Topical Review: Perceptual-cognitive Skills, Methods, and Skill-based Comparisons in Interceptive Sports

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SIGNIFICANCE: We give a comprehensive picture of perceptual-cognitive (PC) skills that could contribute to performance in interceptive sports. Both visual skills that are low level and unlikely influenced by experience and higher-level cognitive-attentional skills are considered, informing practitioners for identification and training and alerting researchers to gaps in the literature.

Perceptual-cognitive 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 article, 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 that 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) that have and have not differentiated across skill groups.

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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 that 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. Our aims are to assist the reader in adopting the most suitable technique for their research, and to gauge 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 a 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. Primarily because of 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 on skill-level differences in these other senses exist. 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 aforementioned skills 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 related, 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 (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, see Refs. 17–19). Prior classifications of visual skills for sports exist (e.g., 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 have mostly seen success in research that has lacked experimental rigor 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 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/nonathlete differences either with sport-specific stimuli and/or in sport-specific contexts, or in nonsport 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 skilled and lesser skilled players. In some studies, players have been compared with a matched, nonathlete control group (e.g., college students). Only studies that 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 to 2020), which meet the aforementioned criteria. We conducted a search of different combinations of keywords related to perceptual-cognitive skills in sport, including the following: skill, sport, expert*, performance, athlete, in combination with percept*, vision/visual (including subkeywords motion, color, depth), cognitive/cognition, attention, anticipation, prediction, decision making, executive function, memory, eye movements (including subkeywords fixation, saccade, pursuit, quiet eye), electroencephalography, and interceptive sport or skill, or any subsport/skill such as baseball, softball, cricket, badminton, table tennis, tennis, goalies, and 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 that 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.

PERCEPTUAL-COGNITIVE SKILLS: DEFINITIONS, METHODS, AND EVIDENCE

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

TABLE 1. Perceptual-cognitive skills and measures with potential relevance to interceptive sports

Skill	Skill subtype or description	Test/task example
1. Fundamental visual skills		
Visual acuity	Static acuity	Optotype identification on a standard letter chart
	Dynamic acuity	Identification of a dynamic object (e.g., Landolt C)
Visual field	Peripheral vision/functional field of view	Detection speed or accuracy for objects presented in the periphery, gaze-contingent displays
2. Low-level visual skills		
Color and contrast sensitivity	Color vision	Ishihara test plates
	Contrast sensitivity	Optotype identification on a low-contrast letter chart (e.g., Pelli-Robson)
Stereoacuity/depth perception	Static depth perception	Randot graded circles test
	Dynamic depth perception	Identification or discrimination task in virtual reality
	Convergence/vergence	Focusing at an object shown at near and far distance
Motion perception/sensitivity	Dynamic object perception	Discrimination of speed or direction of object motion
	Biological motion perception	Discrimination of motion or identification of action in point-like displays
3. High-level visual and attentional skills		
Visual attention	Spatial, feature, or object-based attention	Posner cueing paradigm, eye movement tasks, EEG measures of selective attention event related potentials
	Inattentional blindness	Detection of an object or feature when attention is directed away
	Divided attention/attentional flexibility	2D or 3D multiple-object tracking
	Sustained attention/vigilance	Psychomotor vigilance task
Eye movement control	Gaze shifting	Speed and accuracy of goal-directed eye movements, such as saccades and smooth pursuit
	Gaze stabilization	Speed and accuracy of reflexive movements that stabilize gaze, such as vestibulo-ocular reflex
	Quiet eye	Fixational stability, accuracy of smooth pursuit on critical objects in targeting tasks
	Visual search	Number of fixations on relevant locations
4. Cognitive skills		
Anticipatory decisions	Spatial/action anticipation	Prediction of shot type or outcome location after viewing occluded picture or video material
	Temporal anticipation/coincident timing	Prediction of onset of event or action after viewing occluded visual stimuli, judgment of time to contact
General decision making	Response selection	Choice RT
	Decision skills	Option generation, multiple choice
Memory	Short term	Immediate recall and recognition of scenes or patterns
	Working memory	Recall of words after an interval filled with another task
Situational knowledge	Strategic knowledge	Listing and assigning probabilities to action possibilities
General executive functions	Flexibility of thinking/creativity	Design fluency test, connecting dots in novel ways
	Inhibition/interference control	Stroop task, inhibitory control task, antisaccade paradigm, Eriksen flanker task
	Visual-spatial ability	Mental rotation task

EEG = electroencephalography; RT = reaction time.

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 ft 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 (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 because there were no cross-group comparisons, batting performance in professional cricket batsmen was only impaired when acuity was significantly degraded by

TABLE 2. Perceptual-cognitive skills that have been contrasted across different skill groups in interceptive sports (including penalty goal-tending situations in soccer and handball) in studies published from 1995 to 2020

	Significant differences		Nonsignificant effects	
PC skill/results	**Sport-specific**	**General stimuli**	**Sport-specific**	**General stimuli**
1. Fundamental				
Visual acuity		Baseball[35,36,37]		Badminton,[38] baseball,[39] interceptive athletes,[40,41] table tennis[42]
Visual field/peripheral		Interceptive athletes,[40] table tennis[42]	Cricket[43]	
2. Low level				
Color/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[52,53,54]	Badminton,[55] baseball,[56] tennis[57]	Tennis[58]	Tennis[59]
3. 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,[68,69,70,71] soccer GK,[72,73,74] table tennis,[75–77,78] tennis[53,79–82,83]	Baseball/softball[84,85]	Cricket,[86] handball GK[87]	Squash[88]
4. 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 and knowledge	Badminton,[122] baseball,[123] cricket,[70,71] tennis[4,121,124–128]			Softball[129]
Executive	Baseball,[130,131] table tennis,[132] tennis[133]	Badminton,[134] baseball,[135,136] open sport athletes, including badminton and table tennis[137]	Badminton,[61] tennis[135]	Badminton,[61] baseball,[136] mixture of athlete groups[138]

Comparisons are made across reported statistically significant and nonstatistically significant group differences and separated based on whether the studies used sport-specific stimuli/tests or general stimuli/ability tests. Note: Skills are divided into "fundamental" visual, including visual acuity and visual field; "low-level" visual skills, including "color" and "contrast" sensitivity, "depth" perception, and "motion" perception; "high-level" visual-attentional skills, including visual selective "attention" and "eye" movements "move"; and "cognitive" skills, including "anticipation" skills, "decision" making, "memory" skills, situational "knowledge," and general "executive" functions. Underlined references denote those that appear more than once in the table because of one or more of the following: multiple assessments of various skills, perhaps through test batteries, multiple ways of classifying the assessed skill, or more than one sport group comparison. Some researchers evaluated the same skill in sport-specific and general tasks. Where more than one test was included, studies are categorized as statistically significant or not according to outcomes in the majority of tests. GK = goalkeeper/goaltender; PC = perceptual-cognitive.

experimentally blurring vision with contact lenses of 1 to 3 D (~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),[33] 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 nonexpert 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] There is some recent evidence that fundamental visual skills such as acuity can serve as predictors of on-field performance in baseball.[139] 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 (Nike, Inc., Beaverton, OR), 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, 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 (except for sport-specific strategies to help pick up information in the periphery through gaze anchoring[153]), there is no direct evidence that these techniques are useful in identifying skill beyond correction of acuity to "normal" levels.

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 color and contrast perception, stereoacuity/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.

Color and Contrast Sensitivity

Color vision is the ability to detect objects and discriminate them based on the wavelengths of light they reflect (i.e., color). Because humans have three types of color-sensitive photoreceptors on the retina (for red, green, and blue), color vision is trichromatic. The most common type of color vision deficiency is deuteranomaly (red-green deficiency), affecting up to 5% of men.[154] Color vision can be tested using conventional tests such as the Ishihara test plates.[155] These plates consist of blobs of different colors and may contain a number, which has to be identified. Color perception is often studied as part of the assessment of contrast sensitivity, which is 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 to aid contrast discrimination.[157,160]

Color and contrast sensitivity have received some attention in tests of discrimination across various athlete skill groups (Table 2). Although impaired color 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 nonathletes with 61% accuracy,[40] and male elite table tennis players showed better contrast sensitivity than did nonplaying controls.[42] Although the research is sparse, what does exist points toward visual advantages for athletes over nonathletes. It remains unclear whether differences are a result of experience in the sport. 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 toward 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 that 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 approximately 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 (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, that is, 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 must discriminate its direction (coherence) or speed, through comparisons (i.e., which one was faster, were the dots moving toward 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, which is 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 nonathletes when discriminating looming objects (moving toward the athlete), but not other types of motion.[59] Impoverished or abstract visual displays can distract and bias experts' visual perception more than novices, although expert advantages are still shown.[52,58] 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.

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 several 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 color (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 with no-cue conditions to both validly and invalidly pre-cued 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. 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 milliseconds (N100 and 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 milliseconds) 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 to 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 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] However, 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 (CogniSens, Quebec, Canada).[188]

Multiple-object tracking requires observers to not only divide their attention between multiple targets but 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. When attention must 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 that 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 nonathletes, no differences were shown in behavioral (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 pre-cue study.[63] However, table tennis players, when compared with nonplayers, showed larger event-related potentials, attributed to a strategy of preparing the cued motor response early while simultaneously devoting visual attention to the uncued location. When sport-specific stimuli comprised 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 nonathletes, in the accuracy of their detection of a ball in tennis serve stimuli but not in nontennis stimuli (but there were no reaction time differences).[59] This sport-specific selective attention effect suggests that 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 nonathletes (or elite from less elite). Any positive visual-attention effects related to group differences are isolated to sport-specific contexts, although data are sparse and potentially confounded by movement speed in behavioral 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 seems 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 and 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., Pupil Labs, Berlin, Germany; 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/nonsaves 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 use,[174] and 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. 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 with novices. For example, experts show earlier tracking and higher accuracy and precision of predictive saccades compared to novices. Skill comparisons are nearly exclusively observed for high-level attentional skills when athletes are tested in their sport, with sport-specific stimuli.

Cognitive Skills

What we do with sensory information 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, and the ability to anticipate, make efficient and effective decisions, and 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, and 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 interceptives sports. Anticipation is built upon 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 nonkicking foot in a soccer penalty shot, or the position of the hips in responding to tennis serves.[53,73] Predictions 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).[98] Observers then must 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 do 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. 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]

Most 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 for 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 because 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).[220,221] 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 favor of the more skilled athlete but only in sport-specific situations. For example, college baseball players were better able than nonathletes 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 with 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 nonathlete 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 regarding how long information is retained in memory: for short periods (seconds) versus long periods (hours to decades). Short- and long-term memories 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 reordering 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, while 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 buildup of sport-specific domain knowledge and working memory being a domain general ability.[228]

One technique that 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 several different ways. For example, visual working memory (using the symmetry span test) was compared among varsity softball players and a nonathlete control, but no group differences were noted.[129] In tennis, Schack and Mechsner[128] distinguished between player groups based on the way they classified a tennis serve into its basic action concepts. The experts were, as a group, more consistent in how they performed this task, in comparison with lower-level players and nonplayers, 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.[124]

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 and 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 pickup of kinematic information can negatively impact anticipation.[234,235]

General Executive Functions

Executive functions are cognitive processes enabling the control of abilities and behaviors 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 as well as 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 color of printed words displayed in a list is incongruent with the written words (e.g., the word "yellow" printed in red ink). Participants are instructed to say the colors of the words, inhibiting the automatic tendency to read the word. Speed in saying the colors 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 reaction time) 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 can stop a response, which is the so-called stop-signal reaction time.[133] Sports researchers 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 widely 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[243] created 3D images of human figures from a back view, rotated, and presented with an outstretched or bent arm. 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 previously, 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 specific 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 self-paced sports athletes (e.g., golfers, runners) compared to externally paced sport athletes (e.g., soccer players, baseball hitters).[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 with varsity swimmers and nonathletes.[133] However, no differences in sport-specific or non–sport-specific movement tests of stop-signal–based inhibition were shown among high-skill (national) and low-skill (regional) 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 are 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.

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 to properly focus on the most informative cues for anticipation. Attention to salient areas of the visual scene allows the athlete to acquire the most valuable information from an opponent or object to have the best chance at a successful interception. These skills fuel arguably the most important abilities in these sports, which are anticipation and successful decision making.

Our goal in this review has been to first define and discriminate across various perceptual-cognitive skills and methods that 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 can assist 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 laboratory to more immersive virtual reality settings or to the playing field). Our aim was to facilitate an appreciation of the skills that are most valuable to interceptive sports' athletes (or at least most studied), to assist in identifying, assessing, and training these perceptual cognitive skills.

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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