but rather distinguish them from skills considered more “motor”, such as running or throwing.

In our classification of high-level visual and attentional skills, we distinguish fundamental and low-level visual skills, such as visual acuity and peripheral vision, from higher-level visual skills related to selective attention and eye movement control. These are further distinguished from cognitive skills, which are typically related to variables such as memory and decision making (see **Table 1**). Although we include cortical markers of attention, we do not review studies of brain areas (as assessed through neuroimaging techniques), which get activated when these perceptual-cognitive skills are applied (for reviews[17–19]). Prior classifications of visual skills for sports exist (for example, the pyramid model[20], but not to the same level of specificity we provide. Although we do not review studies related to the trainability of perceptual-cognitive skills, we acknowledge that relatively more success has been gained from training sport-specific skills related to high-level attentional and cognitive skills[21–23] rather than low-level and fundamental visual skills that are domain general [24,25]. Sports' vision training and general cognitive skills training has mostly seen success in research that has lacked experimental rigour and where there is not impartiality from researchers with respect to the software or hardware being marketed.[26–28]

In the following paragraphs, we define the most commonly studied perceptual-cognitive skills, illustrate classic research techniques used in the sports expertise literature, and describe laboratory studies in athlete populations. We consider skills and techniques that have been used to assess expert-novice or athlete/non-athlete differences either with sport-specific stimuli and/or in sport-specific contexts, or in non-sport environments with stimuli independent of the sport context (i.e., domain general skills). Sport-specific tests are designed to be representative of the sport and involve stimuli that are specific to a particular sport (e.g., anticipating the location of a bowled cricket ball). Sport-specific perceptual-cognitive skills are highly dependent on (and sensitive to) experience.[21–23,29] By contrast, general visual and cognitive skills (e.g., visual acuity assessed using an eye chart) are less experience-dependent, but still may be influenced by physical experiences[30–32]. Moreover, individual differences in these general skills might also be fundamental to certain sport-specific skills and their development, potentially aiding prediction of performance on these sports skills[33,34].

Literature Review Methods

We searched published and peer-reviewed sport expertise literature in the past 25 years, where there have been quantitative, statistical comparisons across skill groups. These skill group comparisons may be across professional versus amateur players, experts versus novices or across skilled and lesser-skilled players. In some studies, players have been compared to a matched, non-athlete control group (e.g., college students). Only studies which met these criteria were included in **Table 2**. To the best of our knowledge, the studies presented in **Table 2** give a comprehensive and valid picture of research conducted since 1995 (1995-2020), which meet the criteria above. We conducted a search of different combinations of keywords related to perceptual-cognitive skills in sport, including; skill, sport, expert*, performance, athlete, in combination with percept*, vision/visual (including sub-keywords motion, colour, depth), cognitive/cognition, attention, anticipation, prediction, decision-making, executive function, memory, eye movements (including sub-keywords fixation, saccade, pursuit, quiet eye), electroencephalography (EEG), interceptive sport or skill or any sub-sport/skill such as baseball, softball, cricket, badminton, table-tennis, tennis, goalies, goal-keepers, using PubMed, PsycInfo, and SportDiscus databases and Google Scholar©. Reference lists of selected articles were also checked for related publications. To be included, studies had to be published in English within the past 25 years. Whereas our approach to study identification was systematic, our review is selective. We also review select studies which are not included in our table, as they may lack control group comparisons or be older, but still deemed relevant to our discussion.

This review is organized into four categories of perceptual-cognitive skills (**Table 1**): fundamental visual skills, low-level visual skills, high-level visual-attentional skills, and cognitive skills. Each category has a subset of skills and may or may not include sport-specific or more general tests and measures. **Table 2** summarizes studies using sport-specific or general, non-sport specific assessments, separated by whether predominantly positive or negative statistical outcomes were reported.

PC Skill / Results:	**Significant differences:** **Sport-specific**	**General-stimuli**	**Non-significant effects:** **Sport-specific**	**General-stimuli**
Fundamental				

Visual acuity		baseball[35–37]		badminton[38] baseball[39] interceptive athletes[40,41] table tennis[42]
Visual field/ Peripheral		interceptive athletes[40] table tennis[42]	cricket[43]	
Low-level				
Colour/ contrast		badminton[38] interceptive athletes[40] table tennis[42]	cricket[43]	
Depth/ stereoacuity		badminton[38] baseball[44]	cricket[43]	interceptive athletes[40] table tennis[42]
Motion	badminton[45–47] cricket[48,49] handball GK[4] soccer GK[50] squash[51] tennis[52–54]	badminton[55] baseball[56] tennis[57]	tennis[58]	tennis[59]
High-level				
Attention	baseball[60] badminton[61] cricket[62] tennis[59]			badminton[61] table tennis[63] tennis[59] interceptive athletes[41]
Eye move	badminton[64,65] baseball/softball[66,67] cricket[68–71] soccer GK[72–74] table-tennis[75–78] tennis[53,79–83]	baseball/softball[84,85]	cricket[86] handball GK[87]	squash[88]
Cognitive				
Anticipation	badminton[45–47,64,89–92] baseball[60,93–96] cricket [3,48,49,70,71,97–100] handball GK[4,87,101,102] soccer GK[50,73,74,103,104] squash[51] table tennis[75–77] tennis[11,53,54,58,71,83,105–113]	baseball[84,114]	baseball[115,116] cricket[62,86] tennis[117]	baseball[35]

Decision-making	baseball[67,118,119] tennis[120,121]			
Memory & Knowledge	badminton[122] baseball[123] cricket[70,71] tennis[4,121,124–128]			baseball[129]
Executive	baseball[130,131] table tennis[132] tennis[133]	badminton[134] baseball[135,136] open sport athletes - including badminton & table-tennis[137]	badminton[61] tennis[135]	badminton[61] baseball[136] mixture of athlete groups[138]

Perceptual-Cognitive Skills: Definitions, Methods and Evidence

1. Fundamental visual skills

Vision is fundamentally important in interceptive sports and may be one of the main contributing factors to elite sports performance.[33,34,139] In this section we focus on what we term fundamental visual skills, such as visual acuity, and consider definitions and methods for assessing these skills as well as present evidence relating to their ability to distinguish across skill-groups in sports.

Static visual acuity: Visual acuity is the acuteness or clearness of vision and it is a measure of the spatial resolution of the visual system.[140] It is commonly tested by displaying black optotypes (e.g., letters) of decreasing font size on a white background. The distance between the person's eyes and the testing chart is set sufficiently high (20 foot for the classic Snellen test), approximating the maximum adaptation of the eye's lens when it focuses on an object far away. If the display is correctly illuminated and instructions are followed, this method is highly reliable. Visual acuity has received considerable study in interceptive sports (see **Table 2**), but the evidence is mixed regarding its ability to distinguish across athlete groups. For illustration, although this study is not included in the table as there were no cross-group comparisons, batting performance in professional cricket batsmen was only impaired when acuity was significantly degraded by experimentally blurring vision with contact lenses of one to three diopters (~ 20/40 to 20/160 vision); no performance degradation was observed at lower levels of reduced acuity.[97] Congruently, identifying people with above average acuity is not a useful way of identifying talent potential.[43,141] In a comparison of professional baseball players stratified by how often they made the roster, static visual acuity did not differentiate across performance groups.[39] Even though acuity might differ depending on playing position (e.g., hitter vs. pitcher),[14] it was not a significant predictor of on-field performance in a battery of vision tests with professional baseball players only.[139]

Dynamic visual acuity: Dynamic visual acuity is the acuteness or clearness of vision when viewing an object that moves relative to the observer.[142,143] It is the ability to resolve fine spatial detail in dynamic objects during head fixation (e.g., moving ball, stationary athlete), or in static objects during head or body rotation (i.e., moving athlete, stationary goal). A classic test involves reporting a small feature in a moving object, such as the location of a small opening in a rapidly-moving ring (Landolt C) presented on a computer monitor.[36,37] This task measures the ability to separate two features in space, requiring smooth tracking eye movements to stabilize the object on the retina.

Although differences in dynamic visual acuity have been shown across expert athlete and non-expert groups in older studies[144,145] and more recently, in baseball,[35–37] the evidence is still mixed. Dynamic visual acuity differences have been related to more accurate eye movement control,[146] which is thought to contribute to enhanced performance in manual interceptive tasks in interceptive athletes.[40] The evidence with regard to whether fundamental visual skills such as acuity can serve as predictors of on-field performance in baseball is mixed[15,31] with respect to both whether differences exist across skill groups and what they mean. Longitudinal studies of adolescent athletes would help in discerning the significance of any skill-based differences.

Visual field / peripheral vision: In most tests of acuity, the optotype falls onto the viewer's fovea, the area of the eye where visual acuity is highest.[147] However, in many sports, the ability to detect and identify objects outside the fovea is important. The total visual field area in which useful information can be acquired without eye or head movements (i.e., within one fixation) is referred to as functional (or useful) field of view or visual span.[148,149] The size of the functional field of view can be measured by asking observers to detect small stimuli presented at various distances and eccentricities relative to central fixation. In such tasks, both accuracy and reaction time can be recorded. Peripheral vision is often assessed with automated, computer systems such as the Vienna Test System (Schuhfried GmbH, Moedling, Austria) or the Nike Sensory Stations, with moderate to good reliability.[150,151] Researchers have also manipulated field of view through gaze-contingent displays,[152] where observers watch videos through an aperture that moves with the eyes, revealing only part of the scene (a central mask occludes central vision, restricting vision to peripheral information).

Only two studies demonstrated significant differences across skill groups for functional field of view (**Table 2**). Although general athlete advantages in detecting stimuli across their field of view have been noted and these differences have been linked to better ability to detect and respond to stimuli in the periphery than non-athletes, further research in this area is needed to better determine the significance of visual field/peripheral vision for interceptive sports athletes. With respect to fundamental visual skills in general, although there has been some evidence attesting to skill-based differences and recent research distinguishing within a skill class, the evidence is either lacking or rather mixed as to the importance of acuity and field of view for high level athlete performance. Because these skills are mostly not amenable to training (with the exception of sport-specific strategies to help pick up information in the periphery through gaze anchoring[153]) there is not direct evidence that these techniques are useful in identifying skill beyond correction of acuity to ‘normal’ levels.

2. Low-level visual skills

Low-level visual skills require finer discrimination ability than that assessed by measures of acuity and field-of-view, as detailed in **Table 1**. These include colour and contrast perception, stereo-acuity/depth perception and motion perception. In interceptive sports, detecting and discriminating objects in space and at low contrast are particularly relevant when considering the spatial-temporal demands placed on athletes required to accurately intercept a moving object against varying backgrounds.

Colour and contrast sensitivity: Colour vision is the ability to detect objects and discriminate them based on the wavelengths of light they reflect (i.e., colour). Because humans have three types of colour-sensitive photoreceptors on the retina (for red, green, and blue), colour vision is trichromatic. The most common type of colour vision deficiency is deuteranomaly (red-green deficiency), affecting up to 5% of men.[154] Colour vision can be tested using conventional tests such as the Ishihara test plates.[155] These plates consist of blobs of different colours and may contain a number which has to be identified. Colour perception is often studied as part of the assessment of contrast sensitivity, the ability to see an object in front of its background. Contrast sensitivity is measured similarly to visual acuity, with optotypes of a constant size that decrease in contrast until they can no longer be identified. Letter charts, such as the Pelli-Robson,[156] are used frequently in sports vision testing and have high reliability.[157] In sports' vision testing, the Mars test[158] has been recommended because it involves a small, portable chart, without sacrificing reliability.[159] Contrast sensitivity is involved in detecting where objects or people are in space especially in poor lighting conditions, such as bright sunlight. In sports, athletes have worn tinted contact lenses in an effort to aid contrast discrimination.[157,160]

Colour and contrast sensitivity have received some attention in tests of discrimination across various athlete skill groups (see **Table 2**). Although impaired colour vision limits the performance of cricket players, it appears to do so only at the highest playing level and when the deficiency is severe.[161] Comparing across experienced female badminton players and a sedentary control group, badminton players were better able to detect differences in contrast between blue and yellow.[38] Contrast sensitivity has distinguished interceptive sports athletes from age-matched non-athletes with 61% accuracy[40] and male elite table tennis players showed better contrast sensitivity than non-playing controls.[42] Although the research is sparse, what does exist points towards visual advantages for athletes over non-athletes. It remains unclear whether differences are a result of experience, yet in laboratory studies of perceptual learning, consistent and long-lasting changes in contrast sensitivity have been shown, accompanied by activity change in primary visual cortex.[162,163] However, in a study reporting effects of visual function on batting performance in 585 professional hitters, years of major league service was not related to visual function.[164] Longitudinal studies are needed to better assess when and if differences between skill groups are found.

Stereoacuity: In interceptive sports, objects move in depth towards or away from the observer, causing the retinal image of the object to expand or contract. Stereoacuity is the ability to perceive objects in depth (3D) when a scene is viewed with both eyes. It is the smallest difference in depth that can be detected. This ability is important to successfully navigate around or estimate the trajectory of an approaching object. Stereoacuity at near distance is often tested using standard book tests, such as the Randot graded circles test. Here, participants look at clusters of three stationary circles through polarized 3D viewing glasses (inexpensive glasses with a pair of different polarizing filters). In each cluster, observers identify the circle which appears to stand out (i.e., different depth plane), with difficulty increasing as the difference between individual circles decreases. Although these stereopsis tests have been adapted to the sports domain, this has thus far been limited to soccer.[5]

In a large study of ~400 professional baseball players, far (but not near) stereoacuity was significantly better than general population averages.[141] Researchers also showed that stereoacuity was correlated with walk-rate among professional baseball players,[139] but did not differentiate hitters from pitchers;[165] even though in theory, this visual skill should be more important for hitting than for pitching. There are again few research studies distinguishing across groups (see **Table 2**), with a mixed pattern of overall results making it difficult to draw conclusions about the importance of this visual skill for sports.

Motion Sensitivity: Motion perception includes detecting and discriminating motion along three axes: horizontal, vertical, and rotational (spin) and involves the perception of angle, direction, and speed. For example, a visual target or an array of dots moving against a dark background might appear on a computer monitor and move at a given speed in a given direction. Observers then have to discriminate its direction (coherence) or speed, through comparisons (i.e., which one was faster, were the dots moving towards or away?). Variations of such paradigms are used in sports to test general motion perception.[59]

Motion perception tasks with sport-specific stimuli can involve computer animations of a particular action (e.g., researchers in tennis used digital avatars but did not compare across different skill groups).[52] Point-light figures are also used to investigate the perception of biological motion; the ability to identify actions from small sources of light attached to the major joints of a person's body.[166,167] Most frequently, point-light displays have been used to assess movement cues underlying anticipatory decisions, rather than motion detection per se.[168] Even though kinematic information can be picked up subconsciously,[169] we consider these anticipatory tasks more cognitive than visual, because the emphasis is on the decision or prediction, rather than the detection of motion as a low-level visual skill.

In assessments of low-level visual skills, differences across skill groups have mostly been noted for stimuli that are related to the requirements of the sport. For example, skilled tennis players outperformed triathletes and non-athletes when discriminating looming objects (moving towards the athlete), but not other types of motion.[59] Impoverished or abstract visual displays can distract and bias experts' visual perception more than novices,[52,58] although expert advantages have been shown.[154] Barring a few exceptions, elite athletes across many interceptive sports are better able to recognize sport-specific motion from impoverished displays (**Table 2**). However, because these results were limited to sport-specific stimuli, they are more likely due to athlete's sport-specific experience and not superior motion perception per se.

In summary, skilled athletes differ from less skilled in low-level visual skills, such as contrast sensitivity. Expert advantages in visual processing, recognition and categorization of biological motion are specific to stimuli representative of the sport. Sport vision researchers have suggested that when low-level visual function differences exist, these most likely reflect sport experience.

3. High-level visual and attentional skills

Our sensory system is confronted with an amount of information that is too vast to be processed, given limited processing resources. Visual attention is the mechanism by which we focus on a certain location, object, or feature of a scene, selectively processing the attended information, ignoring the unattended.[170] Some tasks require observers to keep their eyes fixated on a spot and attention is then deployed covertly to objects in the periphery.[170,171] In most situations, observers move their eyes to the attended location (overt attention). Visual attention has been studied using a number of techniques, including electroencephalography and eye movements. Because eye movements are important in interceptive skills and might also index skills that are independent of attention, we consider these separately here.

Visual attention: Visual attention can be directed to a location (spatial), to a stimulus property, such as its colour (feature-based), or to a single person or object (object-based). In sport studies, the most common measure reflecting visual attention is speed of information processing, measured as reaction time. In reaction time tasks, individuals respond to a stimulus as fast as possible, typically by pressing a key.[172] Processing speed represents the time to attend to and detect (in simple reaction time tasks) or discriminate (in choice or go/no-go tasks) the relevance of a stimulus.[173] Variations of this paradigm capture processing time with sport-specific stimuli or responses, such as swinging a bat.[174]

One of the most influential ways of testing visual spatial attention is the Posner (pre)cueing paradigm.[175] Locations are cued and thus attended (or unattended). Benefits (faster reaction times) and costs of cueing are compared to no-cue conditions to both validly and invalidly precued locations. The relative magnitude of benefits to costs indicates attentional flexibility.[176] The Posner paradigm also allows assessment of the ability to inhibit attention to return to previously attended locations.[177] Another form of attentional flexibility relates to the concept of inattentional blindness (or change blindness), where observers fail to notice an unexpected object/event while performing an unrelated task.[178,179] This 'blindness' has been related to perceptual capacity limitations.[180] Tests of inattentional blindness have been adapted to sport-specific scenarios[181] but not for interceptive sports.

A method that has increasingly been used to study expert-novice skill differences as related to visual attention, is electroencephalography (EEG). Through the placement of electrodes on the scalp of an athlete, neural activity in response to events is recorded. Visual-attention has been inferred through event-related potentials: brain activity in preparation of or in response to a particular event or movement. The latency (delay) and amplitude of these potentials allow inferences about attentional processing. Early negative and positive peaks of activity, around 100 ms (N100 & P100), index early visual processing and selective attention. Some studies have indicated that the N100 might be most sensitive to skill-based differences in quickly identifying stimuli.[182] Similarly, the N200 peak (negativity after 200 ms) has been linked to covert orienting of attention to peripheral targets.[183,184]

Even though visual spatial attention is classically viewed as the ability to select information, humans can divide attention to simultaneously and continuously track multiple objects or events.[185,186] In multiple-object tracking studies, observers view several small visual objects (e.g., 6-10 white discs) moving randomly, bouncing off the borders and each other. At the start of a trial, a few objects are highlighted as targets, before reverting back to their original appearance. At the end of each trial, observers select all target objects (mark-all procedure) or respond whether certain items were among the target objects (probe-one procedure). Observers can typically track up to five objects over several seconds.[185] This ability to simultaneously monitor multiple objects or regions in space is most representative of team sport environments[187] even though interceptive sports can have multiple tracking demands when decisions are based on more than just one object/person (e.g., in baseball, where the bases and pitcher/ball need monitoring). Recent technology affords tests of multiple object tracking in an immersive, 3D context, where stimuli appear to move in depth (NeuroTracker).[188]

Multiple object tracking requires observers to not only divide their attention between multiple targets, but to also sustain it. Sustained attention is the ability to maintain attention on one or more stimuli, such as the soccer ball from the perspective of the goalkeeper, for prolonged periods of time. When attention has to be sustained for longer, the term ‘vigilance’ is used. The computer based Psychomotor Vigilance Task involving 500 or more trials, is commonly used, where percentage of missed stimuli and/or decrease in time to respond indicates vigilance.[189,190]

As can be seen in **Table 2**, the literature on visual attention differences among different skill groups points to positive effects for tests which are sport-specific but not general tests of attention. For example, in a comparison of team-sport versus other sport athletes (including those who engaged in interceptive sports) and non-athletes, no differences were shown in behavioural (accuracy and speed) measures of attention, including a 2D multiple object tracking task and an inattention blindness task.[41] Similar results were shown in a study of elite table tennis players versus controls, when reaction time costs and benefits were compared in a Posner precue study.[63] However, table-tennis players, when compared to non-players, showed larger event related potentials, attributed to a strategy of preparing the cued motor response early whilst simultaneously devoting visual attention to the uncued location. When sport specific stimuli showed different baseball pitches, the P300 electroencephalography measure, thought to index stimulus identification, distinguished across skill groups.[60] Differences were shown between tennis experts, triathletes and non-athletes, in the accuracy of their detection of a ball in tennis serve stimuli, but not in non-tennis stimuli (but there were no reaction time differences).[59] This sport-specific selective attention effect suggests athletes in these interceptive sports knew where to look for an object as a result of experience with the sport. In general, there is a lack of evidence that general differences in visual-attention discriminate interceptive sport skill athletes from non-athletes (or elite from less elite). Any positive, visual attention effects related to group differences are isolated to sport specific contexts, although data is sparse and potentially confounded by movement speed in behavioural work.[61]

Eye movements: Eye movements provide a tool to assess both overt and covert visual spatial attention. They provide unique information about how visual attention is allocated and the control of eye movements appears to be an important skill in sport. Humans use a combination of different types of eye movements to enable a vivid percept of the environment. Saccades are quick displacements of gaze from one location to another, signaling overt attention.[191] They can be made in anticipation, such as the saccade landing ahead of the ball, predicting its trajectory. Saccadic eye movements are interspersed with periods of relative stability, fixations, during which visual information can be acquired. Smooth pursuit eye movements are strongly related to the perception of motion, for continuous tracking of objects or people. Vergence eye movements are made to switch between objects located in different depth planes (e.g., near objects, such as the ball and far objects, such as the opponent, in ball racket sports). There are also reflexive eye movements, such as the vestibulo-ocular reflex, which is important in compensating for head or body rotation to keep gaze fixed, especially important for balance. In sports, these eye movements are combined to achieve high-acuity vision.

Eye tracking technology has experienced a boost in recent years[192] and eye movements can now be measured reliably using wireless and portable technology inside and outside the laboratory.[9,10] Inexpensive, open-source eye tracking systems also exist (e.g., pupillabs; https://pupil-labs.com/). In addition to accurate eye tracking, most sports require the precise allocation of gaze on stationary objects of interest. Methods have been developed to assess accuracy and speed of saccades without eye tracking equipment, for example from reading speed under time constraints where the number of successfully read numerals correlates with the interval between saccades (e.g., the King-Devick test).[193,194]

A common fixational eye movement studied in sports is the “Quiet Eye” , defined as the relative stability of the eye focused on a critical location, before the initiation of a critical movement.[195] Although the quiet eye has mostly been explored in self-paced rather than interceptive tasks;[196] research has shown evidence of quiet eye strategies in high-skill versus lower skilled table tennis players, with the former showing an earlier onset of quiet eye coupled with overall better hitting.[78] The quiet eye differentiates performers of different skill and even within individuals based on success (e.g., saves/non-saves in goaltending),[197] in an array of sports. Taken together, studies using eye movement measures have increased and serve to give the researcher or practitioner information about where a person is looking, what information they are likely to perceive and utilize,[174] as well as how they prepare and subsequently control eye movements before and during a goal-directed hand movement.[198]

As is apparent in **Table 2**, most of the research based on skill group comparisons of eye movements has been conducted with sport-specific stimuli and this research has overwhelmingly shown differences in eye movements of more skilled versus less skilled athletes. The detailed kinematics of eye movements have been studied when tracking and predicting the trajectory of moving balls in the laboratory,[199,200] in virtual environments,[201] and in sport-specific contexts.[68,69,202]

In addition to differences in where experts look, superior eye movement control has also been observed in sport-specific settings. In varsity tennis, highly-ranked players tracked the ball after the serve until shortly before racket contact using smooth pursuit eye movements, in contrast to lower-ranked players who made a predictive saccade to the anticipated bounce location only.[82,201] Elite cricket batters relied on a combination of eye and head rotations to keep the ball close to the fovea and predict the location of ball bounce and bat-ball contact.[69] Eye movement differences are particularly important for tasks that involve trajectory prediction.[199,200] Indeed, the timing and accuracy of a predictive saccade can serve as a predictor of expertise.[68,69] In landing at or above the anticipated bounce location of a ball in interceptive sports, these predictive saccades presumably serve to prepare more accurate ball tracking with combined eye and head tracking after the bounce.[203] Even though predictive saccades take the eyes off the target for several hundred milliseconds, they might ultimately enable more accurate interception.[204]

In sum, studies of visual selective attention consistently reveal superior eye movement control in experts in comparison to novices, for example, earlier tracking and higher accuracy and precision of predictive saccades. Skill comparisons are nearly exclusively observed for high-level attentional skills when athletes are tested in their sport, with sport specific stimuli.

4. Cognitive skills

What we do with sensory information in order to produce an accurate and fast response is best captured as the cognitive component of perceptual-cognitive skills. Cognitive skills relate to higher-level cortical processes such as memory, situational knowledge, the ability to anticipate, make efficient and effective decisions, and to multitask.[41,205–208] Cognitive skills also include more general executive functions such as inhibition and interference control as well as cognitive flexibility.[209] Often, cognitive processes such as planning, problem solving, concept formation and abstract thinking as well as working memory and visual-spatial abilities are discussed as executive functions.[210] Here, we consider core executive functions to be those related to cognitive flexibility, inhibition and interference control as well as visual-spatial abilities (**Table 1**), in line with the focus of the sport literature.

The most common method for assessment of cognitive skills in sports has been one where the participant responds to sport-specific stimuli with a verbal or button-press response. Although there is research to suggest that the manner of responding does not impact the accuracy of decisions or the size of skill group effects,[107] there has been a growing trend for the response characteristics to match the physical characteristics of the action response required in the game.[106,211] This response-congruency can improve discriminability (across skills), but also enables better representation of the actual skill where performance can be altered by task and response requirements.

Anticipatory skills: Anticipation is part of decision-making skills and is probably one of the most investigated in sports. It is defined as the ability to predict outcomes before action onset based on prior information.[73,212] Anticipation underpins many sport-situations, both before they begin (based on contextual cues, knowledge of the player, etc.) and when the action starts to unfold (then more accurately referred to as prediction). The ability to anticipate or predict the outcome of a dynamic event, such as a penalty kick in soccer or the trajectory of a pitched baseball, is integral to many interceptive athletes involving many lower level visual-attentional skills required to locate, attend and discriminate. Accurate predictions are often based on early body-kinematic cues, such as the position of the non-kicking foot in soccer kicking or the position of the hips in responding to tennis serves,[53,73] but could also, or instead, be based on later ball trajectory cues.[93] For dynamic events, the skill to anticipate may also be linked to basic visual skills such as motion prediction and accuracy of eye movements.[200]

Commonly-used experimental tools to assess anticipation of the outcome of an event are temporal and spatial occlusion techniques. In temporal occlusion, vision is occluded at a specific point in time, either by freezing / stopping the video or by using occlusion goggles for in-situ paradigms (i.e., responder to a real bowler on the field).[189] Observers then have to predict the outcome, determining where and/or how to respond (spatial/action anticipation) or when to respond (temporal anticipation). In such occlusion studies, comparisons across athletes of varying levels of skill alert to when and what information is affording the expert advantage. Interceptive sport experts tend to focus longer on fewer locations than less skilled performers, attending to those areas that are rich in predictive information. For example, skilled cricket players, in contrast to intermediates and novices, used information from the bowling arm and hand to predict the type of bowl.[98] In spatial occlusion methods, information within the display is occluded to determine how important that information is for decision accuracy.[190] For example, the arm may be hidden (using video editing software), to determine whether this component is being used and hence anticipatory skills will be affected by this loss.[49]

The vast majority of research in anticipation in sport emphasizes spatial aspects of prediction and anticipation; that is, where and what event will occur, rather than when. Temporal anticipation or the coinciding of actions with events (analogous to many interceptive sports), has traditionally been assessed with the Bassin anticipation timer, which simulates motion of an approaching object by showing a track-way of lights that gradually extinguish as they near a coincidence point.[213] Computer versions of these temporal prediction tasks have been designed to simulate various ball speeds and interception points (through touch screen or motion capture technology).[84,214] Assessing the speed of the motor response through motion capture (e.g., the swing) allows analysis of movement onset and duration, variables that are used to compensate for differences between short and long time-to-contact intervals associated with differences in ball speeds (so-called velocity coupling).[215–217] Virtual reality simulations of ball spin and approach velocities and angles have also been used to test anticipatory decisions, with the emphasis on the type of information informing decisions.[218]

As shown in **Table 2**, there have been a considerable number of studies showing expert-novice differences in anticipation across a range of sports and mostly for sport-specific contexts. The most popular have been racket sports such as badminton and tennis, but goalies have also received considerable attention. Although there have been a few exceptions where no sport-specific anticipation advantages were shown across group, there is little doubt that elite athletes are able to make use of advance information to make fast and accurate responses in interceptive sports.

General decision making: It is typical for an athlete to decide between various possible courses of actions and/or outcomes when responding to events in the environment. Choice reaction time provides a general measure of the ability to quickly process information and to distinguish courses of action. Choice reaction time might be measured by the speed to respond to a left or right response button, corresponding to the appearance of an object. There is a lawful relation between the number of stimulus-response alternatives and reaction time, such that reaction time increases in a log-linear fashion as the number of choices increases (termed Hick's Law).[219] Although this relationship is linear, parameters of a linear fit to the data (i.e., intercept and slope) can change as a function of individual differences.

In a sports context, it is difficult to discern tests of anticipation from those more related to decision making as similar methods are often used. To qualify as a test of decision making here and in **Table 2**, the player was required to respond to an event (decide upon a response), rather than merely discriminate between different stimuli (such as a pitch in baseball). Often in tests of decision making, an athlete is asked to indicate the best response for a player with the ball given the current context (perhaps when a video is frozen).[9] Sometimes these decision tests are administered in time-sensitive situations. Accuracy is typically judged in reference to a unanimous decision reached by skilled coaches, with the assumption that coaches are better decision makers than the athletes they coach or test. Classical theoretical approaches assume that athletes generate all possible options internally before deciding how to act. However, this would be costly in terms of knowledge, time, and cognitive capacity. Instead, decision making might rely on simple heuristics, such as that the first available option might be the best.[220] Although this method of option generation has been used to distinguish athlete groups in team dynamic sports (e.g., handball),[221] we are not aware of this research in interceptive sports, where decisions are often more binary.

In general, as shown in **Table 2**, most of the research on decision skills has revealed statistically significant differences across skill groups in favour of the more skilled athlete, but only in sport-specific situations. For example, college baseball players were better able than non-athletes in deciding whether to swing, or not swing in response to a live pitcher.[67] In video analyses of actual in-situ game performance, expert tennis players, across ages (i.e., tournament ranked players), responded with stronger serve and post-serve decision responses in comparison to age-matched novice groups. Although we have distinguished anticipation from general decision skills, thus making this category seem somewhat understudied, if we combine these subskills as others have done,[222] there is considerable evidence supporting the superior decision skills of expert versus less skilled or non-athlete controls.

Memory and knowledge representations: Memory skills have been classified into short-term memory, working memory, and long-term memory. Short-term and long-term memory differ with regard to how long information is retained in memory: for short periods (seconds) versus long periods (hours to decades). Short- and long-term memory are typically assessed by recall and recognition paradigms. In sport-related studies, athletes may be presented with a video clip, a static scene, or altered displays, such as those containing markers placed at player or body-joint locations (point-light displays), and are then required to recall, recognize, or remark in some way on the details of the scene. Recall (or recognition) tasks have been shown to be linked to pattern recognition skills and to strategies such as item chunking, used to improve short-term retention.[223] Working memory also refers to the temporary storage of information, but in contrast to short-term memory, information can be held in an active state and manipulated (such as the rotation or re-ordering of objects)[224] to be readily usable for complex cognitive tasks such as decision-making or reasoning.[225] Tests of working memory typically rely on verbal processing, whereby individuals memorize digits, words or spatial locations, whilst simultaneously performing an attention-demanding secondary task (e.g., the operation span task[226] or the symmetry span task[227]). Individuals with high working-memory capacity can keep information accessible, despite demands placed on processing due to secondary tasks. Superior memory skills of elite performers are thought to be a combination of superior long-term and working memory skills, although there is evidence from work with baseball fans, that these memory skills are somewhat independent, with the former reflecting the build-up of sport-specific domain knowledge and working memory being a domain general ability.[228]

One technique which has been used to assess knowledge and memory representations is to solicit verbal responses about tactical strategies, rules, and procedures.[121,126,229] Some recent attempts to build and assess knowledge profiles (mental representations) using questioning techniques in addition to mathematical parsing/ clustering has been spearheaded by Schack.[230,231] Here, athletes are asked to make decisions about functional relations between various action components, comparing each presented action component (e.g., a visual picture) to another. This might be a series of action components (termed Basic Action Concepts) pertaining to things such as body posture, movement elements, and sensory consequences of an action.

In interceptive sports, knowledge and memory have been studied in a number of different ways. For example, visual working memory (using the symmetry span test) was compared among varsity softball players and a non-athlete control, but no group differences were noted. In tennis, Schack and Mechsner distinguished between player groups based on the way they classified a tennis serve into its basic action concepts.[128] The experts were, as a group, more consistent in how they performed this task, in comparison to lower-level players and non-players, and their organization of action components (e.g., bending the knee and throwing the ball) was functionally structured around the phases of the tennis serve (i.e., pre-activation, strike and final swing). As detailed in **Table 2**, other researchers have shown group differences in knowledge when comparing verbal reports of skilled versus less skilled youth athletes, typically showing these to be more evaluative and elaborate.[124,229] For example, through interviews during and after game play, expert youth tennis players explained their decisions in reference to higher level goals (e.g., games or sets, not points) and generated more (alternative) actions in response to various conditions of play.[53]

Game knowledge and context awareness are other key characteristics of interceptive sport athletes.[21,232] For example, a batter in baseball may anticipate what type of pitch will be thrown based on the preference of the pitcher as well as the current count (strike:ball ratio).[119] This context-related decision effect was shown in squash, where experts were better able to predict shot outcomes than novices, even when occlusion occurred before any preparatory shot information was available.[51] The ability to use context relevant information (e.g., opponent position on the court, or repetition of a play, or ball to strike count) to anticipate and/or make strong decisions is increasingly being shown to distinguish across skills groups, beyond more typical perceptual cues.[127,233] However, an overreliance upon contextual information without integrated pick-up of kinematic information can negatively impact anticipation.[234,235]

General executive functions*:* Executive functions are cognitive processes enabling the control of abilities and behaviours such as inhibitory and interference control, cognitive flexibility or creativity, and visual-spatial abilities. These are thought to be highly dependent on frontal areas of the brain and are mostly tested through standardized neuropsychological test batteries, which have been developed to diagnose disorders involving the prefrontal cortex. They are usually normed to large sample sizes, allow reliable measurement and are frequently used in sport to assess effects of exercise or potentially concussion on cognitive function. One of the main testing platforms used in sport is the Delis-Kaplan Executive Function System.[236,237] It is standardized, quick and easy to perform. However, it is designed to assess neurocognitive impairments and thus not necessarily suitable for fine discrimination within highly functioning adults. Many subtests require a mix of very broadly defined perceptual-cognitive skills. One example is the “design fluency” test, frequently used in sport studies, which operationalizes “problem solving” as the ability to quickly generate different visual patterns and draw new designs, akin to classic creativity tests.

Inhibitory control, as an example of an executive control task, can be measured by asking people to perform a classic Stroop task.[238] In this task, the ink colour of printed words displayed in a list are incongruent with the written words (e.g., the word “yellow” printed in red ink). Participants are instructed to say the colours of the words, inhibiting the automatic tendency to read the word. Speed in saying the colours is thus a measure of inhibitory control. Inhibitory control can also be investigated using Go/No-Go paradigms whereby participants are first trained to identify and respond to a certain object or letter (such as X and Y). Then, in a second test, they are asked to only respond to these letters in particular trials but not in others.[136,239] The ability to inhibit responses on "no-go" trials is taken as a marker of inhibitory control, as long as performance (accuracy and RT) is not negatively affected on the Go trials. Another option to investigate the temporal dynamics of inhibitory control is to test the speed at which observers are able to stop a response, so-called stop-signal reaction time.[133] Sports studies have also used the Eriksen flanker task,[240] requiring participants to make a series of speeded choice reactions to a target stimulus flanked on each side by a distractor. The extent to which distractors slow down reaction time and increase response errors reflects cognitive interference or inhibition. The smaller the flanker effect, the better a participant's ability to exhibit interference control.

Another highly-researched executive function is visual-spatial ability, often measured by mental rotation tasks.[241] In their simplest form, these tasks involve looking at rotated 2D or 3D objects or letters and deciding whether they are the same as comparison objects, which are presented in an upright orientation, or deciding whether objects are mirrored. Response times vary as a function of the degree of rotation and across individuals. Mental rotation paradigms are often used in tests of cognitive intelligence, but they have also been used as a proxy measure of mental imagery skills and have been linked to performance across a range of sports.[137,242] For example, Heppe and colleagues created 3D images of human figures from a back-view, rotated, and presented with an outstretched or bent arm.[243] Figures could then be rotated around either the longitudinal or the depth axis. Participants had to decide as quickly as possible whether the right or left arm was abducted.

Many of the cognitive skills described here overlap with the visual-attentional skills defined above, leading researchers to define these skills with respect to both aspects (i.e., perceptual-cognitive). Skills are often interdependent and assessed in combination (e.g., anticipation and memory), although it is mostly the case that sport-specific skill assessments are researched separately to the general skills measures. It is common to see these sport-specific skills referred to cumulatively as “game intelligence”,[244] particularly when discussed in reference to sport-specific assessments.

As can be seen in **Table 2**, there is mixed evidence attesting to skill-group differences for measures of executive function, regardless of whether the stimuli used are sport or non-sport specific. Superior inhibitory control (based on a Stroop-task) and problem-solving ability (based on the Delis Tower building task[236]) were reported in a study of differences in executive function between self-paced sports athletes (e.g., golfers, runners) to externally-paced sport athletes (e.g., soccer players, baseball hitters) of different skill levels.[138] However, the authors did not provide a breakdown of their athletes as a function of sport. Moreover, neither decision skills nor processing speed distinguished across the athlete groups and no skill-based differences were observed for any of the athlete groups. In a stop-signal task to test for inhibition skills among varsity tennis players, players had superior inhibition scores compared to varsity swimmers and non-athletes.[133] However, no differences in sport-specific or non-sport specific movement tests of stop-signal based inhibition were shown among high (national) and low (regional) skill badminton players.[61] Because a battery of tests is typical in these assessments of cognitive functions, when positive effects are noted, there may be a higher likelihood of statistically significant effects just because of the number of tests completed.

In summary, there is overwhelming evidence that interceptive sports athletes are very good at determining what decision is required based on reading sport-specific stimuli. Differences in general cognitive abilities across skill groups for interceptive sport athletes is sparse, but it is unknown whether this is due to many of these general features not being studied or a lack of significant effects and subsequent publication bias to publishing only statistically significant effects.

Summary and Conclusions

Visual skills required by athletes in interceptive sports are those that focus on the ability to keep a moving object close to the fovea and maintain a clear image, and to gain information about its future trajectory. The skills that most obviously contribute to this are dynamic visual acuity, biological motion processing, and eye movements (both tracking and anticipating). These visual skills must be coherently integrated with attentional processes in order to properly focus on the most informative cues for anticipation. Attention to salient areas of the visual scene allow the athlete to acquire the most valuable information from an opponent or object in order to have the best chance at a successful interception. These skills fuel arguably the most important ability in these sports, anticipation and successful decision making.

Our goal in this review has been to first define and discriminate across various perceptual-cognitive skills and methods which have been used in sports to distinguish across skill-groups, classifying these into four broad skills. With these distinctions, this review helps lay the groundwork for future research and assists practitioners and researchers in using this research to determine if and how to measure perceptual-cognitive skills and where to look for evidence. We acknowledge that we have not critiqued these studies with respect to the methods, particularly issues pertaining to reliability (e.g., stability across time) and validity (e.g., application from the lab to more immersive virtual reality settings or to the playing field). Our aim was to facilitate an understanding of the skills that are most valuable to interceptive sports' athletes in order to assist in developing the most effective or advantageous perceptual-cognitive skill set through identification and training.

With innovations in technologies for measuring or training perceptual-cognitive skills (e.g., gaze tracking, tracking of people or objects, and 3D simulations of game environments), there is an increasing need for clear definitions and categorizations of methods relating to skill measurement. In this review, we outline various methods and measures that have been adopted in sports to assess perceptual-cognitive skills. Rather than distinguishing these methods and measures based solely on whether they are general or sport-specific, we define and classify measures in relation to the underlying processes being assessed. Measures assessing visual and attentional skills range from fundamental tests of visual ability, such as visual acuity, to higher-level assessments, such as the ability to divide or sustain attention. Measures of cognitive skills involve standard neuropsychological or psychometric tests of cognitive function, as well as tests of decision-making in game-relevant contexts. Increased methodological and definitional clarity for researchers and practitioners in the assessment of perceptual-cognitive skills is important for understanding the evidentiary basis for the role of vision in sport. Moreover, it will be valuable for determining the validity and worth of emerging technologies.

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